OBSERVATORIES IN SPACE

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Contents

Summary

Space observatories are having major impacts on our knowledge of the Universe, from the Solar neighborhood to the cosmological background, opening many new windows out of reach to ground-based observatories. Celestial objects emit all over the electromagnetic spectrum, and the Earth's atmosphere blocks a large part of them. Moreover, space offers a very stable environment from where the whole sky can be observed with no (or very little) perturbations, providing new observing possibilities. This chapter presents a few striking examples of astrophysics space observatories and of major results spanning from the Solar neighborhood and our Galaxy to external galaxies, quasars and the cosmological background.

1. Introduction

Observing the sky, charting the places, motions and luminosities of celestial objects, elaborating complex models to interpret their apparent positions and their variations, and figure out the position of the Earth – later the Solar System or the Galaxy – in the Universe is a long-standing activity of mankind. It has been made for centuries from the ground and in the optical wavelengths, first measuring the positions, motions and brightness of stars, then analyzing their color and spectra to understand their physical nature, then analyzing the light received from other objects: gas, nebulae, quasars, etc. It was not before 1930-1940 that a new window to the Universe was opened with the discovery that some celestial sources emitted not only in visible wavelengths but also in radio wavelengths: the centre of the Galaxy and its spiral arms, the Sun and supernovae remnants.

The story of the word “satellite” is a long one as it was introduced by Kepler in 1610 when he was observing the moons of Jupiter, just discovered by Galileo. Even though the first idea to observe celestial objects from space may originate from Jules Vernes with his book *From the Earth to the Moon*, written in 1865, the first scientific work explaining how to send an “artificial satellite” in orbit around the Earth is probably the book of Konstantin Eduardovich Tsiolkovsky, T*he Exploration of Cosmic Space by Means of Reaction Devices*, published in 1903. Half a century later, the study of the Earth environment during a period of solar maximum activity was the occasion to create the International Geophysical Year (July 1957 to December 1958), and its committee urged the participating countries to use the observing possibilities of artificial satellites to better reach their scientific goal, the study of the upper atmosphere. Taking benefit of the technology developments driven by the need for weapons during World War II, the first launches took place late 1957 and early 1958: Sputnik 1 and 2 launched by the Soviet Union on 4 October and 3 November 1957, and Explorer 1 launched by the United States of America on 31 January 1958. Even though a scientific impulse was at the origin of these launches, they were clearly the result of a political race between the two Superpowers. Nevertheless, the scientists - and especially the astronomers – were rapidly the first the exploit the new possibilities offered by space techniques: as soon as 1961, many planetary probes (Mariner, Ranger, Venera, Luna, etc.) were launched to the Moon, Mars and Venus by both the USA and USSR.

The astronomers also realized very soon the importance of installing instruments on-board satellites with the goal of observing celestial sources emitting in wavelengths of the electromagnetic spectrum unobservable from the ground because they are blocked by the atmosphere. Explorer 11 (shown in Figure 1, left) was the first gamma-ray observatory. Launched by the recently created NASA (the USA National Aeronautics and Space Administration) on 27 April 1961, it observed 22 events attributed to cosmic gamma-rays all over the sky. Uhuru (shown in Figure 1, right), also launched by NASA on 12 December 1970, was the first Earth-orbiting mission entirely dedicated to X-ray astronomy. It observed 339 sources, published by W. Forman et al. in 1978 as “The fourth UHURU catalog of X-ray sources”. These sources were mainly identified to binary stellar systems in the Milky Way, supernova remnants, Seyfert galaxies and clusters of galaxies. Besides these pioneering missions especially designed to explore the high-energy domain, many detections of celestial high-energy sources were made by satellites launched for many other reasons: observation of the Sun or watch for countries violating the interdiction of atmospheric testing of nuclear weapons (!).

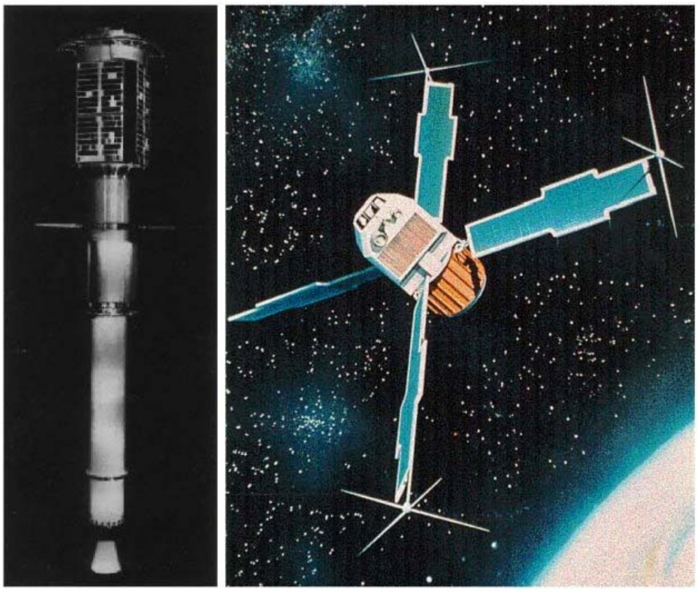

Figure 1. Left: Explorer 11, first gamma-ray satellite, launched by NASA on 27 April 1961 (from http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/explorer11.html). Right: Artist view of Uhuru, first Earth-orbiting satellite entirely dedicated to X-ray astronomy, launched by NASA on 12 December 1970 (from http://heasarc.gsfc.nasa.gov/docs/uhuru/uhuru.html).

After these pioneering high-energy missions, astronomy benefited from space environment to collect observations all over the electromagnetic radiation range. Indeed, space has major advantages for astronomy:

- Space observations are free from the absorption caused by the Earth's atmosphere. Indeed, the Earth's atmosphere is opaque to most of the electromagnetic radiation spectrum, with the exception of the visible light, some infrared (IR) and ultraviolet (UV) wavelengths, and most of the radio domain. Astronomical objects emit in the whole range of the electromagnetic spectrum and going to space opens many new windows to the Universe.
- Space offers a very stable environment: space observations are free from the turbulence caused by the Earth's atmosphere and very little affected by gravity effects. These unique observing conditions lead to unprecedented high-resolution images and optimal photometric and astrometric accuracies.
- Space observatories offer the unique possibility to observe the same targets for very long periods, which is impossible from the ground for various reasons (day-night or seasonal interruptions, bad weather).
- Finally, observing with a satellite is the only way to have access to the entire sky with the same instrument. This is the guarantee of the homogeneity of the data, essential in many global analyses of the sky and, in the case of astrometry, the only way to obtain absolute measurements of trigonometric parallaxes, then absolute distances.

However, of course, ground-based astronomical observations have many other advantages: the telescopes and their instruments can be constructed in successive steps and progressively improved, they can be repaired which makes their lifetime generally much larger than that of space observatories and new instruments can be installed (in space, this has only been possible with the Hubble Space Telescope, at a very high cost), they can be very heavy and/or very large and, last but not least, they can be operated by astronomers. Finally, ground-based telescopes are less expensive than space telescopes, and the risk associated with building a telescope on the ground is of course much smaller than to launch a satellite.

By *space observatory*, we mean space devices able to globally observe the sky or large parts of the sky, leading to a mass of new information, processed homogeneously. This chapter is concentrating on a few striking examples of such observatories that had, are having, or are expected to have major impacts on our knowledge and understanding of the structure, formation and evolution of the Universe, from the Solar neighborhood to the cosmological background. They are presented by increasing wavelength, from High Energy to Microwave and gravitational wave observatories, through Ultraviolet, Optical and Infrared observatories.

2. The Impact of the Earth Atmosphere on Astronomical Observations

The sky as observed from the Earth in the optical (or visible) wavelengths is only a very partial view of all objects observable in the Universe. Indeed, as a function of their temperature, celestial objects emit in various wavelengths, from the extremely high energetic gamma-rays to low radio waves, and different parts of the same object will be scrutinized if observed in different wavelengths. Each part of the whole electromagnetic radiation spectrum will open a new window to the Universe and bring different information. Only from the confrontation of all this information can a consistent picture of the Universe be obtained. Table 1 summarizes key information about the main types of radiation, the typical types of celestial sources observed in these wavelength ranges and examples of space observatories operating in these domains of radiation.

Type of radiation	**Wavelength range**	**Frequency range (Hz)**	**Typical sources**	**Temperature of radiating objects**	**Examples of space observatories**
Gamma-rays	< 0.01 nm	> 3 x 10^{19}	Compacts objects (from neutron stars to black hole candidates or active galactic nuclei), galaxies, Gamma-Ray bursts.	> 10^{8} K	INTEGRAl, Fermi (ex-GLAST)
X-rays	0.01 – 20 nm	3 x 10^{16} – 3 x 10^{19}	Stellar corona, pulsars, star formation regions, colliding galaxies, hot gas in galaxies and clusters of galaxies, supernova remnants, environment of	10^{6} – 10^{8} K	Chandra, XXM-Newton, Suzaku *IXO*

			super-massive black holes.		
Ultraviolet	20- 400 nm	7.5 x 10^{14} – 3 x 10^{16}	Very hot stars, supernova remnants, quasars.	10^5 – 10^6 K	IUE, FUSE, HST
Visible	400 - 800 nm	4 x 10^{14} – 7.5 x 10^{14}	Stars (atmospheres), planets, galaxies, reflection and emission nebulae.	10^3 – 10^5 K	HST, Corot, Kepler, Hipparcos, *Gaia*
Infrared (IR)	0.8– 50 μm	6 x 10^{12} – 4 x 10^{14}	Cool stars, star forming regions, interstellar dust and gas, planets	10 – 10^3 K	ISO, Spitzer, Akari, WISE, *JWST*
Far-IR and microwaves	50 μm - 10 mm	3 x 10^{11} - 3 x 10^{13}	Cosmic Microwave Background, cold interstellar medium.		WMAP, Herschel, Planck
Radio	> 1 cm	< 3 x 10^{11}	Interstellar medium, cold molecular clouds, supernova remnants, planets.	< 10 K	-

Table 1. Wavelengths and type of celestial objects. Right column: examples of satellites within each wavelength range and, in italic, satellites in construction or in project. Adapted from http://outreach.atnf.csiro.au/education/senior/astrophysics/wavebands.html.

All the above is related to the *thermal* radiation emitted by celestial objects considered as blackbodies. As shown in Table 1, the hotter the object, the shorter is the wavelength of the radiation it emits. Some mechanisms also produce *non-thermal* radiation, unrelated to the temperature of the object: synchrotron emission from electrons accelerated or decelerated in a magnetic field (in pulsars or quasars for example); Compton and inverse-Compton scattering increasing or decreasing the energy of X- and gamma-rays, respectively decreasing and increasing their wavelengths (gamma rays from active galaxies, supernova remnants or diffuse gamma rays from molecular clouds; X-rays from accreting black holes or CMB (cosmic microwave background) photons scattered by the electrons in the hot gas surrounding galaxy clusters); masers (microwave-amplified-stimulated emission of radiation) where emission from certain molecular lines can be enormously amplified.

The radiations emitted by celestial objects are very much affected by the Earth atmosphere which is totally or partially opaque to most wavelengths with the notable exception of the optical light and radio wavebands, and those radiations that are not blocked by the atmosphere are suffering various perturbations when crossing it. The Earth atmosphere is a mixture of various gases, mainly Nitrogen (N_2), Oxygen (O_2), Argon (Ar) and Carbon dioxide (CO_2), and water vapor in very small quantities (typically 1 - 4 % close to the Earth), dust, pollen, volcanic ash and other human industrial pollutants. Many other gases are present in extremely small quantities such as Helium (He), Methane (CH4), Hydrogen (H_2) or Ozone (O_3).

Some of these components have major impacts on the radiations received from celestial objects: most of the infrared, sub-millimeter and microwave radiations are absorbed by water and carbon dioxide molecules, the ultraviolet by ozone and oxygen molecules, the X-ray radiation suffers photo-electric absorption when encountering nitrogen or oxygen atoms in the high atmosphere. The γ-rays up to very high energies are absorbed by atmospheric electrons and nuclei. Ground-based astronomy is again becoming progressively possible for energies above the TeV by the indirect detection of the Cherenkov radiation created by the interaction of high-energy particles (cosmic rays emitted by supernovae explosions, high-energy gamma rays emitted by accreting binary systems, etc.) with the upper atmosphere. The atmosphere is transparent to most of the radio domain except for the shortest wavelengths (below 2 cm) absorbed by water molecules and for the very long ones (larger than a few meters), reflected by the ionosphere back into space.

These effects are illustrated in Figures 2 and 3. Figure 2 gives an overview of the Earth's atmospheric transmittance over the whole electromagnetic spectrum. Figure 3 gives the details of the absorption by several molecules in the ultraviolet, optical and infrared domains.

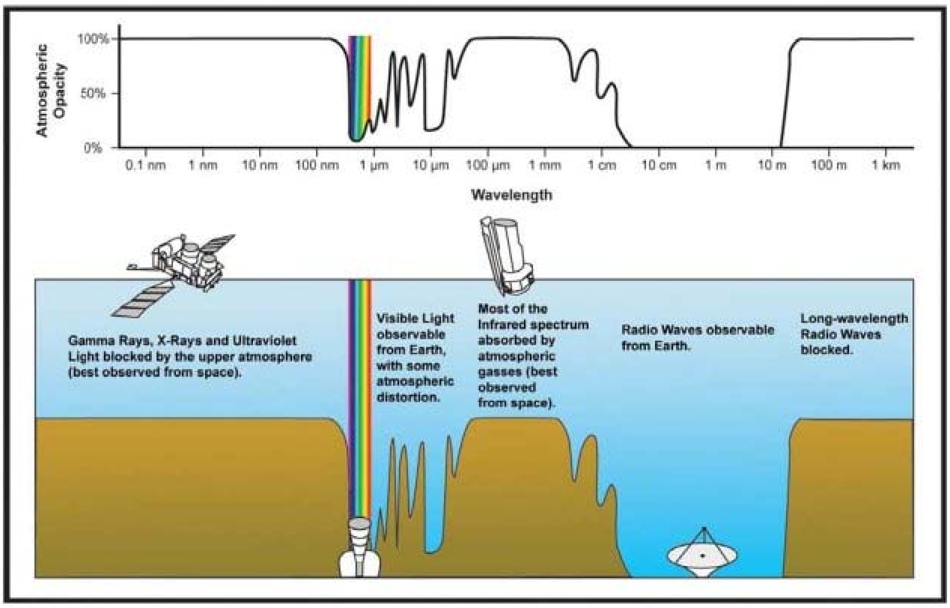

Figure 2. Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation. From http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_astronomy/orbit.html.

Besides these absorption effects, the atmosphere also perturbs the radiation that is transmitted to the ground. This explains why there are also satellites observing the sky in visible light. The dust and mist particles in suspension in the atmosphere produce scattering of the light. The visible light is specially affected by scattering as its wavelength is of the same order of magnitude as the diameter of the scattering particles. Also, the atmosphere is constantly in motion and suffers from small variations in temperature and pressure causing motions and distortions to the incoming light. As a result, images of celestial objects are blurred and constantly affected by tiny changes in brightness and position. The apparent position can vary over angular ranges of a few arcseconds. The intensity of these effects in a given location is called *seeing.* The largest telescopes on-ground are situated in high and dry mountains and far from big towns where the seeing is much better. Best sites achieve, rarely, seeing of better than 0.5 arcseconds. Observatories in space do not suffer any distortion from the atmosphere and obtain very stable images and a much better resolution than the best ground-based telescopes, even those obtained with the powerful techniques of adaptive optics that considerably compensate for these seeing effects.

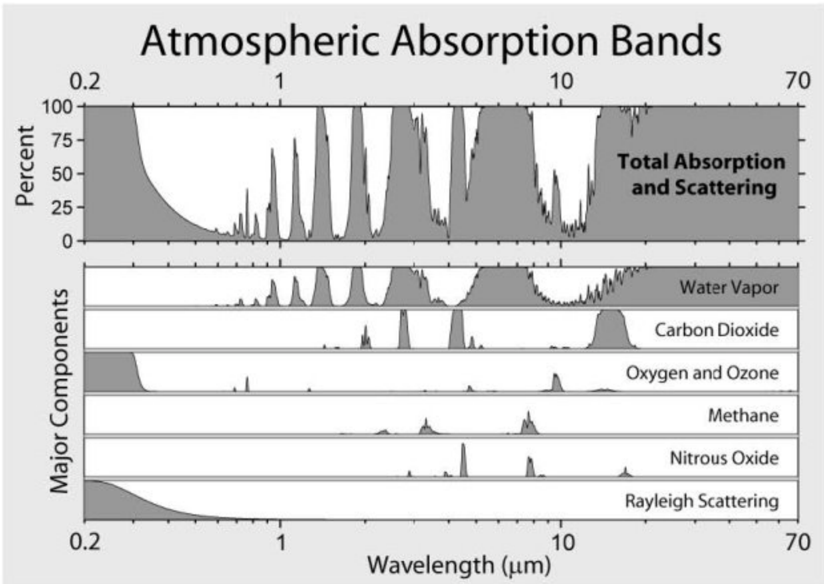

Figure 3. Atmospheric transmission and absorption bands by molecules in the ultraviolet, optical and infrared domains. From http://www.globalwarmingart.com/wiki/ File:Atmospheric_Absorption_Bands_png (by permission of Robert Rohde).

3. High-Energy Space Observatories

By the middle of the 20th century, it was known theoretically that a number of different processes occurring in the Universe should produce high-energy photons, such as supernovae explosions or interactions of cosmic rays with interstellar gas. However, since the Earth atmosphere is mostly opaque to high-energy radiation, only observatories situated above it can detect it. For energies greater than about 30 keV, hard (more energetic) X-rays and gamma-rays can be observed from instruments embarked on rockets or balloons, but only satellites, orbiting above the atmosphere, are able to observe the full range of high energies and obtain, through long exposures, enough high-energy photons to achieve detailed studies of the many celestial objects emitting in these wavelengths, thus opening new windows to the unknown. These characteristics explain the very large number of satellites (more than a hundredth) in this domain of energy since the 1960s.

3.1. Gamma-Ray Space Observatories

Since 1961 and the first satellite carrying aboard an instrument with a detector designed to detect gamma rays above 50 MeV (Explorer 11), much progress has been made both in the sensitivity of the detectors - increased by factors of 1000 – and in the localization of the sources over the sky, even if this last point remains one of the main difficulties for interpreting of such observations. An unexpected discovery boosted the curiosity of astronomers for this energy domain: the gamma-ray bursts, discovered by American military Vela satellites designed to detect clandestine nuclear bomb tests. Instead of nuclear bomb tests, they detected flashes of inexplicable gamma-ray radiations, and rough estimates for their positions on the sky convinced the military teams that this emission does not originate from either terrestrial or solar sources.

Gamma-ray astronomy explores the most extreme environments and the most violent events in the Universe, places where temperatures can reach hundreds of million degrees, where matter is incredibly dense and/or magnetic fields and gravity extremely strong. Typical targets besides gamma-ray bursts are black holes, neutron stars and pulsars, supernovae, active galaxies and quasars, stellar binaries containing a neutron star or a white dwarf, and many unidentified sources.

INTEGRAL

INTEGRAL, INTErnational Gamma-Ray Astrophysics Laboratory, launched on 17 October 2002 from Baikonur on a Russian Proton launcher into a highly elliptical 72 h orbit with an initial perigee of 9000 km and an apogee of 154 000 km, is an ESA-led mission involving Russia, the United States, the Czech Republic and Poland. INTEGRAL remains the most sensitive gamma-ray observatory ever launched and the first space observatory that can simultaneously observe objects in gamma rays, in the range 15 keV to 10 MeV, X-rays and visible light. The satellite is equipped with two gamma-ray instruments: the SPI spectrometer, optimized for high spectral resolution in the energy range 20 keV to 8 MeV, and the IBIS imager, for high spatial resolution providing accuracies in source location of better than 1 arcmin, and two monitors: in X-ray and in the optical V-band.

The first major scientific result from INTEGRAL was the discovery that the low gamma-ray emission from our Galaxy is not due to the interstellar medium but to discrete compact sources, mainly accreting binary systems with a black hole or a neutron star. A second result represents a significant step forward in the identification of the mysterious astrophysical sources that are producing the 511 keV line emission in the centre of the Milky Way, at a rate of about 10^{43} positrons per second. This emission of photons is produced via the annihilation of electrons with their antimatter particles, the positrons. INTEGRAL's all-sky map of the 511 keV line emission, obtained via the combination of more than 4 years of observations using the SPI spectrometer (50 million seconds of data!) and an increased spectral and spatial resolution, revealed that the emission is strongly peaked towards the centre of the Galaxy, with an asymmetry along the galactic disc. A careful study of the distribution and characteristics of these 511 keV data led to the conclusion that dark matter is not at the origin of the galactic positron annihilation and that it can be readily explained in terms of classical sources of positrons such as supernova ejecta, winds of Wolf Rayet stars and low-mass X-ray binary systems. The observed asymmetry could be simply explained by the asymmetry of the Galactic spiral arms as seen from the Solar System.

Finally, the publication in July 2010 of the fourth INTEGRAL Soft Gamma-Ray Survey Catalogue, constructed from more than 70 million seconds of observing time with the IBIS imager, now contains more than 700 sources with a substantially increased coverage of extragalactic fields as compared with previous issues of the IBIS survey. The catalogue is now dominated by Active Galactic Nuclei (AGNs, about 30%), followed by High Mass X-Ray Binaries (13%), Low Mass X-Ray Binaries (13%) and Cataclysmic Variables (5%). Unknown sources now constitute nearly 30% of the source list, but the catalogue also provides hard X-ray sources and multi-wavelength follow-up observations that are expected to lead to a large fraction of identifications. A map of the new sources (fourth catalogue compared to the third one) is given in Figure 4, superimposed on the increase in exposure time since the third catalogue.

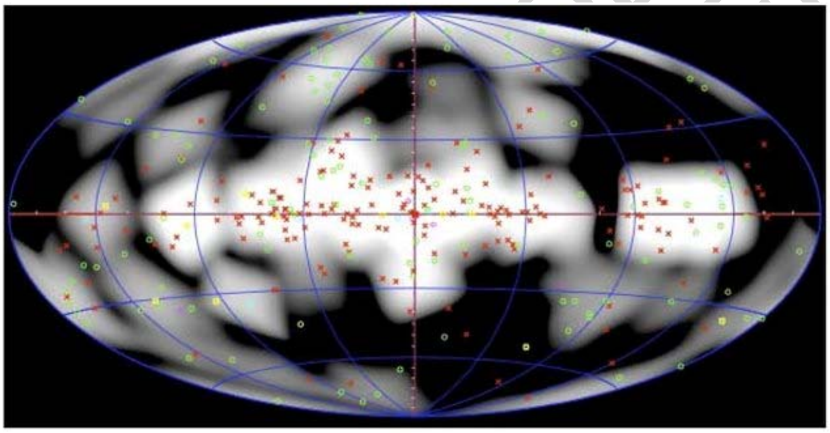

Figure 4. ESA, INTEGRAL mission. Map of incremental exposure since the third catalogue, showing the locations of the new sources found. Key: green circles = AGN; cyan squares = High Mass X-Ray Binaries; magenta diamonds = Low Mass X-Ray Binaries; yellow boxes = Cataclysmic Variables; red crosses = unknown. From http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=45620. Credit: ESA.

Swift

Swift is a NASA-led mission, part of the medium explorer programme (MIDEX), with instruments developed by an international team from the United States, the United Kingdom and Italy, and additional scientific involvement of many other countries. It was launched into a low-Earth circular orbit by a Delta 7320 rocket on 20 November 2004. Swift is a multi-wavelength observatory dedicated to the detection and detailed study of gamma-ray bursts (GRB). Its three instruments are designed to work together to observe GRBs and afterglows in the gamma-ray (Burst Alert Telescope, BAT), X-ray, (X-ray Telescope, XRT), ultraviolet and optical (Ultraviolet/Optical Telescope, UVOT) wavebands. The Burst Alert Telescope is the largest of the instruments, operating in the domain 15-150 keV with a very large field of view (2 steradians) and high sensitivity. Once a GRB is detected, its position is computed on-board with a 3 arc-minute positional uncertainty and relayed within 20 seconds to a network of ground-based observers. In less than about 90 seconds, the spacecraft will autonomously "swift" to that position in order to unable the other two (narrow-field) instruments to observe the burst afterglows and obtain higher accuracy position of the GRB: X-ray spectra between 0.3 and 10 keV will be obtained with the X-ray Telescope, images and spectra (via a grism filter) using the UV/Optical Telescope. For the brightest UV/optical afterglows, the spectra recorded by large ground-based telescopes (such as the VLT) can then be used to determine the redshift of the burst.

The main objectives for the mission are to detect and observe hundreds of GRBs with durations from milliseconds to thousands of seconds and their afterglows, to identify the progenitors of the bursts and characterize their host galaxies, to perform detailed multi-wavelength analysis of their afterglows in order to better understand the evolution of the blast and its interactions with the surroundings, and finally to use these observations to better understand the early Universe.

There is a huge variety of gamma-ray bursts: some of them only last fractions of second while others last a few hundred seconds, occasionally longer. They are followed by *afterglows* in longer wavelengths, observed over much longer times. A major breakthrough in the observation of these extreme phenomena came from the Italian-Dutch satellite Beppo-SAX in 1997, which provided the first precise burst position and discovered its X-ray afterglow, providing the confirmation of the cosmological distances of the bursts. This discovery opened the way to the discovery of afterglows in the whole radiation domain and to their systematic observation. The emerging interpretation of these observations is that the shortest bursts are emitted when two compact objects - either a pair of neutron stars or a neutron star and a black hole - collide and merge, and the origin of longer bursts is the collapse and death of (super) massive stars exploding as "hypernovae".

Soon after its launch, on 27 December 2004, Swift was one of many observatories that observed the brightest gamma-ray source ever seen from outside the solar system: an exceptionally bright flare from the galactic SGR 1806-20, a strongly magnetized neutron star called magnestar, about 15 000 pc away, in the Sagittarius constellation. The total flare energy was about a hundred times higher than the other two previously observed giant flares. The tremendous luminosity of the initial gamma-ray spike was consistent with the catastrophic release of (nearly) pure magnetic energy from the magnestar and probably occurred during a catastrophic reconfiguration of the neutron star's magnetic field.

On 13 April 2010, Swift discovered its 500th burst, GRB 100413B, a long burst in the constellation Cassiopeia. An all-sky map showing the locations of the 500 first gamma-ray bursts detected by Swift is given in Figure 5. These GRBs may be as close as about 30 million pc and as far away as 4 billion pc, covering a span of time equivalent to about 95 percent of the universe's age. The farthest burst of this impressive series was observed on 23 April 2009: GRB 090423 in Leo, 4.3 billion pcs away, is one of the most distant objects known in the Universe.

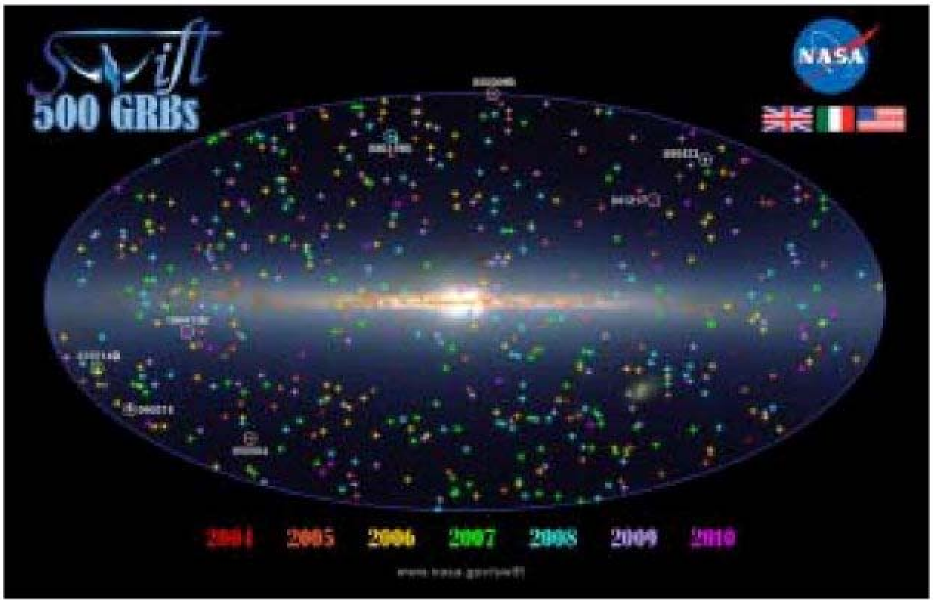

Figure 5. NASA. Swift mission. All-sky map showing the locations of Swift's 500 first gamma-ray bursts, color coded by the year in which they occurred. In the background, an infrared image shows the location of our galaxy and its largest satellites. From http://www.nasa.gov/mission_pages/ swift/bursts/500th.html. Credit: NASA/Swift/Francis Reddy.

Fermi

The NASA-led Fermi Gamma-ray Space Telescope (formerly GLAST) is the last in the series of gamma-ray observatories: it was launched on 11 June 2008 from Cape Canaveral by a Delta II rocket in a low-Earth circular orbit and is the result of an international and multi-agency cooperation between NASA, the U.S. Department of Energy and institutions in France, Germany, Japan, Italy and Sweden. It is operated in the energy range 10 keV - 300 GeV and is also aiming at the exploration of most extreme environments in the Universe. Its main instrument, the Large Area Telescope (LAT), is a gamma-ray, large field of view, imager (20 MeV - 300 GeV) providing all-sky coverage several times per day. Operating more like a particle detector, the LAT uses 880000 silicon strips within a 1.8-meter cube, and is able to detect high-energy gamma rays with unprecedented resolution and sensitivity: it is about 30 times more sensitive than any previous satellite gamma-ray detector and is able to determine the location of a source to better than half an arc-minute. The second instrument, the Gamma-ray Burst Monitor (GBM), is an all-sky monitor in the range 10 keV - 25 MeV aiming at the detection of transient phenomena such as occultations and gamma-ray bursts.

Published in May 2010, the first Fermi-LAT catalogue is the result of the first 11 months of data. It includes 1451 sources, from star burst galaxies and active galactic nuclei (AGN) to galactic pulsars, supernova remnants (SNR), X-ray binary stars (HXB) and micro-quasars. 630 of the sources remain unidentified, not associated with sources detected at lower energies. A map showing the sky distribution of the whole catalogue in galactic coordinates is given in Figure 6.

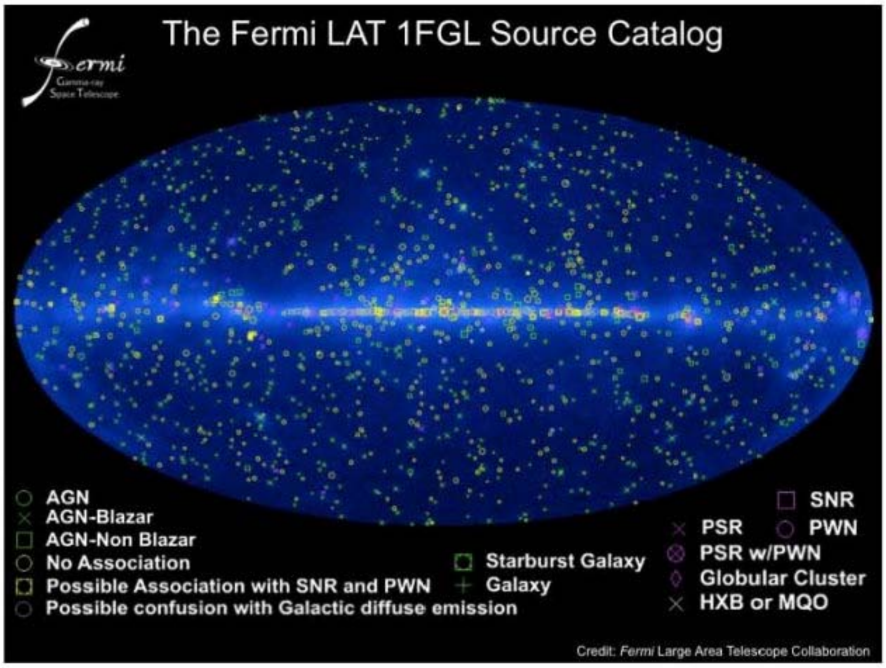

Figure 6. Fermi Gamma-ray Space Telescope's first all-sky catalogue, obtained from 11 months of sky survey data using Fermi's Large Area Telescope (LAT). AGN = active galactic nuclei, PSR = pulsars, PWN = pulsar wind nebulae, SNR = supernova remnants, HXB = x-ray binary stars, MQO = micro-quasars. From http://apod.nasa.gov/apod/ap100318.html. Credit**:** NASA, DOE, International Fermi LAT Collaboration

One remarkable highlight of Fermi is the observation of Centaurus A, one of the closest radiogalaxies, situated at distance of about 4 million pc. In its centre there is a super-massive, very active, black hole, from where jets of magnetized particles are ejected, producing strong emission at many different wavelengths. A radio-optical-gamma-ray composite image of the galaxy is shown in Figure 7. The optical image of the host giant elliptical galaxy, NGC 5128, is in the centre. The diffuse high-energy gamma radiation detected by Fermi's LAT is the much larger purple halo, and the full extent of Centaurus A is given by the giant radio-emitting lobes (color-coded in orange), stretching to more than 0.4 Mpc. This diffuse gamma-ray emission is explained by the collision between the highest-energy particles of the radio lobes and the cosmic microwave background photons. This process was known to produce X-rays in many active galaxies, but it is the first time that microwave photons are shown to be up-scattered to gamma-ray energies.

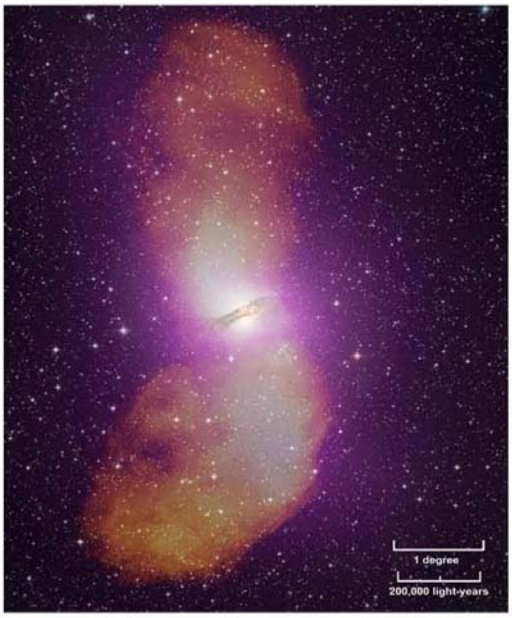

Figure 7. Radio/optical/gamma-ray composite image of the active radiogalaxy Centaurus A. In the centre: the optical image. In purple: the diffuse gamma-ray emission observed by Fermi's LAT. In orange: the radio emission. From http://www.nasa.gov/mission_pages/GLAST/news/smokestack-plumes.html. Credit**:** NASA/DOE/Fermi LAT Collaboration, Capella Observatory, and Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR)

3.2. X-Ray Space Observatories

X-rays are the signature of the hot Universe: from the solar corona to hot gas in the most distant clusters of galaxies, from planets to stars and supernova remnants, from hot gas in star forming regions to colliding galaxies or gamma-ray bursts afterglow, X-rays are an extremely powerful tool to explore the Universe at all scales. Figure 8 is an illustration of the major differences between the X-ray sky and the optical sky. The image on the left shows the constellations of Orion and Canis Majoris with the Moon to the top. To the right is the same area of the sky as imaged in X-rays. Sirius is visible to the bottom left of each image. However, in the optical it is Sirius A, the brightest star in the visible sky, and in X-rays it is Sirius B, the white dwarf companion of Sirius A. The bright blue source to the top of the X-ray image is the Crab Pulsar surrounded by the Crab nebula while the Moon is very faint.

The atmosphere is totally opaque to X-rays and, from the 1960's, many X-ray instruments have been used to study the X-ray Universe from space. The first attempts were just detectors carried to the upper atmosphere on rockets. An X-ray test detector on board a V2 rocket, launched on 5 August 1948, recorded the first solar X-ray. Then a few other attempts were made on the Sun showing that the level of emission from the Sun was so low that it was not worth trying to observe other celestial objects. However, in 1962, a detector with a much-improved sensitivity was embarked on a rocket to try and detect the reflected X-ray emission from the Moon. It indeed detected the emission from the Sun and the Moon, but also, unexpectedly, a strong emission from the Scorpius constellation: a first X-ray source was discovered outside the Solar System: Scorpius X-1. This discovery opened the way to a new field of astronomy: the exploration of the Universe in X-ray band. Riccardo Giacconi received the Nobel Prize in Physics in 2002 for developing this new research domain.

Figure 8. The X-ray sky as compared to the optical sky. These are two images of the constellations of Orion and Canis Majoris. Left: in optical wavelengths. Right image: in X-rays, showing the hottest objects of the field. From http://www-xray.ast.cam.ac.uk/xray_introduction/History.html: The History of X-ray Astronomy, Cambridge X-Ray Astronomy Group.

From the 1960's, much progress has been made - and is still being made – in X-ray technology, especially in the detectors and in the X-ray optics (much lighter mirror assembly, then much larger collecting areas, better angular and spectral resolution), greatly increasing the overall sensitivity and the ability to focus X-ray radiations. These advances are allowing high-quality images and spectra and lead to detailed studies of millions of X-ray sources. Several X-ray satellites are now in operation: RXTE, the Rossi X-ray Timing Explorer (launched in 1995) and Chandra (launched in 1999) operated by NASA, XMM-Newton (launched in 1999) operated by ESA, and Suzaku, the fifth Japanese X-ray astronomy satellite (launched in 2005). The next generation of X-ray observatories is an international cooperative project, pursued by ESA, NASA and JAXA (the Japanese space Agency): the International X-ray Observatory (IXO). It builds on three decades of successful X-ray telescope development and is candidate as one of the next big missions of the three space agencies.

X-ray telescopes

X-ray telescopes are very different from optical telescopes. Because of their high-energy, X-ray photons directly arriving on a mirror would not be reflected by it but would penetrate into it. The most commonly used technique is to make X-rays ricochet off grazing-incidence mirrors which are nested in a coaxial and cofocal configuration. A schematic illustration of grazing incidence in X-ray telescopes is shown in Figure 9 (top left) with only four nested pairs of mirrors. The grazing angles range from about 3.5 degrees for the outer pair to about 2 degrees for the inner pair. In Figure 9 (bottom left) is shown a cutaway of the design and functioning of the High Resolution Mirror Assembly on Chandra. The mirrors are coated with a highly reflective rare metal, the iridium. A photo of one of the three Mirror Modules of XMM-Newton is given in the right of Figure 9. Each Mirror Module consists of 58 gold-coated nested mirrors. Each mirror shell consists of a paraboloid and an associated hyperboloid, precisely aligned. The thickness of the smallest mirror (diameter=306 mm) is 0.47 mm, and it increases linearly with shell diameter in order to guarantee sufficient stiffness. The thickness of the 700 mm diameter mirror is 1.07 mm. The minimum radial separation between adjacent shells is 1mm. Indeed, in grazing incidence optics the effective area of a telescope is a function of the number of mirrors, the mirror shell thickness and their separation. The thinner the mirror shells are and the narrower the shells are spaced, the larger is the collecting area.

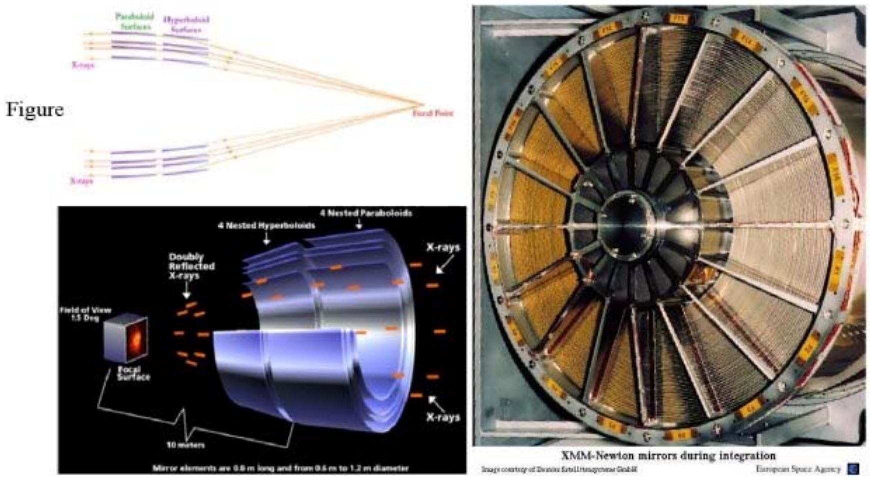

Figure 9. Top left: X-ray optics: Principle of grazing incidence reflection and focusing of X-rays (Credit**:** NASA/CXC/S. Lee). Bottom left: Schematic design of the High Resolution Mirror Assembly on Chandra (Credit**:** NASA/CXC/D. Berry).
From http://chandra.harvard.edu/resources/illustrations/teleSchem.html#xray_mirror.
Right: One the three XMM-Newton mirror modules with a full set of 58 flight mirror nested shells. From
http://xmm.esac.esa.int/external/xmm_science/gallery/public/level3.php?id=65. Credit**:** Dornier Satellitensysteme GmbH and ESA.

Chandra

NASA's Chandra X-ray Observatory was launched and deployed by Space Shuttle Columbia on 23 July 1999 in a high elliptical 64-hour orbit (16 000 to 133 000 km). Such an orbit allows uninterrupted observations as long as 55 hours. Chandra is designed to observe X-rays in the wavelength range 0.1 to 10 keV. Its instruments have approximately fifty times better spatial resolution than the previous big X-ray observatory, ROSAT (the ROentgen SATellite, 1990-1999, Germany, USA, and UK).

This is illustrated in Figure 10 with images of the Crab nebula: the image taken by the Advanced CCD Imaging Spectrometer (ACIS) on Chandra shows how higher resolution can reveal important new features.

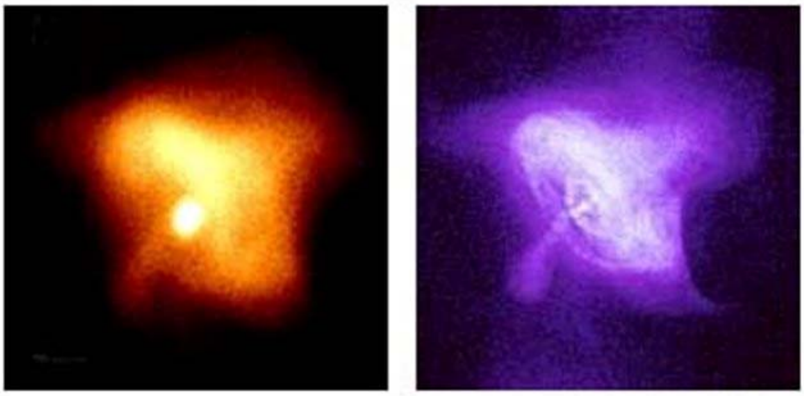

Figure 10. An illustration of the progress of spatial resolution in X-ray observations: the Crab Nebula observed by ROSAT (left, credit: S. L. Snowden, USRA, NASA/GSFC) and by Chandra (right, credit: NASA/CXC/SAO). From http://chandra.harvard.edu/about/axaf_mission.html.

This Chandra image of the Crab Nebula and its pulsar was one of the early observations obtained with the telescope and it is a striking illustration of the observatory's capability for high-resolution imaging of violent phenomena. This image led to a major discovery: the bright inner elliptical ring in the Nebula was showing the first evidence of the shock front where the wind of particles from the pulsar begins to radiate in X-rays via the synchrotron process.

Chandra combines the observing possibilities of four different instruments: two cameras, the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS), and two high-resolution spectrometers, the High Energy Transmission Grating Spectrometer (HETGS) in the energy range 0.4 to 10 keV and the Low Energy Transmission Grating Spectrometer (LETGS) in the energy range of 0.08 to 2 keV. HRC is the camera used to identify the fainter sources and make high-resolution (0.5 arcsecond) images of areas full of hot matter, for example supernova remnants or clusters of galaxies. ACIS can make images in a very narrow range of energy centered on the lines produced by specific ions (for example oxygen, neon or iron ions) and therefore, by taking different images, study temperature and/or chemical variations across clouds of hot gas. The spectrometers are used in the study of detailed energy spectra measuring temperature, ionization and chemical composition of the observed targets.

Chandra's capability for high-resolution imaging is enabling detailed mapping of the structure of extended X-ray sources and its high angular resolution permits studies of faint discrete sources. Also important is its contribution to high-resolution dispersive spectroscopy.

Chandra's high-resolution imaging capability could be illustrated by many spectacular images. Two of them are given in Figures 11 and 12. Figure 11 is an image obtained from a 164-hour exposure (11 pointings over nearly three years) of the centre of our own galaxy. It shows Sagittarius A*, with more than 2000 other X-ray sources and a diffuse extended emission of hot, X-ray-emitting gas, heated and chemically enriched by numerous stellar explosions. Figure 12 presents a composite image of the nearby galaxy NGC 7793, combining X-rays observations made with Chandra, optical data from the ESO's Very Large Telescope and H-alpha data from the Cerro Tololo Inter-American Observatory 1.5m telescope. This image shows, in the outskirts of the galaxy, a microquasar containing a black hole with the most powerful jets ever seen from such a stellar-mass black hole.

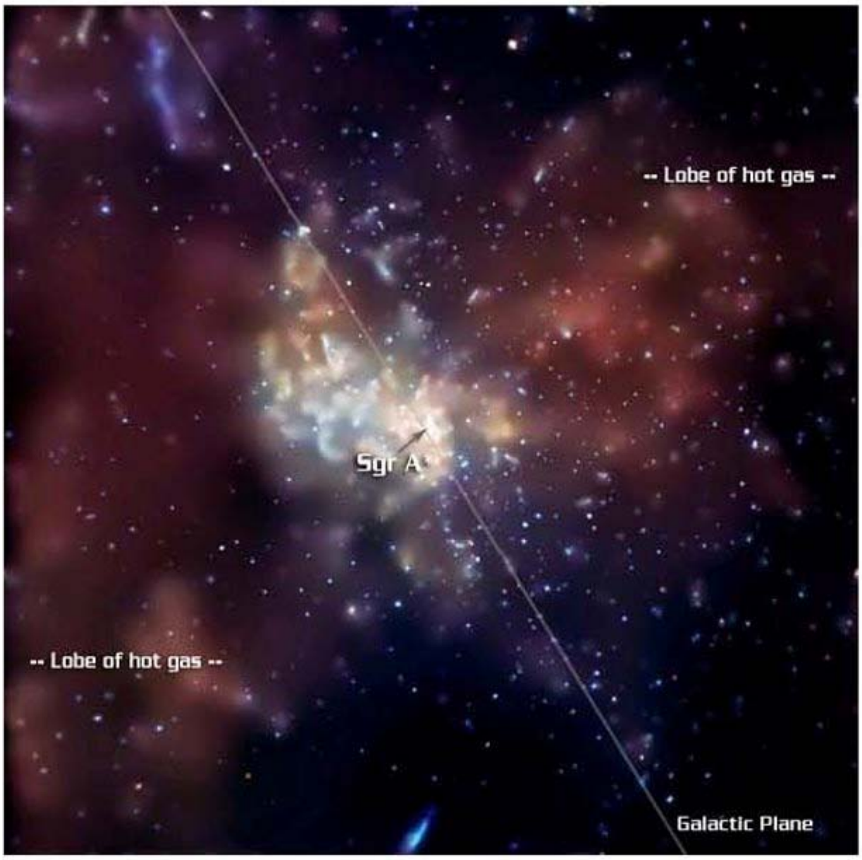

Figure 11. Chandra image of the supermassive black hole at the centre of our Galaxy. The locations of Sagittarius A* and of the galactic plane are indicated. From http://chandra.harvard.edu/photo/2003/0203long/. Credit: NASA/CXC/MIT/F.K.Baganoff et al.

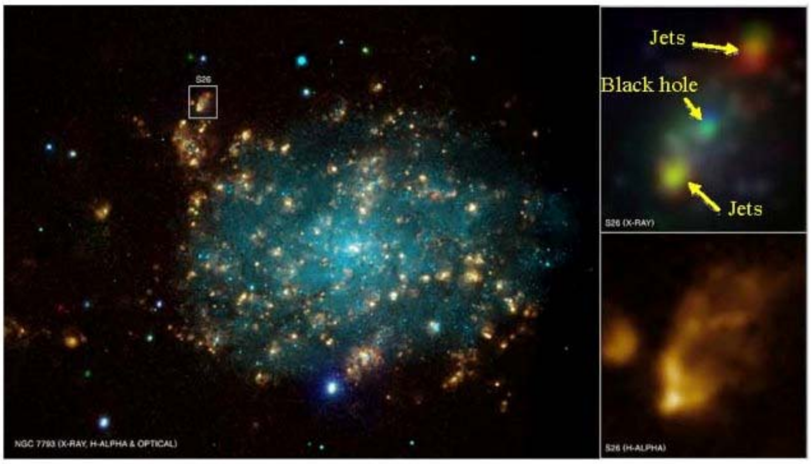

Figure 12. Composite image of nearby galaxy NGC 7793 combining X-ray observations obtained with Chandra's ACIS instrument (red: 0.2-1.0 keV, green: 1.0-2.0 keV, blue: 2.0-8.0 keV), optical data from the ESO's Very Large Telescope (cyan) and H-alpha data from the CTIO 1.5-m telescope (gold). The wide field image of the whole galaxy (left) is 9 arcmin across (about 10 000 pcs); the detailed images of the microquasar (right) in X-rays and H-alpha are 45 arcsec wide (about 900 pcs).
From http://chandra.harvard.edu/photo/2010/ngc7793/. Credits: X-ray image: NASA/CXC/Univ of Strasbourg/M. Pakull et al.; Optical image: ESO/VLT/Univ of Strasbourg/M. Pakull et al.; H-alpha image: NOAO/AURA/NSF/CTIO 1.5m.

XMM-Newton

XMM-Newton was launched by Ariane-5 from Kourou, French Guiana, on 10 December 1999 and placed into a 48-hour elliptical orbit around the Earth. The ESA's X-ray Multi-Mirror (XMM) observatory, renamed XMM-Newton short after launch, is a powerful soft X-ray observatory, concentrating on the radiation range 0.1 – 10 keV. With a perigee altitude of 7000 km and an apogee at 114 000 km, the satellite is traveling out to nearly one third of the distance to the Moon. This very eccentric orbit enables very long and uninterrupted observations. The satellite is the second cornerstone of ESA's Horizon 2000 space science plan, devoted to High-Throughput X-ray Spectroscopy. With three large mirror modules (see Figure 9), three European Photon Imaging Cameras (EPIC) measuring the proportions of different X-ray wavelengths, two Reflection Grating Spectrometers (RGS) diffracting the X-rays to achieve high spectral resolving power (150 to 800) over a wavelength range from 5 to 35 Å (0.33 to 2.5 keV), and an optical-UV monitor, XMM-Newton's capabilities are very complementary to those of NASA's Chandra. As said in a recent review on the first decade of science with Chandra and XMM-Newton (Santos-Lleo et al. 2009): "The complementary capabilities of these observatories allow us to make high-resolution images and precisely measure the energy of cosmic X-rays. Less than 50 years after the first detection of an extrasolar X-ray source, these observatories have achieved an increase in sensitivity comparable to going from naked-eye observations to the most powerful optical telescopes over the past 400 years". As a result of this increase in sensitivity, the number of observed objects also has tremendously increased. This is illustrated in Figure 13, showing the increase in size of X-ray source catalogues produced over the past four decades. XMM-Newton is making about 40 000 new detections per year. A vast majority of these sources (98%) had never been detected before in X-rays.

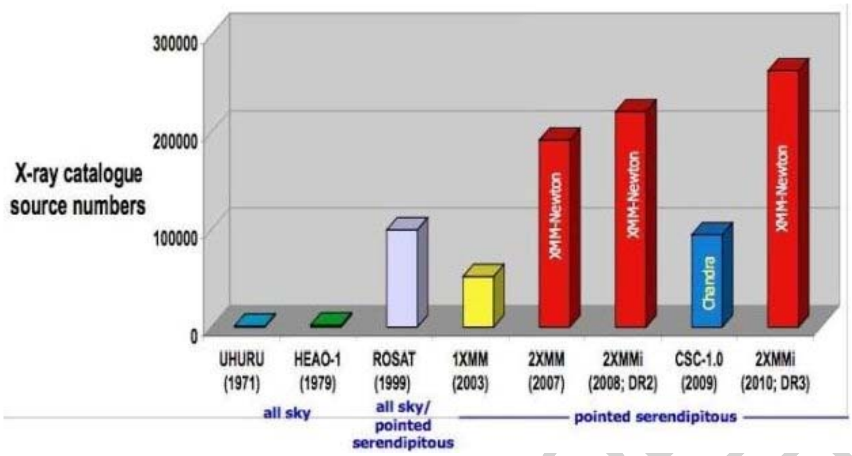

Figure 13. This diagram illustrates the increase in size of X-ray source catalogues that have been produced over the past four decades. From left to right, they are UHURU (1971), HEAO-1 (1979), ROSAT (1999), 1XMM (2003, First XMM-Newton Serendipitous Source Catalogue), 2XMM (2007, Second XMM-Newton Serendipitous Source Catalogue), 2XMMi (2008; DR2, Incremental Second XMM-Newton Serendipitous Source Catalogue, second data release), CSC-1.0 (2009, First release of Chandra Source Catalog) and the latest release of the second XMM-Newton Serendipitous Source Catalogue, 2XMMi-DR3 (2010; DR3). From http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46961. By permission of M. Watson, University of Leicester.

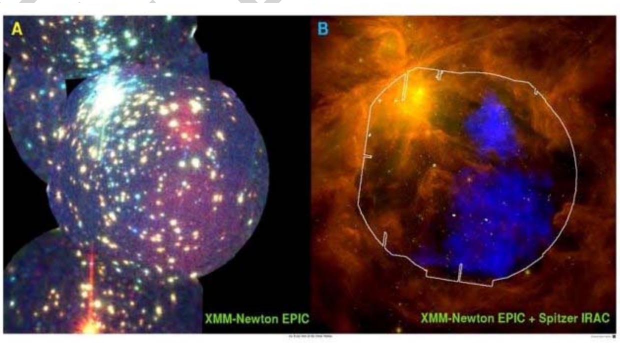

Figure 14. The Orion Nebula. The left panel is an X-ray image obtained with ESA's XMM-Newton, with the hot gas seen as a red haze. The right panel, a Spitzer (NASA) infrared image of the Orion Nebula overlaid with XMM-Newton X-ray data (in blue), shows the newly discovered hot gas cloud. From http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46060. Credit: XMM-Newton EPIC, Guedel et al. (left); AAAS/Science, ESA XMM-Newton and NASA Spitzer data (right).

Figure 14 provides one example of the discoveries made possible by XMM-Newton: a huge cloud of high-temperature gas in the Orion Nebula. The cloud is composed of winds blowing from high-mass stars that are heated to millions of degrees. This result suggests that such X-ray cloud should be common in star-forming regions.

Another very striking result is the contribution of XMM-Newton to the COSMOS survey (Cosmological Evolution Survey), designed to probe the formation and evolution of galaxies as a function of cosmic time (redshift) and large-scale structure environment. Covering a 2 square degree equatorial field, it is a collaboration between XMM-Newton and Chandra (X-rays), the Hubble Space Telescope (optical), Spitzer (infrared), GALEX (UV) and a number of large ground-based telescopes. Over 2 million galaxies have been detected, spanning 75% of the age of the Universe. The X-ray emission as observed by XMM-Newton is shown in Figure 15. One of the goals is to establish the link between X-ray emission and underlying dark matter from the study of one of the largest samples of X-ray-detected clusters of galaxies.

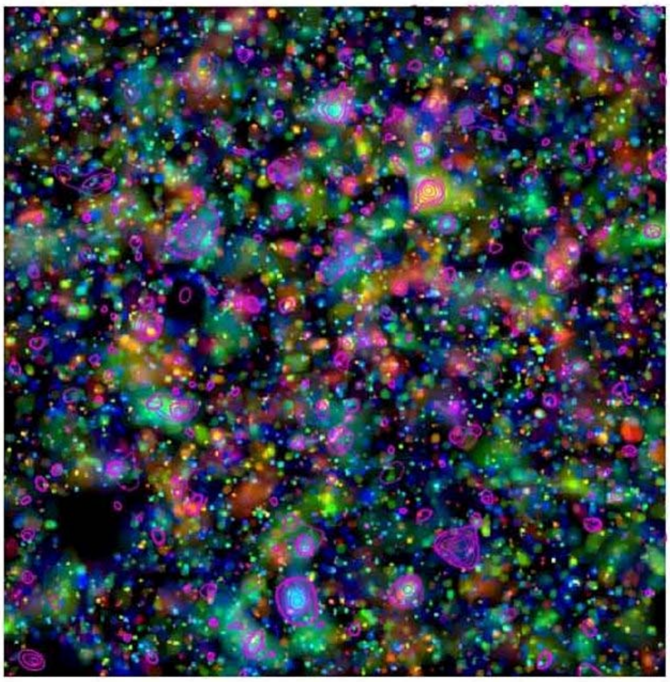

Figure 15. X-ray emission in the COSMOS field. This image shows the galaxy density with colors representing the redshift of the galaxies ranging from redshift of 0.2 (in blue) to 1 (in red). The X-ray contours (in pink) show the extended X-ray emission as observed by XMM-Newton. From http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46328. Credit ESA.

IXO

IXO, the International X-ray Observatory, is the next generation project of X-ray space observatory, developed jointly by ESA, NASA and JAXA (the Japan Space Agency) for a launch in 2020 at the earliest. It is the result of the merger, in 2008, of two preliminary mission concepts developed by ESA (XEUS = X-Ray Evolving Universe Spectrometer) and NASA (Constellation X). It is building on the accumulated scientific and technologic knowledge acquired by the current and previous X-ray facilities. With a large X-ray mirror (about 3 square meter collecting area and 5 arcsec angular resolution), it is planned to observe the hot Universe between 0.1 and 40 keV with a powerful suite of instruments able to deliver high-resolution spectroscopy, deep spectral detailed imaging over a wide field of view, microsecond spectroscopic timing with high count rate capability and unprecedented polarimetric sensitivity. Its main science drivers are the formation and evolution of galaxies, clusters and large-scale structures (co-evolution of galaxies and their central supermassive black holes, creation of chemical elements, chemical evolution along cosmic time), black holes and matter under extreme conditions of gravity, temperature, magnetic field, and the life cycles of matter and energy.

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Intensive use was made of the web sites of

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http://sci.esa.int/science-e/www/area/index.cfm?fareaid=1#,
http://www.rssd.esa.int/index.php?project=ASTRONOMY,
http://xmm.esac.esa.int
http://herschel.esac.esa.int/

NASA:
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Cambridge X-ray Astronomy
http://www-xray.ast.cam.ac.uk

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Bibliographic Sketch

Dr Catherine Turon is an astronomer at the Observatoire de Paris-Site de Meudon (GEPI department, UMR-CNRS 8111), France. She is the author of close to 200 scientific papers, all related to galactic astronomy (she was a student of Jean Delhaye) and performing astronomy from space. She was a member of the Hipparcos Science Team, leading the Input Catalogue Consortium. She was then involved in the preparation of the science case for micro-arcsec astrometry and the ESA Gaia mission. She participated in the actions of the European Science Foundation (she was one of the successive chairs of the Astronomy & Fundamental Physics). She was also, for your years, chair of the Astronomy Working Group and member of the Space Science Advisory Committee of ESA, and contributed to the Cosmic Vision 2015-2025 document. Then she was the chair of the fourth ESA-ESO Working Group, on Galactic Populations, Chemistry and Dynamics. Finally, she was a member of the Astronet Working Groups "Science Vision" and "Infrastructure Roadmap", and contributed to the two documents: "A Science Vision for European Astronomy" and "The Astronet Infrastructure Roadmap: a Strategic Plan for European Astronomy". At present she is the French representative on the European Leadership in Space Astrometry panel – an organization preparing for the scientific exploitation of data from the ESA mission Gaia, and chair of the French "Action Spécifique Gaia", a similar organization at the French level.