OBSERVATORIES IN SPACE

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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 (!).

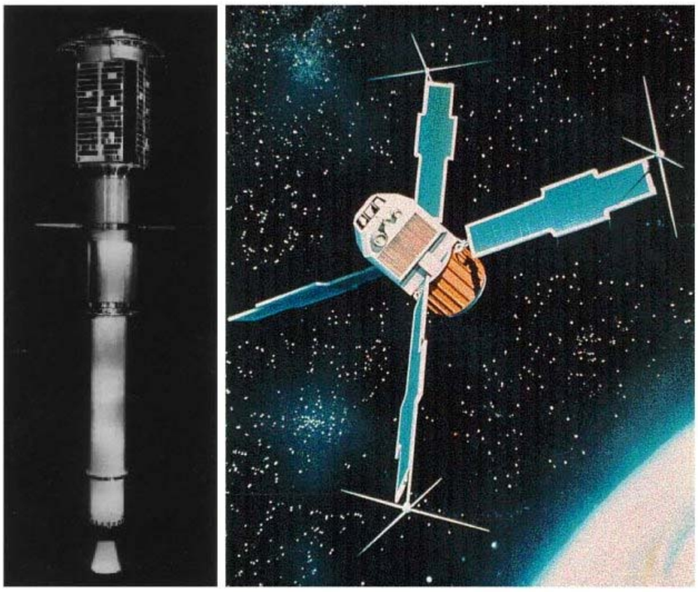

Figure 1. Left: Explorer 11, first gamma-ray satellite, launched by NASA on 27 April 1961 (from http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/explorer11.html). Right: Artist view of Uhuru, first Earth-orbiting satellite entirely dedicated to X-ray astronomy, launched by NASA on 12 December 1970 (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	$7.5 \times 10^{14} - 3 \times 10^{16}$	Very hot stars, supernova remnants, quasars.	$10^5 - 10^6$ K	IUE, FUSE, HST
Visible	400 - 800 nm	$4 \times 10^{14} - 7.5 \times 10^{14}$	Stars (atmospheres), planets, galaxies, reflection and emission nebulae.	$10^3 - 10^5$ K	HST, Corot, Kepler, Hipparcos, *Gaia*
Infrared (IR)	0.8– 50 μm	$6 \times 10^{12} - 4 \times 10^{14}$	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	$3 \times 10^{11} - 3 \times 10^{13}$	Cosmic Microwave Background, cold interstellar medium.		WMAP, Herschel, Planck
Radio	> 1 cm	$< 3 \times 10^{11}$	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.

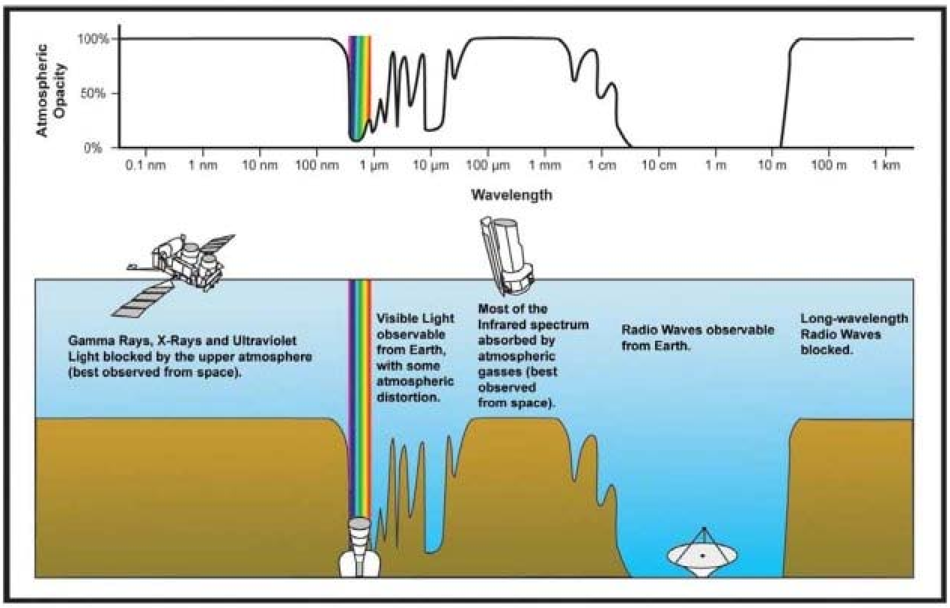

Figure 2. Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation. From http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_astronomy/orbit.html.

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.

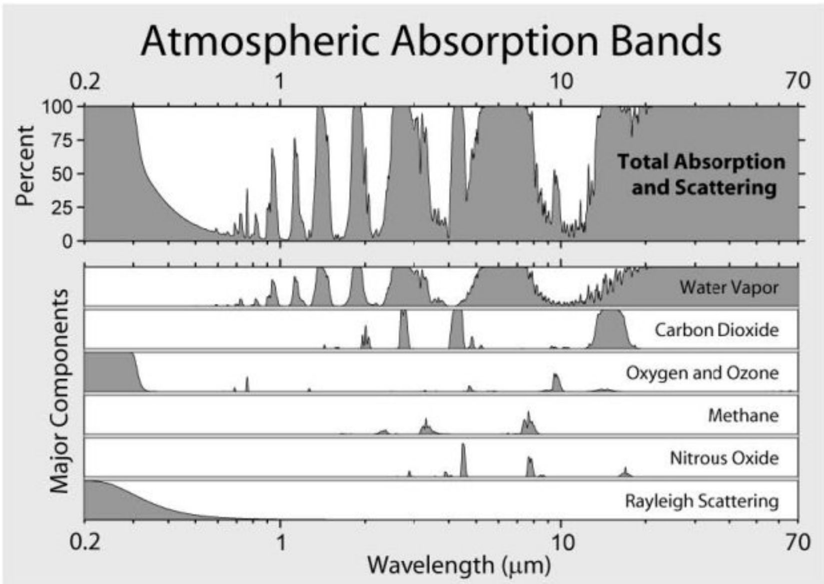

Figure 3. Atmospheric transmission and absorption bands by molecules in the ultraviolet, optical and infrared domains. From http://www.globalwarmingart.com/wiki/ File:Atmospheric_Absorption_Bands_png (by permission of Robert Rohde).

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.

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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.