Seeing the invisible: a short account of a grand conquest

For more than 2,000 years, astronomers remained ignorant of the lights pervading the cosmos, except, of course, for visible light. There was a good reason for this: most other kinds of radiation are unable to get past the barrier formed by the atmosphere. Bypassing this barrier entailed using suitable instruments: balloons first, then rockets, and ultimately satellites.

CEA

The discovery of gamma radiation from pulsars. The payload, and stratospheric balloon at Aire-sur-l'Adour (July 1969).

On 27 January 1959, facing the abrupt coastline of the Corniche des Maures, out on Levant Island – a dependency of the French coastal municipality of Hyères (Var *département*, southern France) – preparations were under way for an event that would remain as a landmark in the history of French astrophysics. In the late afternoon, from the secrecy of the naval base on the island, a thin streak of light rose up into the sky, swiftly losing itself in the clouds. Was this a test launch, to try out some new weapon for the nascent French nuclear deterrent? Nothing of the sort! This, indeed, was a converted missile, taking up, to an altitude of more than 100 kilometers, the first French experiment in space astrophysics, built in CEA laboratories.

CEA's pioneering role in space

CEA's space saga began virtually from the time the organization was set up. Indeed, on 18 October 1945, the French Government approved the ordinance – as drafted by Jean Toutée, a member of the French Council of State (which has oversight on all administrative acts of state) – setting up the Atomic Energy Commission (CEA) the then head of the government, General de Gaulle, had decided to create, for the purposes of "[…] conducting scientific and technological research to promote the uses of atomic energy in various fields of science, industry, national defense." No-one could yet imagine that this new research organization would become a tremendous melting-pot of expertise, with regard to discovering the Universe. And yet…

On 2 January 1946, General de Gaulle appointed as High Commissioner for Atomic Energy the head CEA, Frédéric Joliot, who had been awarded the Nobel Prize in Chemistry, in 1935, jointly with his wife Irène Curie, for their discovery of artificial radioactivity. This novel property exhibited by matter is characterized by the disintegration of **atomic nuclei**, which then emit strange, hitherto unknown forms of **radiation**, which were dubbed alpha, beta, gamma, for want of any better inspiration. While the first two of these forms of radiation are, in fact, made up of particles (**helium** nuclei, and **electrons**, respectively), on the other hand, the third kind would soon be found to be the most powerful form of light extant in nature.
From then on, the engineers at CEA would put all their energy in devising instruments affording the ability to sense, and measure these forms of radiation. For several years, these investigations were carried out in the laboratory; however, the date of 4 October 1957 marked a veritable revolution, for these scientists: Sputnik I had been put in orbit, this being followed, a few years later, in 1961, by the first spaceflight by a Soviet cosmonaut, Yuri Gagarin, opening the way to space exploration.

CEA

The first space experiment to be carried out by CEA, on 27 January 1959. A Geiger counter was mounted on board a converted missile, to effect one of the first measurements of gamma radiation from the sky.

Such was the motive for the launch carried out, on 27 January 1959, on Levant Island, using a Daniel rocket, originally designed by the French National Aeronautical (subsequently Aerospace) Design and Research Bureau (**ONERA**: **Office national d'études et de recherches aérospatiales**).
Of course, that mission, led by physicist Jacques Labeyrie, had the prime objective of providing answers to the queries raised by atmospheric nuclear tests, and, consequently, concerning the possible dissemination of radioactive materials in the upper atmosphere. However, the battery of Geiger counters carried by that rocket proved equally able to measure gamma radiation from the sky. While the experiment allowed the conclusion to be drawn that no radioactivity was to be found in the upper atmosphere, it equally achieved a breakthrough, in world terms, in the area of astrophysics: it brought back one of the first records of gamma rays originating in the cosmos. Until that time, no researcher had imagined that the Universe yielded such radiation. There was a good reason for this: apart from visible light, which is able to reach the surface of the Earth, most other kinds of radiation are blocked by the atmosphere. As a result, from the beginnings of astronomy, more than 2,000 years ago, astronomers had had no means of sensing the other forms of cosmic light. The sole exceptions that could be adduced being the discovery of the radio wave emission from our own **Galaxy**, realized, in 1932, by US physicist and radio engineer Karl Jansky; and the demonstration, by German scientists working in the United States, after the Second World War, of X-ray emissions from the **Sun**, using a V–2 rocket.
Such a finding propelled CEA into the ranks of world astrophysical expertise, a position it has never relinquished. Fifty years on, a new generation of research scientists, now gathered within CEA's Astrophysical Service (SAp), has just delivered a very-high-technology camera, to be mounted at the core of Herschel, the largest space telescope ever to be placed in orbit, but equally a gem of research capability, able as it is to capture the faintest infrared radiation from the Universe. In the interval, spanning these two ventures, astronomers at SAp were to make their mark at every step, in one of the most exciting adventures of all times: the detection of the "invisible" radiation from the cosmos, totally inaccessible as this is to our human eyes, which are solely suited to the light reaching us from our own **star**, the Sun.

Success with available resources

In June 1962, a major discovery brought about an upheaval, once again, in the view astronomers then had of the sky. This was due to a US team, led by Riccardo Giacconi, who was awarded the Nobel Prize in Physics in 2002. He had had the idea of mounting X-ray detectors on board an Aerobee rocket, for an attempt to measure X-radiation from the Sun, reflected from the surface of the Moon. Virtually no X-rays could be sensed coming from the Moon, however, as they swept the sky, the onboard instruments recorded an intense X-ray spike, coming from a region lying within the Scorpius Constellation (the Scorpion). Given the name Scorpius X–1, this source was long to remain as a puzzle to astrophysicists. It took more than five years before it was understood that X-rays yielded by the Universe originate in very dense, exotic stars – **white dwarfs**, **neutron stars**, or even **black holes**. With that discovery, a new observation window was opened up onto the cosmos.


CEA

The discovery of cosmic X-radiation: a stratospheric balloon being prepared for takeoff, and another being released, at Aire-sur-l'Adour (May 1965).

At the time, France had not yet developed a rocket program of its own, so researchers at CEA had to be inventive, if they were to carry their observations forward. For want of a better solution, they hit on the idea of mounting their measuring instruments on stratospheric balloons, giving the ability to go up to a height of 40 kilometers.
On 21 May 1965, an inaugural flight was sent off from the Aire-sur-l'Adour base (Landes *département*, southwestern France), using such resources as were available. For instance, to shield the detectors against the


CEA

The payload carried by the balloon: detectors shielded from the vacuum in a leaktight pressure cooker, data being recorded on a tape recorder, recovered after the flight (May 1965).

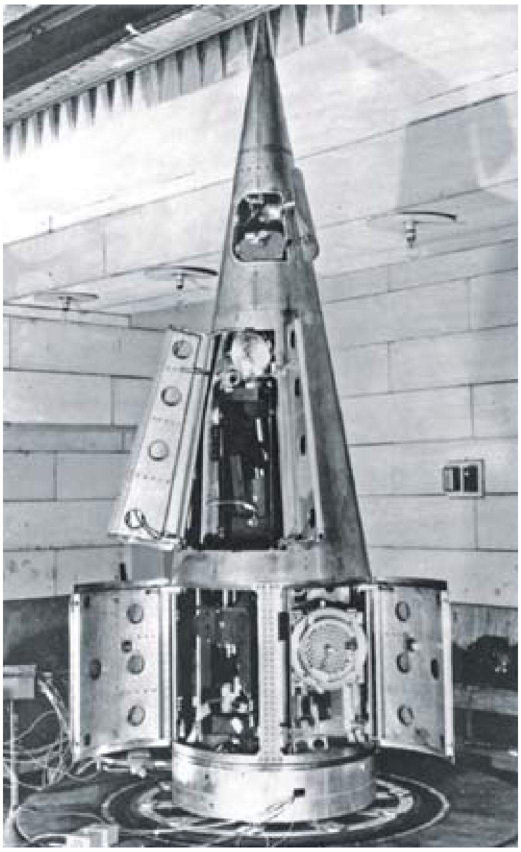
vacuum, and cold conditions, the astrophysicists used a pressure cooker, and polystyrene; to record their data, they could only use a run-of-the-mill commercial tape recorder. Recovered after the flight, this simple data recorder gave CEA one of its historic firsts: the detection of high-energy X-rays emanating from a number of sources lying in the Cygnus Constellation (the Swan).
However, those were just the first surprises researchers were to come up against. In 1967, British radioastronomers discovered rapid, regular sequences of radio signals coming from the sky. Once the – briefly entertained – hypothesis of signals sent by extraterrestrial beings had been ruled out, another surmise came up: these "pulses" could be emanating from very rapidly rotating neutron stars, dubbed **pulsars** (as an abbreviation of "pulsating stars").

From Kourou to Gap

In the meantime, the development, by France, of its own rocket program had come to fruition, with Véronique. Astrophysicists could not let such an opportunity go by. In 1967, the team led by Robert Rocchia mounted, on one such rocket, detectors previously developed by CEA for the purposes of studying radioactivity. The outcome was a terrible disappointment: the rocket's trapdoors had failed to open. Another opportunity was to arise, however, and success came, as a Christmas present, on 23 December 1968, from the newly opened Kourou space center (French Guiana), just a few months after it had been commissioned. The results of the experiment proved conclusive: during the 200 seconds of observation, some 25,000 X-rays were recorded, emanating from one of the most powerful pulsars in our Galaxy. The astrophysicists at CEA had just demonstrated that pulsars emit high-energy X-rays – another first.
Not content with this, however, the following year, they took up another challenge: using a novel dedicated detector, for the purposes of observing gamma rays from pulsars. This complex instrument had been developed by Bruno Parlier, Bernard Agrinier, and Yves Koechlin from CEA, in collaboration with Giuseppe Occhialini, a renowned physicist from Milan University (Italy). In effect, this was a spark chamber, in other words an enclosure kept under vacuum, and to which a voltage is applied. The chamber, contains a stack of lead plates, having the ability to stop gamma rays, causing them to decay, yielding charged particles which generate sparks along their track. To reconstruct the direction of the incident gamma ray, these tracks were photographed, using a 16-mm movie camera. This time, the operation was carried out at Gap (Hautes-Alpes *département*,

CEA

A Skylark rocket unit, used for the purposes of detecting celestial X-ray sources (1972).



CEA

The first detection of high-energy X-rays from pulsars: the nosecone of the French Véronique rocket, carrying the X-ray detectors (December 1968).

southeastern France). A balloon took up the detector to a height of 40,000 meters. Results were forthcoming, once again, for the CEA research scientists, who were able to show, for the first time, that pulsars also emit gamma rays across the Universe.

From balloon to satellite

Carrying this line of research further, at that time, entailed that an essential limitation be overcome: to wit, the all-too-short observation time afforded by balloons, and rockets. To that end, it was imperative that the availability of scientific satellites be secured, thus ensuring sustainable access to space. Europe had to wait until 1972 before such a satellite became available, in the form of TD–1. Astrophysicists at CEA made use of this first opportunity to be offered to them, placing three instruments on board the satellite, which was to remain in orbit through to 1974. These included S–133, a brand-new 40-kg spark chamber, now fitted with an electronic video camera, dubbed VIDICON. Unfortunately, this flight experiment proved to be a failure, owing to the proximity of other instruments, inducing an overwhelming background of spurious particles, drowning the experiment in false detections. This served as a learning lesson, benefiting the COS–B satellite, launched in August 1975, carrying a 114-kg spark chamber, as the outcome of a broad Europe-wide collaboration. With a completed lifetime of 7 years, this program outshone its US competitor, SAS–II, this having been planned to last just 6 months. It provided a major scientific result: the first complete gamma-ray picture to be obtained of our Galaxy.
This exploration of the high-energy X-ray and

gamma-ray domain was to carry through to the present time, with CEA's involvement in the SIGMA/GRANAT (1989), XMM–Newton (1999), and INTEGRAL (2002) missions. Nowadays, the view available to astrophysicists has opened out to cover thousands of sources, bearing witness to that tumultuous Universe, in which temperatures run to millions of degrees. By contrast, going over to the infrared radiation side, obstacles were not readily overcome: first of all, the Earth's atmosphere stands as a barrier that must be bypassed; and, second, detector technology, arising as it does from military applications, does not always progress in step with the requirements of researchers. CEA's involvement in this new domain was the outcome of a chance circumstance, to wit the delay that affected international collaborations on high-energy projects, subsequent to two different events: the accident that befell US Space Shuttle Challenger, in 1986, and the demise of the former USSR, in 1991.

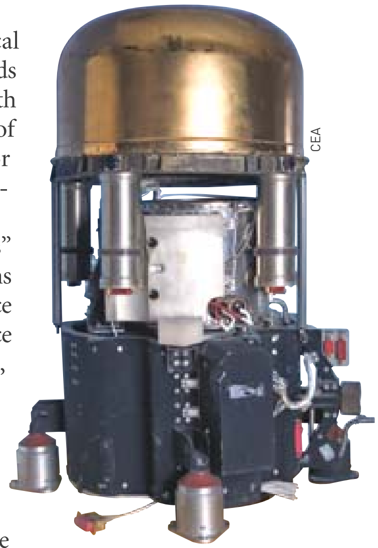
Waiting for the grand symphony of the cosmos...

Europe then decided to take up the challenge, with the Infrared Satellite Observatory (ISO) project, designed to carry the first spaceborne infrared camera. It should be said that the US Infrared Astronomical Satellite (IRAS), placed in orbit in 1983, for 6 months, had yielded but an initial glimpse of the infrared sky. Be that as it may, no European laboratory appeared to have the capability to build the camera for ISO. Only two units at CEA, SAp, and the Electronics and Information Technology Laboratory (LETI: Laboratoire d'électronique et de technologies de l'information) were able to undertake providing detectors for the instrument, and carrying out their integration into a complex optical unit, to weigh less than 10 kg. Through the drive of Catherine Cesarsky, the ISO camera (ISOCAM) was readied to go into space, in 1995, for three years. Featuring an array of semiconductor detectors of just 32 × 32 **pixels**, this camera produced a mosaic of images, revealing, in full detail, the gas and dust **nebulae** inside which stars are born. It has been bettered, at the present time, only by the recently launched Spitzer satellite.

Currently, out of the vast rainbow of nonvisible light, only one region remains as yet unexplored: that of the far infrared, close to radio **waves**. If this new challenge, set by the observation of such very-low-energy radiation, is to be met, the present boundaries of technology will need to be pushed further back yet. The camera of the future is to be fitted with specific detectors, known as **bolometers**. The challenge is to preclude its being blinded by its own environment. To achieve this, astrophysicists must ensure cooling down to a few thousandths of a degree above absolute zero. Some cameras of this type are already being operated from the ground, using narrow atmospheric windows that let through part of that radiation. However, the first major exploration is now being carried out in space, with the Herschel satellite, successfully launched by the **European Space Agency** (**ESA**), on 14 May 2009. It is carrying the Photoconductor Array Camera and Spectrometer (PACS), a camera featuring the largest bolometer array ever constructed, standing as a major success for CEA. As all true scientific breakthroughs, and indeed as all technical successes, PACS nevertheless gives some grounds for humility, when the size of this camera, with its 2,048 picture elements, is compared to that of the large dedicated astronomical cameras, for the purposes of visible light observation, featuring millions of picture elements.

In many observational domains, the "glasses" used by researchers prove barely better, in terms of performance, than Galileo's telescope. Space exploration has always had to adjust to the pace of technological innovation: at every step, specific tools had to be invented, and, most crucially, taken outside of the atmosphere. Thus, bit by bit, the unknown fraction of the Universe is relentlessly being narrowed down. For a long time, astrophysicists had thus been in the situation of a music-lover able to hear but the sound of one instrument, in the interpretation played by a musical ensemble, and then gradually extending their perception, to cover the full orchestra. Presently, what scientists desire would be finally to be in a position to listen to the full range of the grand symphony of the cosmos.

> Jean-Marc Bonnet-Bidaud
Astrophysics Service (SAp)
Institute of Research into the Fundamental Laws of the Universe (IRFU)
Physical Sciences Division (DSM)
Joint Astrophysics Research Unit on Multiscale Interactions
(CEA–Paris-VII University–CNRS)
CEA Saclay Center (Orme des Merisiers)


CEA

The first spark chamber to be placed in a satellite: the S–133 experiment, carried on board the European TD–1 satellite (March 1972).

Cosmic radiation: key dates in the discovery of the various kinds

No confidence may be placed in the colors that are plain for all to see in the rainbow, since these are but a minute fraction of the true extant gamut of colors. Our own human eye is unable to perceive them, as it is solely adapted to the light reaching us from our own star, the Sun. It was thus through work in the laboratory that other kinds of radiation could be discovered, step by step, by researchers:

- 1800: physicist William Herschel, by means of a mere prism, and thermometers, is able to show that, beyond "red", there is another type of radiation, having the ability to heat a thermometer: the infrared. This was the first truly significant breakthrough.
- 1800: carrying out a similar experiment, Wilhelm Ritter discovers that, beyond "violet," a radiation is found, that is able to darken paper prepared with silver chloride: this is ultraviolet.
- 1810–64: James Clerk Maxwell unifies electricity and magnetism, this enabling him to suggest that visible light is but a special case of a more general phenomenon: electromagnetic waves.
- 1895: Wilhelm Röntgen discovers that electrical discharges inside vacuum tubes yield hitherto unknown rays (therefore named by him "X-rays"), having the ability to go through glass.
- 1896: Henri Becquerel discovers natural radioactivity: emanating from within the nuclei of uranium atoms, unknown rays are found to be able to make an impression on photographic plates.
- 1898: Pierre and Marie Curie discover further "radioactive" materials (polonium, thorium, radium), which emit forms of radiation dubbed alpha, and beta radiation (in fact consisting of particles).
- 1900: Paul Villard discovers a form of radioactive radiation that has the ability to go through lead: gamma radiation.

For the most part, these various types of radiation are blocked at varying heights in the Earth's atmosphere. Only space astrophysics affords the ability to capture such radiation, and thus study it. At the present time, this discipline is just 50 years old.

FOCUS A

Probing the Universe across the entire light spectrum

Light is an **electromagnetic wave**, which may be characterized by its **wavelength**, or its **frequency**. The various types of radiation are distributed across the **electromagnetic spectrum**, according to their wavelengths, from the shorter (gamma rays) to the longer wavelengths (radio waves), through visible light (see Figure 1). Light may equally be described in terms of a massless particle, the **photon**, having an energy that is proportional to its frequency.


NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)

ESO

The three "Pillars of Creation" in the Eagle Nebula, as viewed by the Hubble Space Telescope in visible light (left), and in the infrared (right). Infrared radiation makes it possible to see through clouds.

Types of radiation

Radio-wave radiation (radio waves) covers the frequency domain below 1 **GHz**, corresponding to wavelengths longer than 30 cm. The **microwave** region extends over the 30 cm (1 GHz)–1 mm (300 GHz) range. Wavelengths for **infrared (IR) radiation** range from 780 **nm** to 1 mm. This region is further subdivided into **near IR** (780 nm–2.5 **μm**), **mid-IR** (2.5–27 μm), **far IR** (27–100 μm), and **submillimeter IR** (100 μm–1 mm). Infrared is often related to heat, since, at ambient temperature, objects spontaneously emit this type of light radiation. **Visible light** covers that part of the electromagnetic spectrum to which the human eye is receptive. This region covers a wavelength segment extending from 380 nm (purple) to 780 nm (red). Wavelengths for **ultraviolet (UV) radiation** fall in the range from 380 nm to 10 nm. **X-rays** are high-frequency electromagnetic waves, with wavelengths ranging from a few fractions of a nanometer (0.01 nm) to 10 nm. A distinction is made between **soft X-rays** (at longer wavelengths), and **hard X-rays** (short wavelengths). The energies involved, for the photons associated to X-rays, range from 100 **eV** to 100 **keV**. **Gamma (γ) rays** come in at even shorter wavelengths, of less than 0.01 nm, and the corresponding photons have high energies, higher than 100 keV.

Our eyes can see but a tiny fraction of the full light emitted by celestial bodies. Making use of the entire wavelength range has opened up windows onto the Universe, allowing new objects to be detected, or showing already known objects under a new light. This ability to scan the skies at every wavelength is heavily indebted to the placing into orbit of dedicated satellites, for the observation of celestial objects, making it possible to be freed of **absorption** by the atmosphere. Nowadays, all wavelength regions are permanently being exploited, with correlations being drawn between the various regions, in order better to narrow down the physical mechanisms involved, for the objects observed.

Moreover, instrumental optics has likewise undergone a revolution, with the construction of giant telescopes, having the ability to collect the extremely weak light originating in the most distant objects.

Skip to page 32

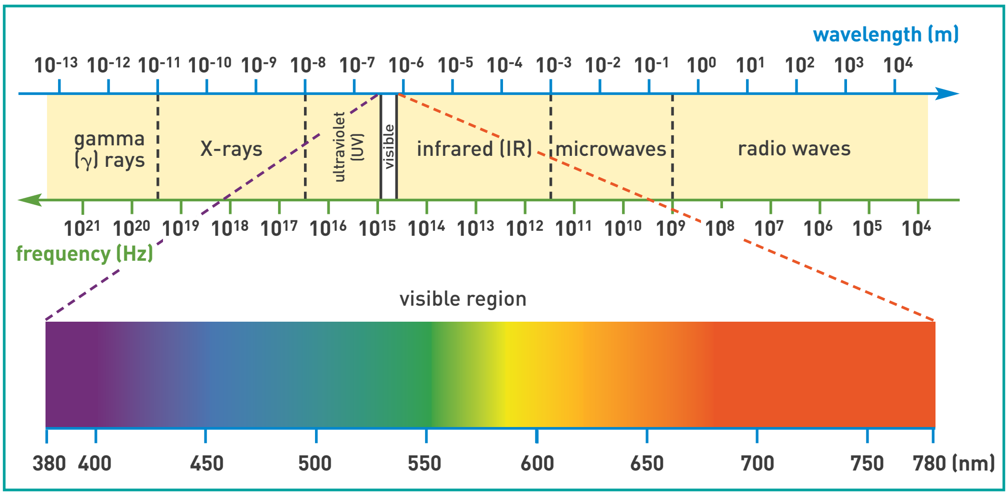


Figure 1.
The electromagnetic spectrum. Electromagnetic waves are grouped into families, of differing frequencies and wavelengths.

Page 31 cont'd
These new telescopes further stand out through the use of innovative techniques, and technologies, ensuring that the quality of astronomical imagery has leapt forward: active optics (the ability to adjust, in real time, the shape of the mirror surface), and adaptive optics (correcting for alterations in the image due to the atmosphere, by altering the shape of the mirror).

Highly informative spectra

Any matter at a temperature higher than **absolute zero** (0 **K**, i.e. –273 °C) emits electromagnetic waves, making up thermal radiation. Of itself, temperature determines the quantity of power emitted by any one body, this being proportional to the fourth power of temperature. Thus, a body at an absolute temperature of 600 K (i.e. about 320 °C) radiates a quantity of light power that is sixteen times larger than that from a body at ambient temperature (300 K, i.e. close to 27 °C). All wavelengths are present in thermal radiation, in unequal amounts however. Again, it is temperature that determines the **spectrum** of the radiation thus emitted, i.e. the distribution of energy across the various wavelengths present. The emission maximum occurs for a wavelength that is inversely proportional to temperature. In other words, any given body emits the greater part of its light at a wavelength that is all the longer, the cooler the body is. Our chief source of light, the **Sun**, exhibits a power maximum, in its emission, in yellow visible light, at a wavelength of around 0.5 μm. This corresponds to a temperature of 5,770 K. At the same time, any given body exhibits the ability to emit light at highly specific wavelengths. Indeed, an **atom** may not emit, or absorb any arbitrary quantity of energy. Its energy may only vary by definite, discrete steps, these depending on the way its **electron** cloud is configured. When energy is absorbed, or emitted, the electron distribution in the atom is modified. Light is emitted when an electron undergoes a transition from a high energy level to a lower energy level; absorption of light corresponds to the transition of an electron from a lower energy level to a higher one. The ensemble of such transitions, manifesting themselves in the form of as many **lines** in the spectrum, is characteristic for any given atom, and stands as its identifier. Such **emission lines** are also found for **molecules**, these being sets of atoms that are bound together, only the range of wavelengths involved being affected. When light passes through a gas, the latter may absorb such light as has a wavelength matching its own lines. This results in an **absorption spectrum**, i.e. an ensemble of dark lines on a luminous background, forming a kind of barcode, so to speak, making it possible to obtain information as to the light source, and absorbent gas. Thus, the Sun's spectrum takes the form of a continuous spectrum, ranging over the entire gamut of the colors of the rainbow, over which are superimposed absorption lines characteristic of the atoms present in the Sun's atmosphere.
While a source's spectrum makes it possible to determine its temperature, and composition, it further allows many other important parameters to be measured. Thus, a **magnetic field** splits a given spectral line into a number of close, distinct lines (**Zeeman effect**). This offset in wavelength is used to measure the intensity of the magnetic field, for some astronomical objects. A light source's spectrum is also affected by the source's relative motion, with respect to the observer, according to the selfsame principle that leads to the sound made by a vehicle that is approaching an observer being found to be higher pitched, while that sound is lower pitched when the vehicle is moving away. The apparent variation in frequency (this being all the higher, the shorter the wavelength) is proportional to the relative velocity of the observer, and source. The frequency increases as the light source approaches the observer (**blueshift**), and decreases as the source draws away (**redshift**). To put it in more quantitative terms, the **spectral shift *z*** is equal to the relative variation found, between the wavelength observed, λ_{obs}, and that anticipated in the rest frame, λ_0. This takes the form: $z = \lambda_{obs}/\lambda_0 - 1$. If z is positive, the shift found is a redshift, a blueshift if z is negative. This effect was independently discovered by French physicist Hippolyte Armand Fizeau (1819–96), and Austrian physicist Christian Doppler (1803–53). It is used, in particular, for the purposes of ascertaining the velocity of **stellar** motions. This physical phenomenon, known, broadly, as the **Doppler effect**, is termed the **Doppler–Fizeau effect**, when applied to light waves.
Finally, the spectral lines of distant objects are found to be systematically shifted to longer wavelengths (i.e. to the red, for the visible spectrum). This redshift may be measured easily, since atomic spectral lines can be identified, and their characteristics are well known, through measurements in the laboratory (see Figure 2). This phenomenon has been interpreted as evidence of the *global expansion of the Universe*, affecting cosmological scales.

redshift	age of the Universe, at the time of the light emission (billion years)
0	13.7
0.5	8.7 (63.5%)
1	6.0 (43.8%)
2	3.4 (25%)
3	2.2 (16%)
5	1.2 (8.7%)
7	0.8 (5.8%)
10	0.5 (3.6%)

Table.
Some representative values of the age of the Universe, at the time of emission, as a function of the redshift for the source observed.

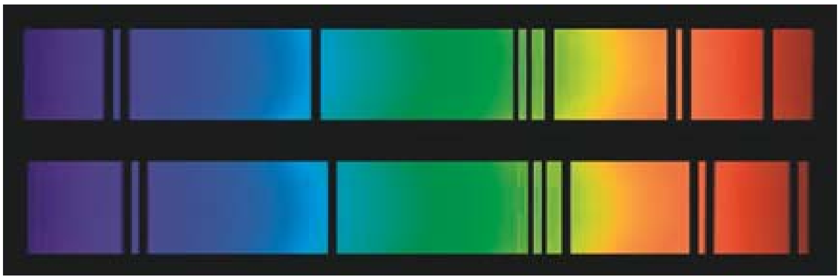


Figure 2.
Spectrum of a light source, exhibiting no shift of spectral lines (top), and featuring a redshift (bottom).

This arises from the fact that, once a radiation is emitted, it reaches us after a time lapse, during which space has stretched. This is why the radiation's wavelength is found to be dilated. It should be noted that cosmological expansion modifies the spectrum of distant sources through a purely **gravitational** effect, which has no bearing on the source's relative motion with respect to the observer (causing the Doppler effect). The redshift found for light from distant sources indicates these sources' spatiotemporal distance, making it possible to range them in terms of increasing distance (see Table).

The lights of the Universe

In their quest to gain an understanding of the Universe by way of observation, astrophysicists make use of the entire electromagnetic spectrum, from radio waves through to gamma rays, each region of the spectrum yielding specific information (see Figure 3).

Microwave radiation, at very long wavelengths, is not readily blocked by matter. It emerges quite freely from the cold, dark clouds inside which stars are formed. This radiation is ideal, for the purposes of penetrating the secrets of such clouds, and observing the initial stages of stellar development. When stars are born, they are enveloped in dust, and may only be seen by way of their *infrared radiation*. Grouped as they are in the sky in the form of **clusters**, young stars appear in *visible light*. The energy source that ensures a star may shine **brightly**, and lastingly, is provided by the nuclear reactions arising within the star, throughout its lifetime. A star may not live forever, and it experiences a convulsive end of life, in the course of which its extremely hot, very dense core ultimately becomes apparent. This then shines with an intense *ultraviolet light*. Very hot objects, at temperatures higher than 10,000 K, preferentially emit ultraviolet radiation. Objects at temperatures higher than 1 million degrees are X-ray emitters. The spectacular death undergone by stars spreads a searing wind, which may be viewed by way of *X-rays*. Some dead stars leave behind a very dense core, out in space. In some, yet more extreme cases, the stellar core turns into a more exotic object, a **black hole**, with a mass that may be as large as 10 **solar masses** or so. The black hole itself emits no light, however matter, as it infalls into it, may be brought to very high temperatures. This matter then emits high-energy radiation, in the form of *X-rays*, and *gamma rays*.

Bringing together the entire electromagnetic spectrum is thus essential, if an understanding is to be gained of the structure of the Universe, and its evolution, each type of radiation manifesting a different aspect.

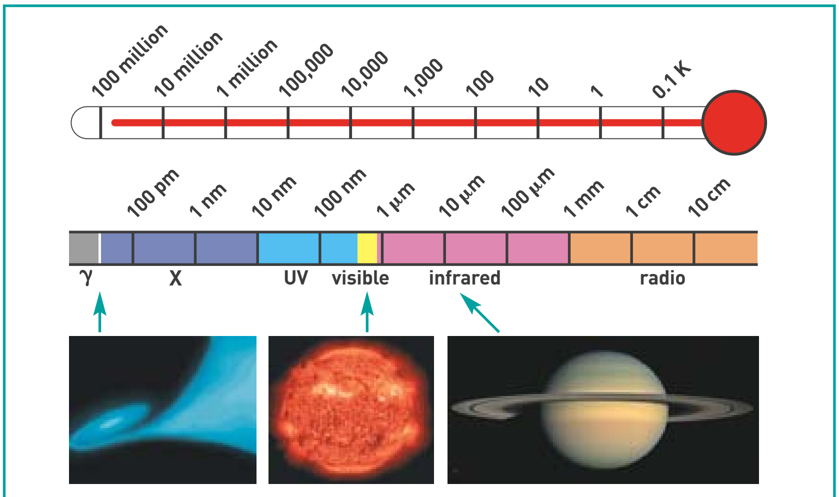
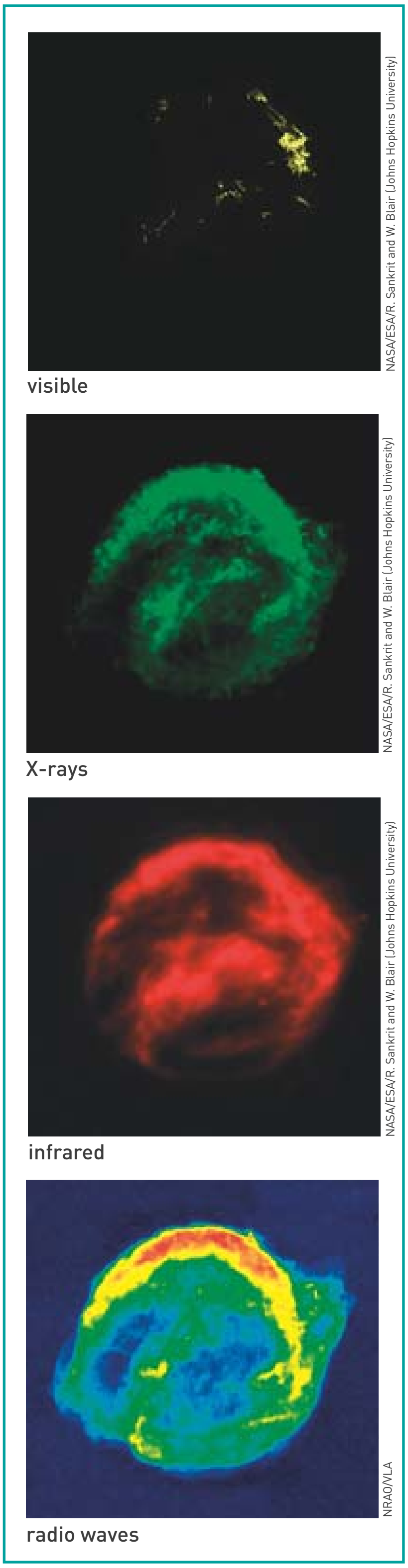


Figure 3.
The distribution of radiation yields information as to the temperature of a celestial body, and its characteristics. In two major segments of the electromagnetic spectrum, infrared on the one hand, X-rays and gamma rays on the other, advances in spaceborne detection are making it possible, by way of ever finer measurements, to access crucial information on the first stars, and **galaxies**.



Remnant of Kepler's **Supernova** (SN 1604), the explosion of which, visible to the naked eye as it was, was observed in 1604 by German astronomer Johannes Kepler. This bubble of gas nowadays emits very little visible light. It is bright in terms of X-radiation, infrared, and radio waves.