X-ray and γ-ray astronomy

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The Universe, as seen in X- and γ-rays, is a very exotic place, largely filled with extremely hot gas, with temperatures of 10^6 to 10^8 K, and dotted with cosmic accelerators of all sizes launching particles to relativistic speeds. One can see bright eruptions from young stars, admire cosmic laser shows with beams of radiation circling in the sky from spinning neutron stars, watch matter fall inside a black hole or "miss" the hole and shoot out at nearly the speed of light, follow matter blasted away by giant stellar explosions or by titanic explosions when neutron stars and black holes collide and coalesce. On a quieter but even more energetic scale, one can witness the colossal merging of clusters of galaxies.[1] In these exceptional conditions, far beyond the dreams of the 19th & mid-20th century physicists, both hot gas and relativistic particles are intimately related and their joint observation in X- and γ-rays bears new diagnostics to investigate these extraordinary media.

Most X- and γ-rays are absorbed in the Earth's atmosphere, and so must be detected from space-borne telescopes. Only the highest-energy γ-rays (those above 50 GeV) can be observed from the ground by means of the particle showers they initiate in the upper atmosphere. New X-ray instruments, such as *Chandra* and *XMM-Newton*[2], are revealing hot plasmas with unprecedented angular (sub-arcsecond) & spectral precision. Detailed maps of the density, temperature, "chemical", and velocity distributions of the hot gas are derived from precise spectroscopic line measurements from many atoms in various ionisation states. The γ-ray telescopes still struggle to catch sparse γ-photons one by one and strive for sensitivity and angular resolution in the realm of arcminutes to degrees. Yet, the late *Compton Observatory* in space and the ground-based instruments (e.g. Whipple, CAT, Cangaroo, Celeste)[3] have revealed many powerful cosmic accelerators and have used the penetrating power of γ-rays to deeply probe the conditions inside accelerator cores, otherwise hidden from view at other wavelengths.

Stellar-mass and supermassive black holes

There is now convincing evidence that black holes exist in two varieties: stellar-mass ones, produced by the implosion of the core of a massive star at the end of its life, and super-massive ones weighing 10^6 to 10^9 solar masses, lurking at the centres of galaxies. Whether black holes of intermediate mass exist (with 10^2 to 10^5 solar masses), and why, are still hotly debated. The gathered evidence indicates that black holes of all masses show strikingly similar behaviour. They attract matter from their environment (stellar companion or host galaxy) into a thin disc of gas that spirals inwards; heated by turbulent friction, it brightly shines in UV and X rays. The hungrier the black hole, the softer the radiation! During violent flare episodes, black holes expel highly collimated jets of plasma accelerated to relativistic speeds. Their synchrotron radiation is seen from the radio to X rays. Inside the jets, e^+-e^- pairs are further accelerated to TeV energies and shine profusely in γ-rays. Given these basic ingredients, a source can, however, show up in many disguises from different points of view because of screening by intervening matter and relativistic effects. Sources possess different states and can change from one to another within hours or days, supposedly because they "eat" more or less. Thus it took forty years to disentangle the underlying continuity in the wide variety of sources seen at all wavelengths and this daunting task is far from complete today!

The huge energy release, of 10^{29} W to 10^{31} W in stellar systems and 10^{36} W to 10^{41} W in super-massive ones, originates from the intense gravitational potential of the black hole. Interestingly, neutron stars accreting matter from a companion star develop similar features. With increasing gravitational energy, jet plasma is propelled to $0.5c$ by neutron stars, $0.9c$ by stellar black holes, $0.995c$ by super-massive black holes, and over $0.99999c$ by γ-ray bursts (c being the speed of light). Jets from stellar systems extend over light-years while the galactic ones span millions of light-years. Which mechanisms can generate the acceleration required to maintain jet collimation over such distances? What triggers the ejections? Theorists are at a loss, but answers will hopefully come in the near future with greatly improved observations.

When a star explodes into a supernova, matter is ejected at thousands of km s^{-1} and the released energy of 10^{44} J is enough to power the Sun for 8 billion years! The blast wave rams into the surrounding interstellar gas and heats it up to 10^8 K while a reverse shockwave travels back to the centre and heats the ejecta up to 10^7 K. Thus the whole remnant becomes a bubble of hot gas that brightly shines in X rays. It provides an attractive laboratory for atomic physics and thermodynamics, illustrating how ionisation slowly takes place behind a shock in a rarefied gas (just a few atoms per cm^3), and the distinct thermal responses of ions and electrons.

Nuclei synthesized in the star during its lifetime, or freshly "cooked" in the exploding stellar layers, are ejected into space. They enrich the surrounding medium with elements heavier than hydrogen and helium, but little is known about their ejection and mixing. Recent X-ray maps have revealed complex filamentary structures and marked abundance variations, perhaps even the turnover of the stellar layers before or during the turmoil of the explosion. Next year, a new satellite, *INTEGRAL*[4], will bring precious information from the γ-ray lines produced by the radioactive decay of fresh elements. Those lines will constrain the element densities, but also the temperature, pressure, and isotopic composition at the time of their production, allowing, for the first time, to look back in time into the supernova furnace.

Acceleration of particles

The blast wave can also accelerate electrons and ions up to 10 and 100 TeV, respectively, loosing as much as 10% of its kinetic energy in the process over several hundred years. It is indeed the time required for the particles to bounce back and forth across the wave and steal a little energy at each crossing before finally escaping. The rackets in this ping-pong game are provided by the turbulent magnetic field. The accelerated "cosmic-ray" electrons have long been observed by their radio and X-ray synchrotron radiation inside supernova remnants, or recently in γ-rays when they up-scatter the cosmological microwave background light. Frustratingly, the accelerated "cosmic-ray" ions, which should produce γ-rays by nuclear interactions in the ambient gas, have evaded detection so far. So, we are still unable to prove the origin of cosmic rays nearly a century after their discovery! While waiting for new-generation γ-ray telescopes (such as *GLAST*[5] from space, or HESS[6], VERITAS[7] and others from the ground), new diagnostics on the ion acceleration can be found in X rays since their pumping of energy from the shock-wave leaves an imprint on the thermodynamics of the shocked gas at those energies.

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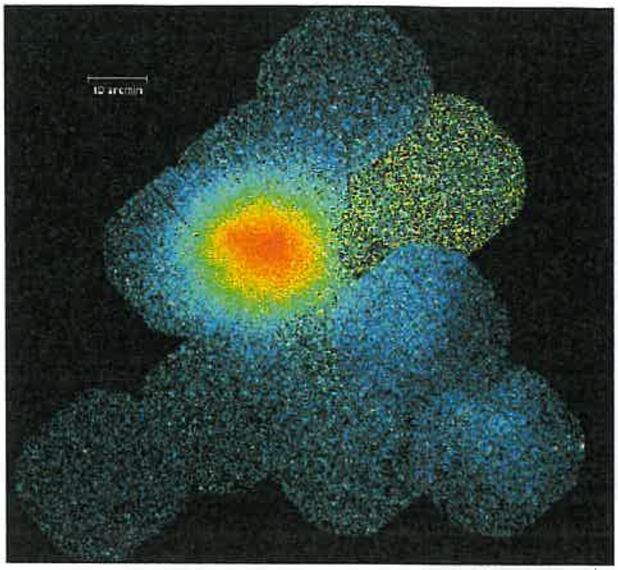

Fig. 1: *XMM Newton* observation of the nearby Coma galaxy cluster. The Coma cluster is one of the most massive clusters in the neighbourhood of our Galaxy. The observed diffuse X-ray emission comes from the hot intra-cluster medium (with a temperature of roughly 10^8 Kelvin), which fills the intervening space between the cluster's thousands of member galaxies. One distinguishes sub-structures in the diffuse emission: this is indeed a group of galaxies (to the lower right of the image) falling onto the cluster. Mapping the hot intra-cluster medium also serves to map the total gravitational potential, both of the visible matter and of the mysterious dark matter. The non-thermal emission of this cluster was also discovered by the Italian satellite *BeppoSAX*, from this last observation, a measure of the intra-cluster magnetic field was obtained.

The collapse of a supernova core may leave an incredibly compact neutron star, with a little more than a solar mass squeezed within 20 km, which spins, like a dazzling top, tens of times per second. Its magnetic field is amplified to 10^8 T, sometimes 10^{11} T! The rapid rotation of this great magnet generates huge electrical fields that accelerate particles to 10 TeV or more. Copious e^--e^+ pair production in the neutron star's magnetosphere creates narrow beams of light emitted in the range from radio- to γ-rays that sweep across the sky like giant lighthouse beacons sending us brief flashes of light, which won them the names of "pulsating stars" or "pulsars". Relativistic particles are blown into a "wind" that powers an energetic nebula around the pulsar and shines at all wavelengths. In fact, the highest-energy photons (~ 50 TeV) ever detected in the sky were produced in the wind of the nebula of the famous Crab pulsar. Yet, little is known about pulsars. Only a handful, the tip of the iceberg, have been seen at high energies where they radiate the bulk of their power. This number is expected to grow by an order of magnitude with *GLAST* within a

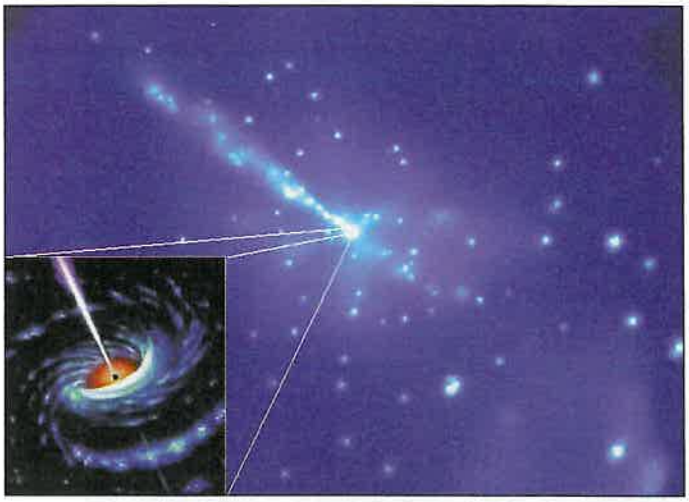

Fig. 2: *Chandra* observation of the active galactic nucleus Cen-A. As shown in the small sketch, this system is thought to be constituted of a super-massive black hole surrounded by an accretion disk. A very long jet, visible in the X-ray image, is produced in the vicinity of the black hole. This jet accelerate particles to very high velocities, which in turn produce γ-rays detected by *CGRO*/EGRET, to be studied in much more detail by *GLAST*, the next generation GeV γ-ray telescope.

few years. In fact, we may have already detected a number of them without recognizing their nature. A few years ago, the Compton Observatory has indeed discovered about 150 mysterious sources of γ-rays in our Galaxy. Some even lie in our backyard, within a thousand light-years from Earth, but their origin remains an enigma. *GLAST* will hopefully tell us what they are and how many of them are γ-ray pulsars to help us understand these fascinating stellar lighthouses.

The hot intergalactic gas

Hot gas... the most abundant form of visible matter in the Universe for at least several billion years

Hot gas (10^5 K to 10^7 K) has been the most abundant form of visible matter in the Universe for at least several billion years. A large fraction is trapped in the vast intergalactic space inside clusters of galaxies. There, it amounts to 2 to 10 times the mass locked inside the galaxies themselves. Clusters are the largest gravitationally bound structures in the Universe. They grow over billions of years to vast assemblies millions of light-years in size, as smaller clusters slowly merge together and through continuous accretion from the surrounding medium. In the process, they release tremendous amounts of energy (10^{56} J per billion years per merger) that heat the cluster gas to 10^7 K to 10^8 K. The typical cooling time of 1 billion years in this extremely rarefied gas (10^{-3} atom per cm^3) is, however, quite unusual in thermodynamics! On the other hand, galaxies inject heavy elements (coolants) and energy into the cluster gas, so that cluster history and galaxy formation are deeply interwoven. Mapping the hot X-ray glowing gas in clusters also serves to map the total gravitational potential, both of the visible matter and of the missing dark matter. The latter contributes from 5 to 8 times more to the total mass of the cluster, so it controls the evolution and fate of structures in the Universe, yet its nature remains elusive. If it is composed of slow, massive, elementary particles left over from the early phases of the Big Bang, there is hope that their annihilation will be detected in γ-rays in the near future paving the way to unravel their mysterious origin.

Massive black holes are also important keys to understanding the evolution of the early Universe. They were already quite numerous a billion years after the Big Bang. If, as currently proposed, mass structures of 10^5 to 10^7 solar masses were formed first, it is unclear what fraction of them turned into clusters of stars and black holes. In other words, whether stars or black holes first populated the Universe continues to be an open question whose answer requires searching for black holes at high energy to very large distances, deep into the past.

Observing the Universe at high energy thus highlights its immense diversity and exuberance, but also the deep unity of physical processes that create such a wealth of phenomena. The current physical laws, developed in terrestrial laboratories, appear to apply remarkably well under conditions far more extreme, billions of light-years away, and into the past. Observational means are still, however, cruelly limited to discover new physical processes. Far more advanced instruments will be needed to allow us to peer near the black hole horizon or form images of high-energy phenomena in the early Universe.

Footnotes

[1] Other highly-energetic phenomena, such as g-ray bursts and ultra high-energy cosmic rays are presented in the articles by L. Piro and A.A. Watson in this issue.

[2] 'Chandra' is NASA's Advanced X-ray Astrophysics Facility and XMM-Newton is ESA's X-ray Multi-Mirror mission, whose emphasis is, respectively, on imaging and spectroscopy.

[3] Cherenkov Telescopes

[4] International Gamma-Ray Astrophysics Laboratory

[5] Gamma Ray Large Area Space Telescope

[6] High Energy Stereoscopic System

[7] Very Energetic Radiation Imaging Telescope Array System

About the authors

Isabelle Grenier is Professor of Astroparticle physics at the University of Paris VII and works in the Service d'Astrophysique at the Centre d'Etudes de Saclay (Commissariat à l'Energie Atomique). Her main field of research are gamma-ray sources, focusing lately on the unidentified sources discovered by GRO-EGRET. She also works on the high-energy aspects of the solar neighbourhood, in particular on the clouds, supernovae, pulsars, and cosmic-ray sources of the Gould Belt. She is also Principal Investigator of the French contribution to the future NASA gamma-ray satellite, GLAST.

Philippe Laurent is an astrophysicist at CEA in France. He has participated to the data analysis of the French SIGMA coded mask telescope, on board the Russian GRANAT satellite. He is now deeply involved in the design and realisation of the INTEGRAL/IBIS telescope, which will produce high resolution images of the sky between 15 keV and 5 MeV.