# THE LEGACY OF
# EDOARDO AMALDI
# IN SCIENCE AND SOCIETY

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F. Ferroni

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# Physics in space

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## 1 A cultural heritage

Physics in space came after physics on Earth. While we are sure of that statement, we don't have a precise date for the conception of physics on Earth. But we do know the date of the first serious, constructive move for starting physics work in space, at least in Europe. It was exactly half a century ago, in 1959, barely two years after Sputnik, and on the year immediately following the creation of NASA.

The conception of European physics work in space took the form of a letter written by Edoardo Amaldi in Rome to his friend Pierre Auger in Paris. This was followed by a seminal walk of the two physicists in the Parisian "Jardin du Luxembourg" and finally by the paper of Amaldi entitled "Space Research in Europe", published in December. Three years later, the European Space Research Organization was a reality, and a concrete chance for physics in space was born in Europe.

It was the same year, 1962, in which Riccardo Giacconi, Bruno Rossi and others in the US first flew their home-made X-ray counters in a rocket above the atmosphere. They were to discover the first source of celestial, non-solar X-rays and the existence of a diffuse X-ray emission from the deep sky (Giacconi *et al.*, 1962). They were also to open a new way of looking at the Universe, and, exactly forty years later, Giacconi was to share a physics Nobel prize for this, and his many other, discoveries.

Both Edoardo Amaldi and Bruno Rossi had been part of the original Enrico Fermi team in Rome in the thirties. While working on their momentous discoveries on neutron-induced radioactivity, they were also very much working on the theory and practice of the physics of cosmic rays, and in general on the mysteries of our Universe.

The Fermi school of physics, both in Italy and later in the U.S., created a tradition which is still alive, at least three generations later. If Amaldi and Rossi were direct collaborators of Fermi, Giuseppe Occhialini in Milan, himself a pupil of Rossi, was the thesis advisor of Giacconi and the man who sent Riccardo off to his U.S. adventure. Together with Amaldi, Occhialini also contributed to the birth of physics in space, both in Europe and in Italy, especially after his visit to Rossi at MIT in 1960, but also by exploiting his strong British and French connections.

Once the European Space Agency was formed, in 1975, it was again Amaldi who gave a special impulse to its science programme. A few years later, he became Chairman of its Science Programme Committee and, more concretely, of its top science advisory board, the Space Science Advisory Committee (SSAC), in 1983. In that year, together with the ESA Director of Science at the time, Roger Bonnet, they started the first long-term planning exercise for European Science in space, dubbed "Horizon 2000".

Exactly 20 years later, ESA started a new long-term planning exercise, dubbed "Cosmic Vision 2015-2025". This time I was in the SSAC Chair, the first Italian in that position after Amaldi (and also a pupil of Occhialini).

## 2 ESA and ASTRONET, or, converging visions

In fig. 1, "L'Astronomia", frescoed by Raffaello in the Vatican Chambers around 1510, is shown with a slightly altered celestial globe. In place of the original constellations painted by Raffaello, we at ESA took the frightful responsibility of substituting the two halves of the space science Universe: a deep sky frame (in this case an X-ray one from XMM/Newton)on one side and a picture of the surface of Mars from the ESA probe MarsExpress on the other.

It appeared to be a fit cover for Europe's "*Cosmic Vision 2015-2025*" report. Its text was written after having defined the priorities for European space science, or Grand Themes, expressed in the form of fundamental questions

1. What are the conditions for life and planetary formation?
2. How does the Solar System work?
3. What are the fundamental laws of the Universe?
4. How did the Universe originate and what is it made of?

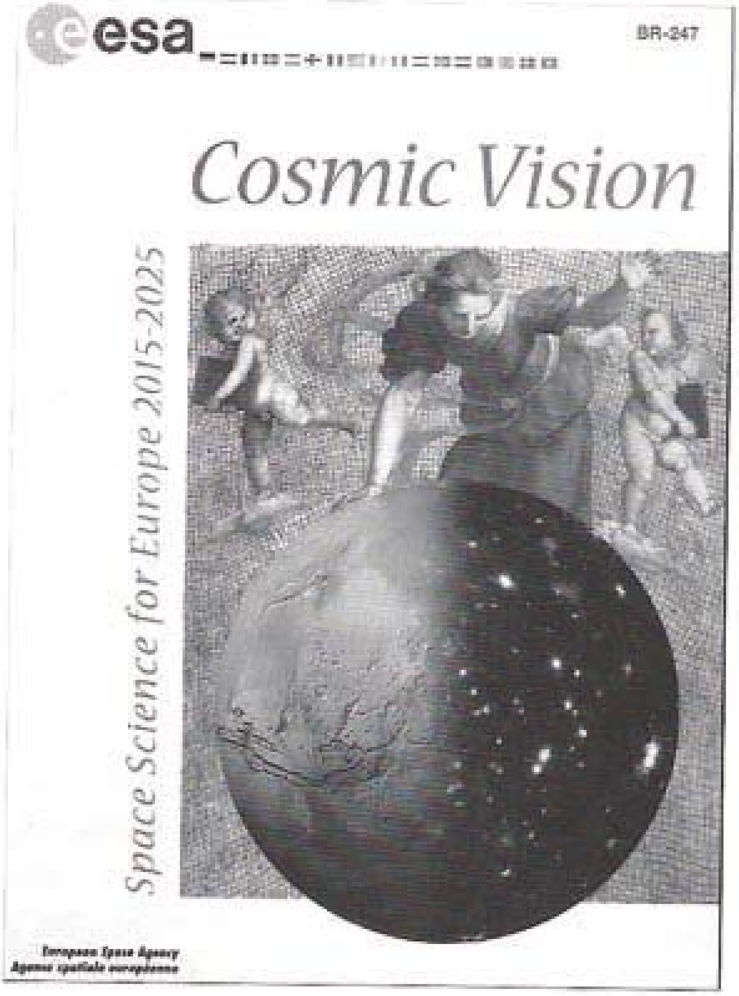

Figure 1: Cover Page of Cosmic Vision 2015-2025.

In trying to answer such questions, the European community had sent in 151 proposals, for missions of different calibers and topics. To better understand the amplitude and importance of the exercise, three points are worth mentioning.

First of all, there is the *idea itself of a long term programme*, conceived from the start to be as binding as any plan can be. One does so consciously, in spite of knowing that, of course, the future can be influenced by many factors, most of them escaping the control of the planners. Especially for the two previous programmes, Horizon 2000 (1983, with Amaldi in the SSAC Chair) and Horizon 2000 Plus (1994, with Lo Woltjer) respectively, it was possible for the ESA Executive to adhere to both plans with astonishing precision. Scientists knew that what they contributed to was not a joke: if their mission had been selected, sooner or later its turn would come, without all those uncertainties, delays, cancellations and resurrections, which are so frequent in other programmes, other Agencies, other Organizations.

Secondly, there is the *very machinery of our planning exercise.* Here you have the scientific community, often flanked by their industry experts, on the one side, and ESA, represented by a relatively small executive force, on the other. The critical interface between the two parts of the machine is composed by the three working groups (Astronomy, Solar System and Fundamental Physics) and of course the SSAC. About fifty people altogether, neither too many nor too few. No European space scientist can say that he/she did not have the opportunity to make a proposal, to defend it and finally to have it judged by peers. Decisions were not taken by bureaucrats, no matter how enlightened.

In the space science community of Europe, we are grown so accustomed to the above two points, that perhaps we fail to appreciate how innovative they have been. They were put together in the early eighties and they proved instrumental in giving Europe a special status among space-faring agencies. Still today, they represent a tradition which we cherish and which we were proud to continue at the time of the Cosmic Vision exercise. It is mainly thanks to such a tradition that the visibility and charisma of European space science far exceeds the modest budget of the ESA space science programme itself.

There is also a third element, *i.e. how to make the plan known and acceptable* to the whole scientific community. This is the last task before implementation, and in general it is carried out just before an ESA Ministerial Conference, in the hope that Ministers understand the need to grant appropriate funds to the Science Programme of ESA.

One must remember that the Science Programme has been from the start, and remains today and for the foreseeable future, the only mandatory programme of ESA. Such a status was decided very early in the history of ESA (thanks also to Amaldi) to protect its funding to science. But it remains a programme which is as fragile as science itself. In it are the basis of all future application developments, but, of course, by itself it does not yield any immediate fallback, especially in terms of economical return for the investment. In fact, its return cannot be evaluated easily, other than by saying that thanks to it we are all enriched by feeling a little bit less ignorant. To complicate matters, the crucial decision on the three-year funding (the level of resources) for the science programme must be taken unanimously. All Ministers, therefore, must share this need to feel less ignorant. This is not always easy to obtain.

So, to the question: why is the science programme protected? Is it done just to protect intellectual games of European scientists? The correct answer, we have learnt to make known (perhaps with some surprise), is that

Table I: *Panel A: High-energy astrophysics, astroparticle astrophysics and gravitational waves.*

| | | | |
|---|---|---|---|
| Guenther Hasinger | Chair | MPE | Germany |
| Patrizia Caraveo | Co-chair | INAF-Milan | Italy |
| Felix Aharonian | | Dublin | Ireland |
| Catherine Cesarsky | | ESO | ESO |
| Anthony Peacock | | ESA-ESTEC | ESA |
| Stefano Vitale | | Trento | Italy |
| Bob Warwick | | Leicester | United Kingdom |
| Ralph Wijers | | Amsterdam | Netherlands |

no, science is only one face of the value of the science programme. The other face, at least equally as important, is its technological innovation content. All space science missions (along with the Earth Observation Envelope Programme missions) are the most challenging and innovative missions at ESA, both from the mission planning and management point of view and from the technological point of view. This is the message we had to, and did, get across.

Thus Cosmic Vision 2015-2025 was made (see ESA BR 247, 2005). I remember that the scientific community was extremely excited when ESA issued the call for proposals, and they will be even more so when, about one year from now, after the competitive phase A studies, the final winners will be announced. Contenders are strong, in astrophysics as well as in solar system and fundamental physics studies. Stay tuned.

An exercise similar to ESA's "Cosmic Vision 2015-2025" was initiated, somewhat later, by the European astronomy community. In astronomy as well Europe has learnt how to cooperate, join forces and pool human and practical resources.

The European Union, in the context of the Lisbon vision of a knowledge-based Europe, has created the concept of European Research Area, valid in many disciplines, including astronomy. All major astronomy-funding Agencies then created ASTRONET, a community network dedicated to preparing plans for long-term European astronomy investments. The ASTRONET Board, comprising eminent European astronomers, defined a Science Vision by prioritizing scientific questions to be addressed in the next 20 years or so.

The broad headings under which the priority questions could be grouped in the Science Vision were as follows:

- Do we understand the extremes of the Universe?
- How do galaxies form and evolve?
- What is the origin and evolution of stars and planets?
- How do we fit in?

ASTRONET then proceeded to create a Roadmap Working Group, comprising three specialist Panels of top-rank European scientists for project analysis and two Panels dedicated to data archiving and to education, respectively. Table I gives the composition of Panel A, the one directly concerned with the sort of physics and astronomy which one does mostly, but not only, from space.

It is comforting to report that the priorities identified by the ASTRONET Panel A (`www.astronet-eu.org`) are quite close to those identified by the similar Working Groups of the ESA Cosmic Vision exercise. The top recommendations are for a Gravitational Wave space mission, a world first, and for a major high-energy astrophysics observatory, of the caliber to represent a next generation after ESA's XMM Newton and NASA's Chandra.

The space science and the astronomy community, in carrying out these two parallel and independent exercises with converging results, have validated again the time-honored tradition of peer review choice. No other form of project selection (or imposition), when dealing with public research money, must be accepted, be it at the European or National levels. The maximum transparency for ideas/proposal selection must be guaranteed, taking the utmost care in avoiding possible conflicts of interests of all types: scientific, industrial, economical or political. Such is the lesson our founding fathers, like Edoardo Amaldi, passed on to us, and it is our duty to safeguard it.

## 3 Gravitational waves, plus the riddle of inertia: General Relativity in space

Immediately after it was presented to the world by Albert Einstein in 1916, the General Theory of Relativity (GTR) appeared to everyone as a robust theoretical result, hardly in need of any improvement. Both the elegance of its formulation and the substance of its predictions called not for theoretical work but for experimental verifications. Arthur Eddington was the first, with his measurement of the bending of starlight during the solar eclipse of 1919, showing beyond doubt that light is attracted by mass, as foreseen by the GTR.

Since then, light deflection by mass has been measured many times in a consistent way, including numerous "gravitational lens" images, also taken from space. The last, but not at all the least, has been the brilliant experiment of Bruno Bertotti (University of Pavia) and colleagues, who used the radio signals from Cassini NASA-ESA space probe on its way to Saturn to obtain unprecedented accuracies (Bertotti *et al.*, 2003). It's experiments like this one, and the ones to be performed in space in the future, to which Amaldi and his school contributed directly or indirectly.

One of the most obvious tests of the GTR would be the direct detection of gravitational waves, the very existence of which is one of the pillars of the theory. Indirect proof was already obtained over three decades ago by observing that the anomalous orbital behaviour of the binary pulsar PSR B1913+16 was qualitatively and quantitatively accounted for by energy loss from the system through gravitational waves. Russel Hulse and Joe Taylor shared the 1993 Nobel Prize in physics for this discovery of theirs. But we still lack a direct detection of gravitational waves, a feat which will bring us well beyond a simple proof of the GRT. It will also open a window on a part of the Universe (and of its evolution) so far unseen. We are talking of the first 300000 years, when photons could not get out. A whole new astronomy is waiting for us there.

Detecting gravitational waves is very difficult, unfortunately. Amaldi and his group started in 1970 working on ground-based detectors. Ground-based gravitational antennas remain, so far, below the sensitivity level necessary for the undisputable result needed, but are rapidly improving. Ground-based detectors, however, suffer from an insurmountable signal-to-noise problem above wave frequencies around one Hertz. Unquenchable Earth seismic noise makes it useless to try to detect those tiny celestial gravity perturbations while sitting on a still active rocky planet.

The need to go to space then appears as obvious, and plans now exist for doing so. A gravitational wave observatory in space also offers the undisputable advantage, over a ground-based one, of giving a chance to detect the arrival direction of the waves. Many potential sources have been identified, from coalescing massive black holes to standard neutron star-neutron star binaries and more. Plus, of course, there ought to be random events such as supernovae (and maybe gamma-ray bursts?), which would come as a bonus to the patient and attentive observer.

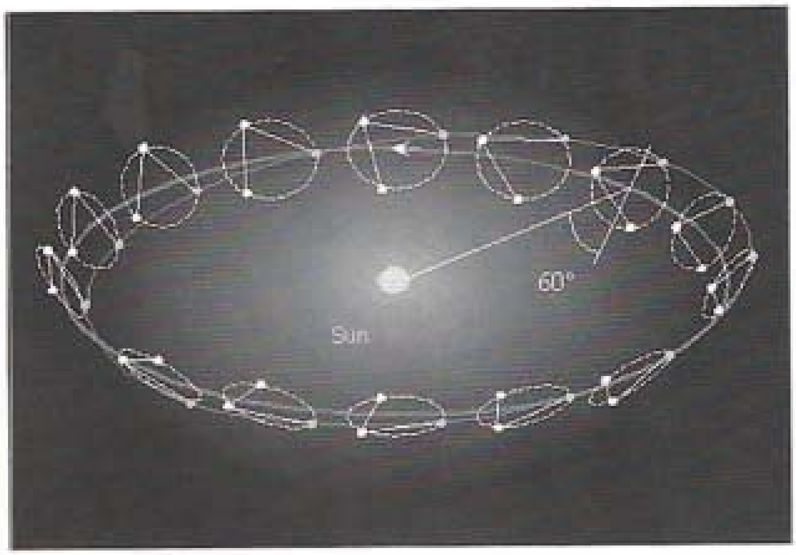

Figure 2: Lisa's orbit.

The most important space experiment now being planned by both ESA and NASA, and by the space science, astronomy and fundamental physics communities, is LISA (Laser Interferometry Space Antenna). It is a very impressive conception, based on a space interferometer built with three satellites positioned at 120° intervals on a circular orbit with a radius of three million km. The orbit itself is centred on a point following the Earth, on its orbit around the Sun, at a distance of 20° and has a 60° inclination w.r.t. the ecliptic plane. Laser beam interferometry between the different satellites will then yield an antenna base of about 5 million km, capable of detecting the tiny graviton-induced displacements with sufficient accuracy in the range 0.1 to 100 mHertz. The displacements will be between a reference mass and the satellite reference system. Figure 2 gives an idea of the elegant orbital arrangement foreseen for LISA and of the types of target objectives over the accessible frequency range.

The LISA mission looks so complex and challenging that ESA and NASA have decided to launch a precursor mission, the LISA Pathfinder. Hopefully ready for launch in 2010, LISA Pathfinder is dedicated to testing the key LISA element, or the measure (and control) of the motion of test particles in free fall. To reach this objective, LISA Pathfinder will have to test in space such essential technologies as inertial sensors, laser metrology, control systems for a drag-free satellite and, of course, ultra-high accuracy propulsion systems.

As of today, it is still unclear if the final decision to go ahead with the LISA mission will depend on the LISA Pathfinder mission results, or if it will be taken earlier, depending as it does on an ESA-NASA agreement. The physics community on both sides of the Atlantic has expressed itself very clearly, however: LISA must soon be a reality, since gravity waves will add a new dimension to theoretical physics and observational astronomy alike.

Several other aspects of the GRT can be tested in space. Examples include the prediction of time dilation induced by a gravity field, an experimental verification of which was carried out in 1976 (Gravity Probe A) and yielded results good to 70 parts per million. Or the verification of the equivalence principle between the inertial and gravitational mass, currently the topic of ESA/CNES mission MICROSCOPE, of the NASA mission STEP and of the proposed Italian mission GALILEO GALILEI.

In this context, however, we are especially interested to the Italian success story related to the verification of another elegant prediction of the GTR: the "frame dragging" of a mass in rotation. Our Earth, in particular, acts on an orbiting satellite by slightly altering its expected "Newtonian" position owing to the GRT frame dragging. The small amplitude of the effect can only be detected if one can measure the position an orbiting mass with cm precision w.r.t. the Earth reference frame.

The way to obtain this seemingly impossible accuracy is, apparently, relatively simple. A compact, inert mass, covered with laser reflectors, is placed in an orbit located as far away as possible from non-gravitational perturbations. Laser beams, shot to the satellite from several locations on to ground, allow accurate timing of the photons return trip, yielding distances to the satellite reflectors with the required accuracy.

Two missions, LAGEOS 1 and LAGEOS 2, carried out in a collaboration between NASA and ASI, launched respectively in 1976 and 1992, have already performed a coarse verification (20%) of the GTR predictions. The work, in Italy and indeed in the world, was largely led by the Rome-Lecce group of Ignazio Ciufolini, author on this topic of a recent Nature cover story (Ciufolini, 2007).

Capitalizing on the strength of this tradition, ASI in 2007 decided to start a new, all-Italian mission, called LARES, aimed at improving by an order of magnitude the verification of the Lense-Thirring effect, as the GTR frame-dragging is called. Ignazio Ciufolini was willing to accept the burden of the P.I.-ship of the LARES mission, on the strength of his unique experience. Moreover, ASI saw the chance of putting a scientifically meaningful payload on the first launch of the ESA VEGA rocket, largely designed, built and financed by Italy.

The LARES satellite (see fig. 3) will consist of a single, compact sphere, made of tungsten for packing the maximum mass in the minimum volume, and will be covered by special laser reflectors. The Vega rocket will place

Figure 3: The Lares satellite.

it in a 60°-to-80° inclined orbit, with a perigee height of 1400 km, but with small eccentricity. It was the best possible orbit resulting from a compromise between the rocket maiden flight requirements and the satellite science requirements. ASI and INFN (the other Italian Agency involved in the mission) are confident that the LARES small mission will be a large success, again in the tradition of doing physics in space which Amaldi taught to all of us.

## 4 Particle astrophysics: matter, antimatter and more...

There is more to exploring our Universe from space than just doing the good old electromagnetic type of astronomy discussed above. Actually, a lot of the physics done in space refers to detecting and understanding fluxes of elementary particles arriving at or close to the Earth. Setting aside, for the purpose of the present text, the all-important work carried out on the solar cosmic rays and on the particle interactions between Sun and Earth, we will briefly review some of the more recent particle astrophysics results and future missions in which the influence of the Amaldi school can be more felt.

On June 15th, 2006, the PAMELA experiment, designed and produced by an international collaboration led by INFN and ASI, was put into a low-altitude, high-inclination orbit from the Baikonur cosmodrome. PAMELA consists of a set of detectors optimized for the study of antiparticles in the cosmic radiation, and is particularly good at distinguishing between electrons and positrons. It does so thanks to the combination of a permanent magnet spectrometer with a silicon tracking system.

Careful analysis of the data collected between July 2006 and February 2008 suggests a very interesting result on the fraction of positive electrons impinging on the detector. Apparently confirming previous balloon results from US groups (Chang *et al.*, 2008), PAMELA sees the positron fraction (w.r.t. all electrons) increasing with increasing particle energy. If true, this result may have heavy implications, for example, it is claimed, on the presence of dark-matter particles in the halo of our Galaxy. Alternatively, the positron excess may be due to pair-production processes in the atmospheres of nearby pulsars, such as, for example Geminga (see sect. 6). In any case, a very interesting result.

Confirmation (or not) of the PAMELA result may come in the near future by another space astroparticle experiment, involving for Italy both ASI and the INFN. It is the AMS (for Alpha Magnetic Spectrometer), planned to operate on the International Space Station around 2011. A preliminary version of the experiment, called AMS-01, flew a test flight on the Shuttle in 1998, with good success (and, by the way, also saw a lot of positrons...).

The AMS experiment is designed and built by a huge international collaboration, under the leadership of Nobel laureate Sam Ting. It is primarily devoted to the search of cosmic antimatter and dark matter, possibly of cosmological origin, but also to the study of cosmic rays themselves, as well as of celestial gamma-rays. The core central detector, a stack of tracker planes with silicon ladders, is built in Italy.

At the moment, the main AMS concern, which is getting ready on schedule and is performing flawlessly from the physics point of view, is to ensure a passage on the Shuttle Transportation System to get to the ISS in the next two or three years, before the aging Shuttle itself is retired. Prospects are looking good at the moment, but let's keep our fingers crossed for what promises to be a major step forward in our understanding of the basic physics of our Universe.

An indirect measure of the distribution of antimatter (in the form of positrons) in the centre of our Galaxy has already been obtained by the ESA INTEGRAL gamma-ray mission (fig. 4). The narrow positron-electron annihilation line at 511 kev has been observed to show a telling asymmetry around the Galacitc Centre. The obvious conclusion, suggested in the Nature letter shown (Weidenspointner *et al.*, 2008), is that positron sources must reflect the asymmetry shown by their gamma-ray decay products. Pos-

Figure 4: INTEGRAL Image of the Galaxy in the 511 keV line (Weidenspointner *et al.*, 2008).

sibly certain types of X-ray binaries (again involving neutron stars) may be responsible, since they seem to show the same asymmetric galactic distribution. Gamma-ray astronomy may once again be the key for understanding a lot of the physics going on in space: astronomy with photons can certainly help astroparticle physics.

Neutrinos are the only other type of particle (other than barions and electrons) detected as coming from space, if not detected in space. Neutrino astronomy, owing to the huge detector mass dictated by the low neutrino cross sections, is so far confined to the ground. Two celestial neutrino sources have been observed, however: the Sun and Supernova 1987A. Two very special cases, and two very different production physics, of course. Still, neutrino astronomy, in whatever form, is the most promising potential development for enlarging our view on the Universe with astroparticle physics.

More exotic, axion-like particles have also been considered in an astrophysical context. Again, they could not be directly detected in space, but the possibility has been investigated to observe the signature of their presence, for example, when photon beams pass through strong magnetic fields. The particular example of the neutron star-neutron star binary J0737-3039 has been studied for the possible detection of light pseudoscalar bosons (Dupays, *et al.*, 2005) and could show proof, in the near future, of the presence of these particles in an astronomical context.

## 5 Photon astrophysics, or, the spectrum of everything

During at least four millennia, mankind has been doing astronomy with their naked eyes. The crowning successes of those 4000 years, from the Sumers through Ptolomy, the Arabs, the Chinese and many more, were those of Tycho Brahe, Nicklaus Kopernikus and Johannes Kepler, leading up to the first years of the 17th century. Kepler, in particular, summed up all western astronomical observational and theoretical skills by deducing, prior to 1609, his famous laws on the conical nature of planetary orbits. Astonishingly, this was based solely on his (and Tycho's) naked-eye observations of the orbit of Mars, and on his understanding that it deviated significantly from a circle (had he taken Tycho's observations of Venus or Jupiter, someone else, probably much later, would have discovered Kepler's laws and even the great Isaac Newton would have had his problems. . . ).

Then, exactly 400 years ago, in 1609, Galileo Galilei, professor of mathematics in Padua but also extraordinary experimental physicist, decided that he would build a better "specillum" than anything they could make in the Flanders. He reasoned that in Venice there was, after all, the best glass in the world. To his credit, Galileo did not use his new gadget (the "occhiale") just as a toy or as a secret military detector to improve his standing in Venice: he also pointed it at the sky. Since then, astronomers have been using ground-based telescopes with increasing success. Needless to say, the accumulated astronomical wisdom in the intervening 400 years far surpasses the one of the previous 4000.

Finally, exactly 40 years ago (if we take the 1969 Moon landing as the symbolic date of our first look to the sky from outside our Earth) we have been doing astronomy from space. And again, as it will be easily seen, the increase in our knowledge of the Universe as obtained from space far surpassed anything collected in the preceding 4400 years. The accumulation of wisdom in astronomy over the whole 4440 year period, as well as its first and second derivatives, stand as a nice example of the acceleration of science.

Europe, again thanks to Amaldi, did not stand still during the forty years of space astronomy. Both as ESA alone and in collaboration with NASA, most notably in the case of the Hubble Space Telescope, European astronomers have contributed mightily to fig. 5, an incredible "summa summarum" of all that's known in the electromagnetic emission from our Universe. It is contained in a single graph, covering more than 15 orders of magnitude of photon energy (expressed in wavelengths).

The peak at the left of the graph represents the Cosmic Microwave Background (CMB), the relic radiation from the Big Bang. A lot has been learnt about it already, after its discovery with a ground based antenna by Arno Penzias and Bob Wilson in 1965. It was a serendipitous discovery, which confirmed the cosmology of an expanding Universe, and a discovery for which they shared the 1978 physics Nobel Prize. Nearly 30 years later, in 2006,

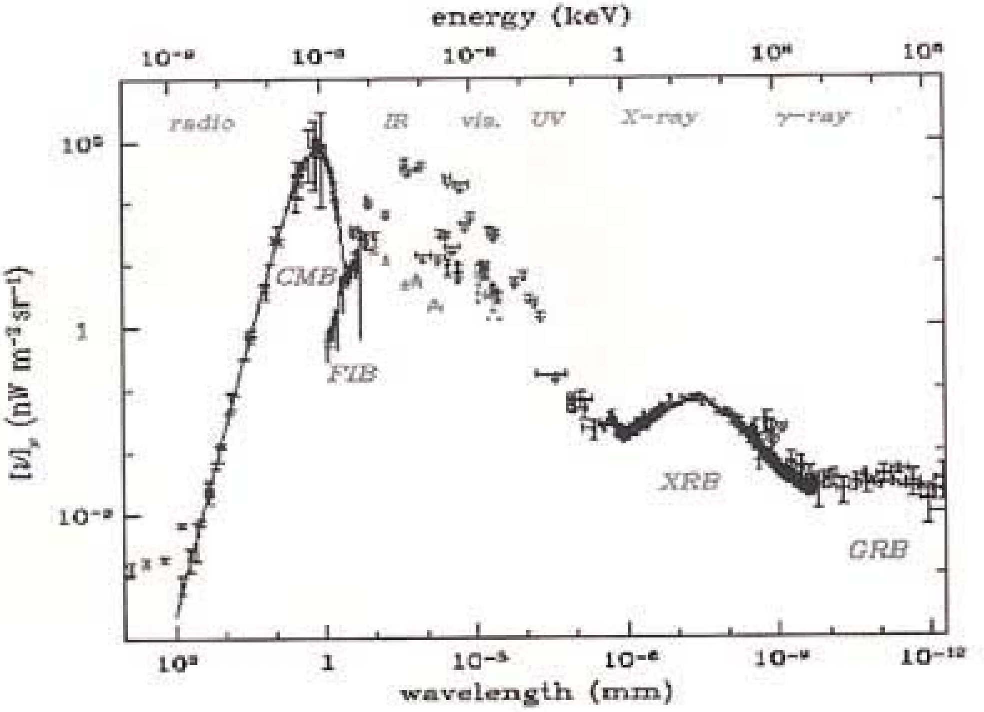

Figure 5: Spectral distribution of the electromagnetic emission from our Universe.

George Smoot and John Mather also shared a Nobel physics prize for discovering (with space astronomy this time) that the CMB carries imprinted into it the future history of the Universe, written in its tiny fluctuations and anisotropies.

The next European mission to go, hopefully in 2009, will also study the CMB. It is named after Max Planck, quite appropriately, and will be able to give an unprecedented precision both on the angular anisotropies and at the same time on the spectral characteristics of the cosmological radiation. It's a massive telescope, over four meters in length and with a mass of two tons, its payload featuring a mirror of one and a half meter diameter.

It will be flown on the same Ariane 5 rocket that will also carry in orbit another European observatory, studying an adjacent photon spectral band. This one will be named after another great European in astronomy and in physics, the German-Anglo William Herschel. Herschel will cover the infrared band, form far to near.

Planck and Herschel promise to be a pair of observatories holding great promises for European astronomy, ranging as they do from nearby molecular clouds to stars to galaxies close and far away up to the very end of our electromagnetic Universe. It is fitting to remember here that the first European infrared space mission (ISO, the Infrared Space Observatory) was approved by ESA in 1983, under the SSAC Chairmanship of Edoardo Amaldi. Here again, tradition counts.

Following Planck and Herschel, the next big space astronomy enterprise for Europe will be GAIA, to be flown in 2011. It will be dedicated to the study of the first, fundamental ladders of the cosmic distance scale by doing astrometry with an unprecedented accuracy, building on the European tradition of the Hipparcos mission, flown in 1989-1993.

GAIA will chart a three-dimensional map of our Galaxy, measuring in passing the composition and evolution of it. This will be obtained with position and radial velocity measurements for about one billion stars, or one percent of all the stars in our Galaxy. Naturally, it will also discover and observe in detail tens of thousands extra-solar planetary systems, but also an estimated half a million quasars. A true revolution in astronomy, the full consequences of which have not yet been fully imagined.

In 2013 (again, hopefully), ESA and NASA will share another great astronomical adventure, following up on the glorious Hubble Space Telescope, still operational after nearly two decades in orbit. Another Ariane 5 will put in orbit the James Webb Space Telescope, also (appropriately) known as the Next Generation Space Telescope. Named (for reasons not obvious to outsiders...) after the second NASA administrator, it will have a mirror surface about 6 times that of Hubble, and will be optimized for near infrared work. This is because it will probe, for the first time, that highly redshifted part of the Universe were the first stars and Galaxies were born. JWST will thus do astronomy that will carry us back well before 13 billion years ago, which was (and still is) the limit of the Hubble Ultra-Deep Field. So far, the HUDF represents the furthest mankind has reached in astronomy, and yet we still miss that crucial physics steps when the first stars were born and lit up. It should be fun to watch the JWST results closing the gap, as it were, between HST and the CMB data: it's in that first few hundreds of millions of years that everything happened.

## 6 High-energy astrophysics: an Italian specialty

High-energy astrophysics, *i.e.* astronomy with X- and gamma-rays, needs to be done from space, because of the absorption of our atmosphere (luckily for all terrestrial life forms). As we have seen, it was all started in the U.S. by Giacconi, Rossi and their group in the early sixties, but Europe caught up fast. In particular, the idea of doing astronomy with gamma-rays, first started at MIT and at NASA GSFC, became a reality in the ESRO of the late sixties thanks to Beppo Occhialini in Milan. After the first difficult

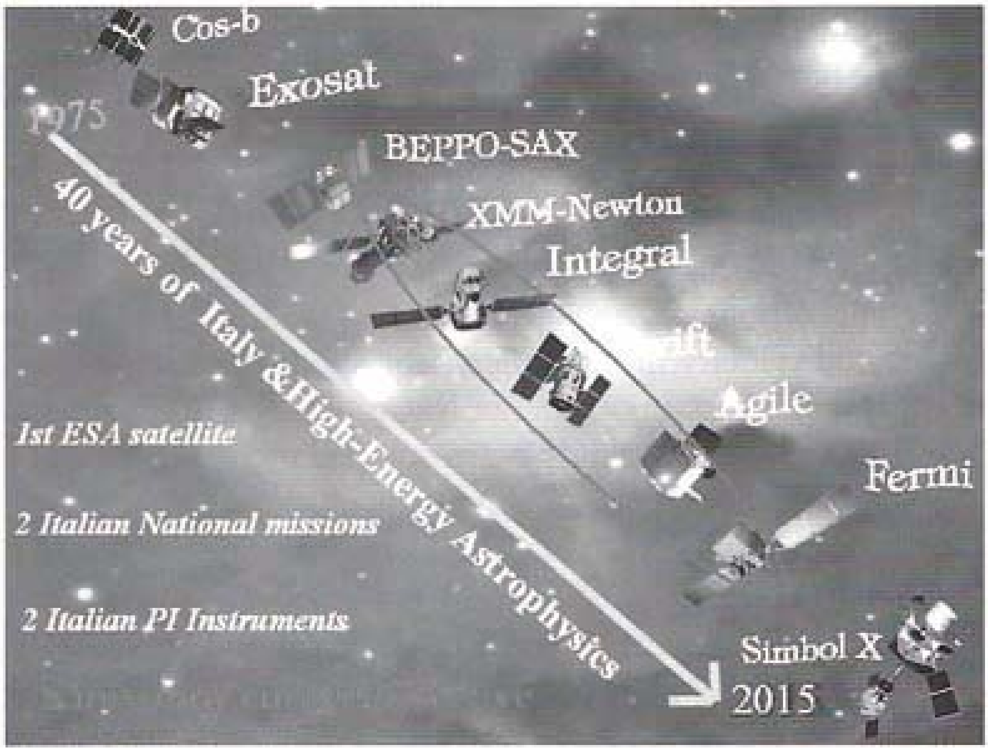

Figure 6: Italian contribution to high-energy astrophysics.

attempts with gamma-ray space detectors (for example S-88, built in Milan in the sixties and the topic of my own thesis in '68) on the ESRO TD-1 satellite, a major European collaboration was set up, including Italy, France, Germany and England for an orbiting gamma-ray observatory. Thus, with a significant Italian contribution, the COS-B mission was born.

Launched in 1975, COS-B was to be the first ESA satellite, and was fortunate enough to discover not only the first extragalactic gamma-ray source (the quasar 3C273), but also found evidence of numerous "discrete" galactic sources. Thanks to its longevity, COS-B (1975-1982) really opened the gamma-ray astronomy sky and its data led to the eventual understanding of Geminga, the first celestial object discovered with gamma-rays.

COS-B marked the beginning of a series of high-energy astrophysics missions (see fig. 6) in which Italy has had (or still has) an important or leading role. Not only were Italian groups significantly present in the first ESA satellites for gamma-rays (COS-B) and X-rays (EXOSAT 1983-1986), but later, in less than two decades, ASI produced two national missions, BeppoSAX (named after Occhialini), active from 1992 to 1996, and AGILE (P.I. M. Tavani), launched in 2007 and still going strong.

Moreover, the two ESA missions XMM/Newton (X-rays, 1999 to present) and INTEGRAL (gamma-rays, 2002 to present) have had, for the first time in the history of ESA, Italian Principal Investigators, supported by

ASI and INAF. G.F. Bignami was Principal Investigator (1987-1997) of the EPIC XMM instrument, currently the most scientifically productive instrument of the whole of X-ray astronomy, and P. Ubertini is the P.I. of the IBIS instrument on INTEGRAL. The two gamma-ray astronomy NASA missions currently active (Swift and Fermi, formerly GLAST)also have a very significant Italian contribution, through ASI, INAF and INFN, both in the flight hardware as well as in the science data analysis.

To illustrate more completely this tradition of high-energy astrophysics work, we will now propose a few recent results. We are sure that Edoardo Amaldi would have been interested in them, and they are thus given here also to honour his memory.

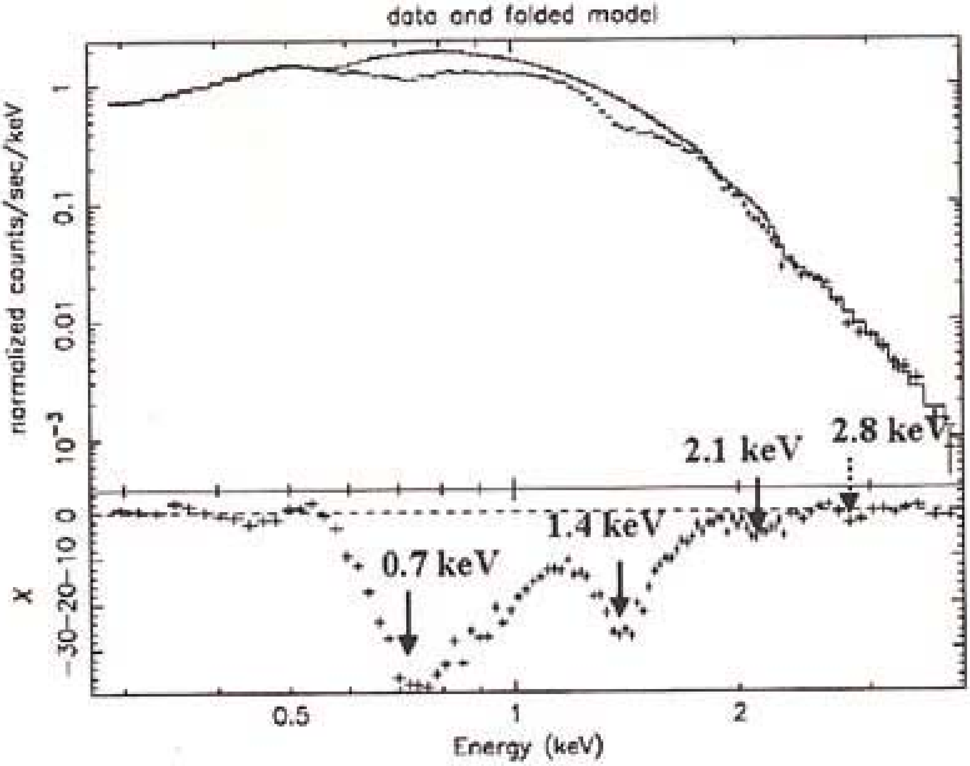

Figure 7: X-ray spectrum of 1E1207.4-5209, as measured by the pn detector on XMM-Newton (Bignami *et al.*, 2003).

*6.1 Newton, X-rays and neutron star physics* – The European Photon Imaging Camera (EPIC), on board the ESA XMM/Newton X-ray Observatory is a perfect tool for the study of isolated neutron stars (INSs). This newly discovered and highly challenging galactic population requires a combination of throughput breadth, excellent energy and time resolution, plus of course imaging capabilities for the faint structures which were discovered around INSs.

Figure 8: XMM-Newton Geminga X-ray image on the "Physics World" cover.

One of the first spectacular results on neutron stars came from the Milan group early in the mission from the study of 1E1207.4-5209, an ISN located close to the center of a recent ($10^4$ yrs) SNR (Bignami *et al.*, 2003). The detector combination of grasp and resolution mentioned above showed, for the first time in astronomy, clear absorption lines in the X-ray spectrum of an INS (fig. 7). The same spectrum also shows unambiguously that such absorption lines are harmonically spaced in energy (at 0.7, 1.4, 2.1 and 2.8 keV), thus revealing their nature as cyclotron absorption lines.

Depending on whether one assumes that the particles gyrating in the star magnetic field, and thus responsible for the effect, are protons or electrons, one has only 2 possible values for such a field: $8 \times 10^{10}$ G or $1.6 \times 10^{14}$ G. Other considerations allow to exclude the higher (proton-related) field value, so that the XMM/Newton observation yield the first measurement *in situ* of an INS magnetic field.

Next, XMM/Newton, with EPIC, observed Geminga, the prototype high-energy neutron star. Here, a surprising result showed that the gamma/X-ray pulsar is surrounded, or rather trailed, by a complex extended structure, tracing the star's motion in the interstellar medium. In a paper which made the cover of "Science" and of "Physics World" (fig. 8), Patrizia Caraveo and her Milan group showed that the structures are due to synchrotron emission from high-energy electrons escaping the pulsar magnetosphere (Caraveo *et al.*, 2003). Also, for the first time the energy of such electrons was shown to reach $10^{14}$ eV, or exactly the maximum electron energy foreseen by the rotating dipole pulsar theory.

*6.2 Catching Gamma-Ray Bursts on the fly* – Launched in Nov. 2004 with the promise of revolutionizing gamma-ray burst (GRB) studies, the NASA Swift mission is exceeding even the most optimistic expectations. Swift is a versatile, multi-wavelength observatory, combining a new-technology gamma-ray camera (BAT) with sensitive telescopes in the X-ray (XRT) and UV-optical (UVOT) ranges. All instruments are placed on a robotic fast-slewing spacecraft.

Italy was invited to participate to the NASA mission on the strength of its tradition in high-energy astrophysics in general, but in particular thanks to the unique results of the Italian-Dutch satellite BeppoSAX, flown from 1996 to 2002. Dedicated to studying X-ray sources, by far its most important result was to open the road to the identification of the GRBs, till 1997 a complete mystery. BeppoSAX showed that the road to GRB identification is to catch their fast-fading X-ray afterglow which, we now know, it is a characteristics all GRBs share. This renders possible optical follow-up work, thus permitting to understand the nature of the counterpart, a distant galaxy.

Using the same method, Swift has discovered and thoroughly studied more than 300 GRBs, while performing follow-up observations of GRBs detected by other satellites. It has also slewed on an impressive number of TOOs (Targets of Opportunity) for rapid follow-up observations of all kinds of variable sources, such as Novae, flaring AGNs, Supernovae, etc.

Swift's ability to lo locate GRBs (both long and short) and to follow their decay at X-ray and optical wavelengths has improved dramatically our understanding of GRB physics. For example, it has shown that their central engine activity can last for hours after the explosion. While establishing the connection between long GRBs and supernovae (and thus with star formation rate) in the local Universe, SWIFT has also convincingly demonstrated

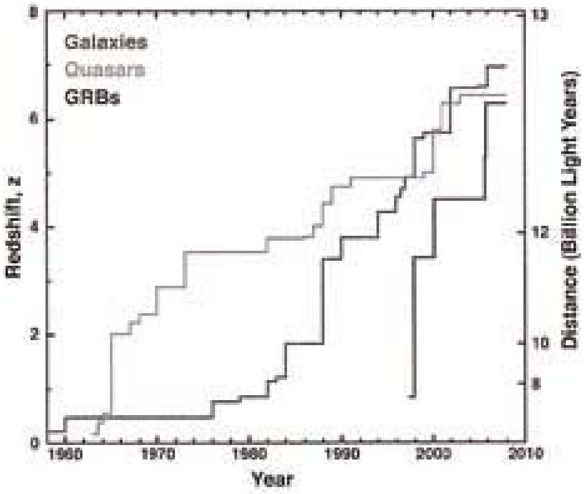

Figure 9: Cumulative redshift distribution for galaxies, quasars and GRBs.

that such GRBs can be used to probe the first generations of stars in the early universe.

The detection of at least two long GRBs with $z > 6$ has been a landmark result. Indeed, GRBs' redshift distribution (shown in fig. 9) is rapidly approaching the maximum values measured for Galaxies and QSOs, and it grows at a much faster rate than that of any other extragalactic population. The connection between long GRBs and SNe made it possible us to use the redshifts of long GRBs to infer the cosmological star formation history.

On the other hand, precise localization of several "short" GRBs unveiled elliptical host galaxies with very low star formation rates. Short bursts are on average at 6 times smaller redshifts than long bursts and their isotropic energies are smaller by $\sim 100$. Moreover, none is associated with a supernova. This supports the interpretation that short bursts occur in old stellar populations, and are likely to arise from mergers of compact binaries (*i.e.*, double-neutron-star or neutron-star–black-hole binaries).

*6.3 AGILE, at last* – On April 23, 2007, finally the ASI mission called AGILE was launched by an Indian PSLV rocket and put into a perfect low-altitude, equatorial orbit. The satellite and payload have been working nominally ever since, and the ASI Malindi station catches regularly every pass over it, once per orbit.

The mission had been conceived in 1997, and was supposed to be the first of a series of small Italian scientific satellites, to quickly follow the BeppoSAX success. In reality, the AGILE mission development took much longer than it should have, covering 10 years from conception to launch. It also remains, so far, the only small scientific satellite of ASI.

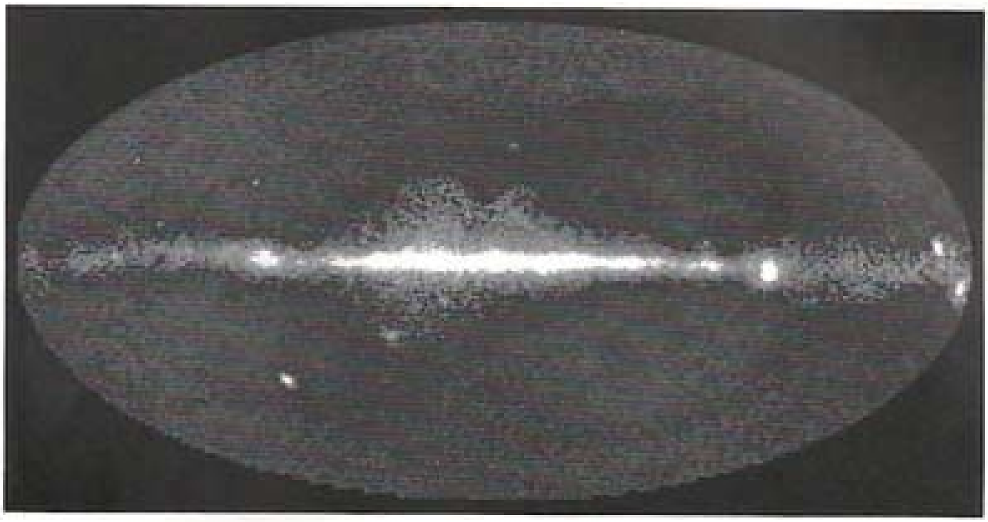

Figure 10: Agile 9-month image of the sky using photon with $E > 100\,\mathrm{MeV}$.

AGILE, however, is a spectacular success of science and technology made in Italy. It contains an innovative instrument, the gamma-ray tracker, which detects high-energy photons through their pair-production process and then tracks electrons as they pass a stack of silicon detector plates. It is directly inspired by high-energy physics work and allows for an excellent photon positioning in the sky, very ample field of view, low dead-time and very high time resolution. The AGILE payload, conceived and constructed by INFN and INAF in collaboration with Italian small and medium space industry, is also complemented by a soft and hard X-ray detector acting also as a gamma-ray burst detector, and a small calorimeter, to increase the global mission scientific output (Tavani *et al.*, 2009).

After over one year in orbit, AGILE has already provided us with a new view of the gamma-ray sky, given in galactic coordinates in fig. 10. The well-known global emission from the galactic plane is apparent, as well as the emission from point sources in the extragalactic sky (the erupting AGNs) and in the Galaxy. Many of these are now identified with radio pulsar (Pellizzoni *et al.*, 2009, 2009b), and AGILE has, in fact, just discovered five new objects, thus nearly doubling the available catalogue of radio pulsars visible in gamma-rays.

Many more discoveries are fast pouring in from AGILE, from detailed studies of AGNs (Vercellone *et al.* 2008), to interesting GRBs (Giuliani *et al.*, 2008) to X- and gamma-ray emission from galactic binaries and much more. Stay tuned for unique new physics from space from this small, highly technological, all-Italian satellite.

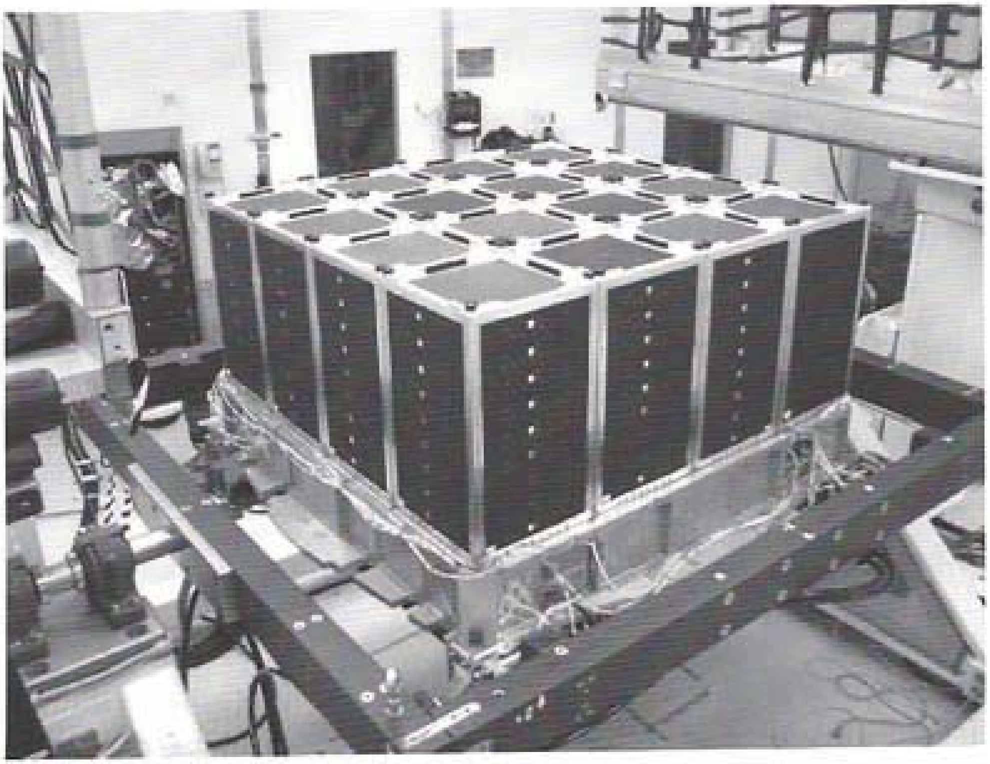

Figure 11: The 16-tower modular structure of the Large-Area Telescope on Fermi (Atwood *et al.* 2009).

*6.4 Fermi, or, a skyful of Gemingas* – AGILE's Big Brother, formerly named GLAST, went into orbit on June 11, 2008. It was then renamed, following NASA's tradition for its great observatories, and became the Enrico Fermi Observatory. An apt name for a U.S. mission which carries a very significant fraction of Italian ideas and hardware in its payload and which is now seeing a community of Italian scientists participating in its scientific exploitation.

Again, the Italian participation to GLAST/Fermi has been rendered possible, financed and coordinated by ASI, but its science had been conceived by an INFN/INAF collaboration similar to that responsible for AGILE and the instrument's hardware was once more realized thanks to small and medium Italian space industry.

It is clear that the work done for the AGILE small mission was essential for enabling Italian participation in Fermi. That AGILE was a precursor to Fermi is particularly apparent if one looks at the heart of the Observatoty, the Large Area Telescope (LAT), the principal instrument for gamma-ray astronomy on Fermi.

It consists of 16 "towers" (see fig. 11), each of which has similar dimensions and characteristics of a whole AGILE: a tracker stack of silicon detectors, for a global unprecedented active surface area. Complete with

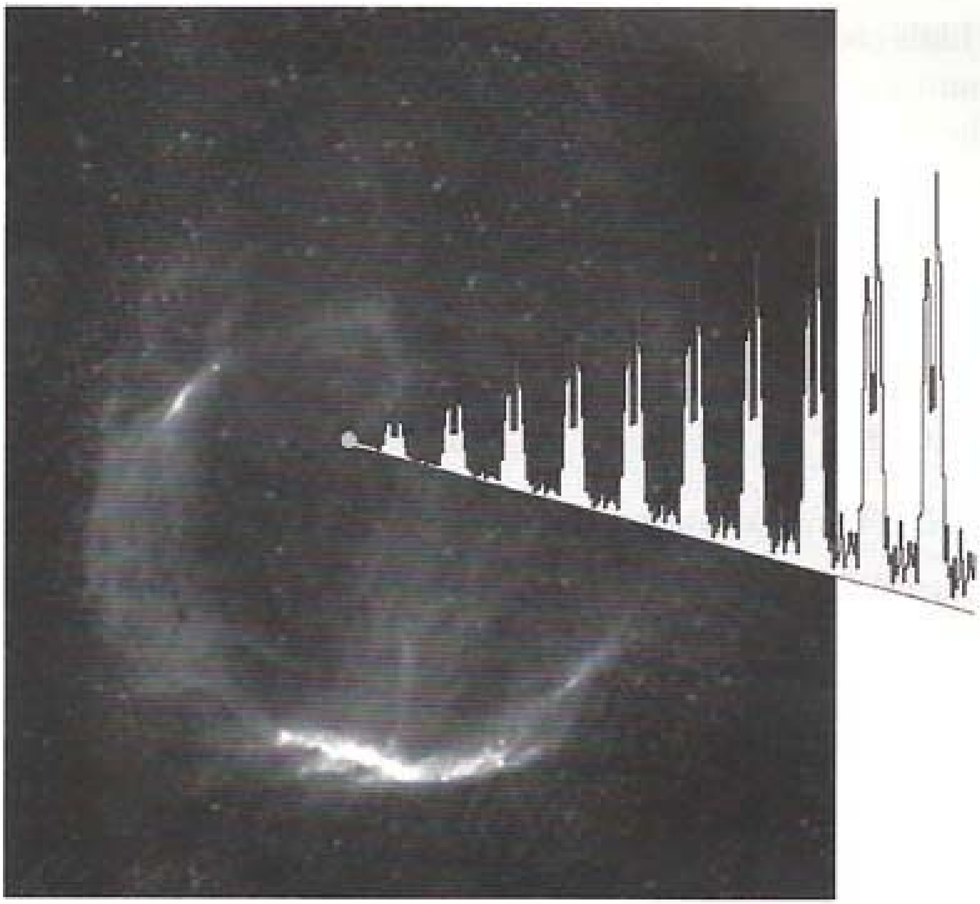

Figure 12: Gamma ray light-curve superimposed to the radio image of the SNR CTA-1.

a huge (couple of tons) calorimeter located below the trackers for accurate energy measurement, the LAT of Fermi is the most powerful gamma-ray astronomy machine ever conceived and flown.

Even if Fermi has been in orbit for only a few months at the time of this writing, it has already produced at least one spectacular result. It has demonstrated its capacity to discover gamma-ray pulsars even in the absence of radio pulsations, something no previous instrument could ever come close to doing. The first object so discovered is the rotating young neutron star at the center of the CTA1 supernova remnant (Abdo *et al.*, 2008, see fig. 12).

As recently pointed out by Bignami (2008) this first Geminga-like gamma-ray pulsar discovered in CTA1 is likely to be rapidly followed by several more similar objects. They could systematically provide a very plausible identification to the decades-old UGO (Unidentified Gamma Objects) problem in our Galaxy.

Since their discovery by COS-B in the late seventies (Bignami & Hermsen, 1983), and their subsequent confirmation by NASA's EGRET/Compton in the nineties, UGOs have remained one of the mysteries of high-energy astrophysics. It now appears that they may be but many Gemingas (Bignami & Caraveo, 1996). While the feeling of having bagged the first example of a new galactic population is certainly exciting, it is tempered by the observation that it took twenty years of front-line astronomy (1973-1993) for nailing Geminga, but that just a few weeks of Fermi data alone were sufficient to show what its cohort is made of. That's progress in science for you.

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