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WHAT FALLS FROM THE SKY

Not everything which comes from the sky is good for us. But if we're worried about comets or meteorites crashing into Earth, we should also remember that much of what comes to us from the sky can be the source of momentous discoveries.

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Astroparticle physics, also known as particle astrophysics, studies the radiation reaching Earth as particle streams or gravitational waves. The field is currently flourishing in Poland and around the globe, mainly driven by the huge advances in observation and detection techniques. Researchers working in this relatively young discipline have been awarded several Nobel Prizes in recent decades.

Astroparticle physics is a multidisciplinary field intertwining the latest developments in physics, astrophysics and cosmology. The range of scales of objects and physical phenomena it studies is certainly impressive: from the Planck length and yoctoseconds, which describe the earliest moments of our Universe, to the radius of the observable Cosmos, measured in gigaparsecs, and the billions of years of its evolution. To clarify, a gigaparsec is a billion parsecs; a parsec, a standard unit used in astronomy, measures 3.26 lightyears or 3.08×10^{16} meters.

Until the 1960s, astroparticle physics was generally described as the physics of space radiation and cosmic rays. Elementary particle physics, as it is practiced today through experiments at ground-based accelerators, has evolved from studies of elementary particles and the processes they undergo which manifest as cosmic radiation. Cosmic radiation comprises electromagnetic waves, fast moving elementary particles and atomic nuclei and gravitational waves reaching Earth from space. Research on astroparticles and their interactions with atmospheric ions has led to the discovery of the first antimatter particles (positrons) and the first second-generation leptons (muons).

Even though some of the greatest discoveries – such as the detection of the Higgs boson – are being made by Earth-based detectors such as the Large Hadron Collider at CERN near Geneva, cosmic radiation helps us study phenomena with the highest achievable energies. The energies of some of the particles hitting Earth's atmosphere can reach almost 450 TeV – significantly higher than those reached at the LHC.

While studies of cosmic rays and elementary particle physics have always gone hand in hand, the links between cosmology and particle physics were not recognized until much later. In the wake of Hubble's discovery of the expanding universe and the subsequent formulation of the Big Bang theory, it became clear that there was a point during the Universe's history when it was extremely dense and hot. In its primordial state, the Universe was a quantum microcosm whose properties and evolution are described by quantum mechanics and elementary particle physics. Many studies conducted today at particle accelerators attempt to recreate the conditions found in the very young, hot Universe by colliding high-energy proton/anti-proton and electron/positron beams to simulate miniature Big Bangs. However, it will never be possible to recreate the ultra-high temperatures and energies found in the moments following the Big Bang. This means that a symbiosis of elementary particle

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physics, astronomy and cosmology is the only natural progression of research, giving rise to contemporary astroparticle physics.

Achievements and challenges

The road to the contemporary symbiosis of particle physics, high energy physics, astrophysics and cosmology has been long, but it is paved with many surprising discoveries. Some of them are milestones towards our understanding of the physics of the Universe. It has frequently been observed that the phenomena concealed in the far reaches of the Universe, making themselves known as particles and radiation reaching Earth, are so extraordinary and bizarre that they exceed the wildest speculations of science fiction authors, never mind physicists' expectations.

Studies of various sources of cosmic radiation have revealed the existence of objects such as quasars – the most highly luminous objects currently known. The absolute luminosity of quasars is approximately equivalent to a billion of our Suns. The only brighter objects are the brief explosions of certain supernova. Quasars maintain their luminosity for millions of years. Astroparticle physics provided the solution to the puzzle of quasars: their luminosity is explained by accretion of matter onto a supermassive black hole. The discovery of pulsars which also emit in the radio wave range led to the development of the field of relativistic electrodynamics which studies fast rotating and highly magnetized neutron stars. Both quasars and pulsars were highly surprising; however, it was solving the problem of the anomaly of atmospheric and solar neutrinos that was one of the greatest achievements of astroparticle science. This anomaly was the mysterious deficit of solar neutrinos in the streams reaching the Earth, in contradiction with theoretical predictions. The solution turned out to be the fascinating phenomenon of neutrino oscillation, originally predicted by Bruno Pontecorvo in 1957, which implied that neutrinos have non-zero mass.

> Today's symbiosis between particle physics, high energy physics, astrophysics and cosmology has arisen out of many surprising discoveries.

The research and observations which are at the core of astroparticle physics have resulted in more fascinating discoveries, including gamma-ray bursts, experimental verification of the theory of special and general relativity (using muons from cosmic rays), measurement of background cosmic radiation (Nobel Prize for the COBE mission) and the discovery of the accelerated expansion of the Universe (Nobel Prize for observations of distant supernovas). Some of the greatest discoveries made in the last two years, achieved by the LIGO and Virgo teams, concern gravitational waves originating from merging black holes and neutron stars.

The 2017 Nobel Prize in physics was awarded to three physicists whose hard work conducted over many years has led to the foundation of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and its European partner Virgo. Kip Thorne, Rainer Weiss, and Barry Barish were awarded the prize for making the first direct observations of gravitation waves passing through a terrestrial laboratory. On 14 September 2015, both laser interferometers of the LIGO system registered gravitational wave signals emitted during the violent merger of two black holes. The characteristics, duration and shape of the signal perfectly matched the predictions of Einstein's gravitational theory. And so almost a century after Einstein proposed his theory of general relativity, its most exotic prediction – that of the existence of gravitational waves – was finally confirmed by direct measurements in a lab. This gave rise to a brand-new, 21st-century scientific discipline: gravitational wave astronomy. The events of 14 September 2015 were just the beginning of a stream of fascinating discoveries (see also *Academia* magazine, no. 1 (45) 2016). The phenomenon has been further detected a few times since.

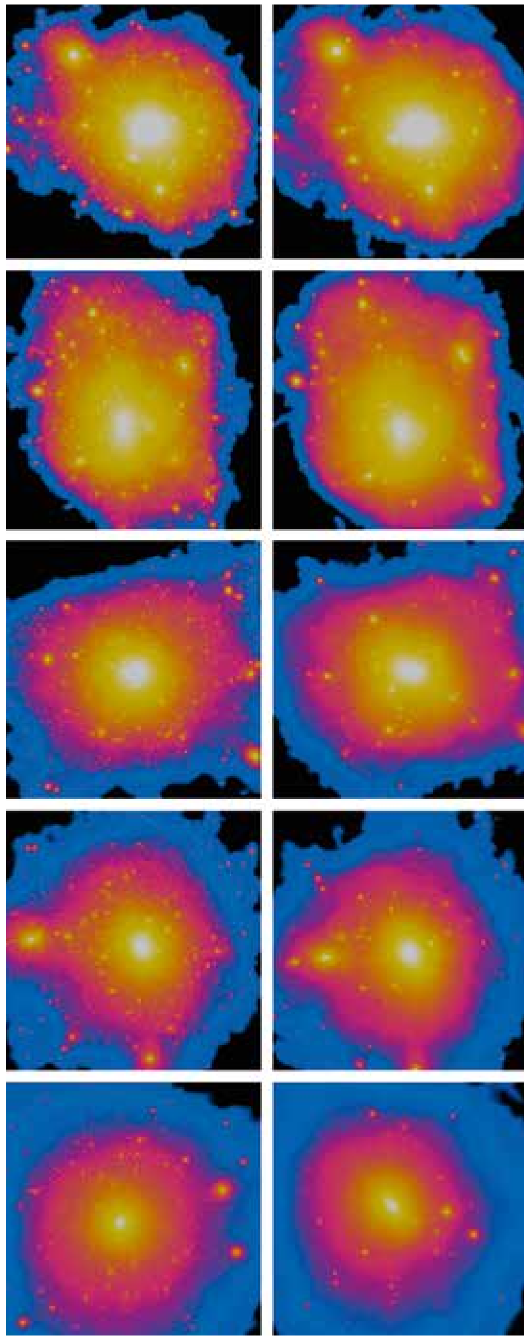
Although the first detection of gravitational waves was hailed as a major breakthrough, just a year ago the LIGO and Virgo observatories registered the signal of an even more extraordinary phenomenon. On 17 August 2017, astronomers detected for the first time the signal of two colliding neutron stars (event GW170817). Neutron star collisions are even more fascinating for physicists, because – in contrast to black holes – neutron stars comprise atomic matter which also emits electromagnetic radiation. Alerted to the signal registered by LIGO/Virgo, dozens of terrestrial and orbital laboratories turned their watchful eyes towards the NGC 4993 galaxy – the source of the gravitational signal. The equipment detected a new, transient radiation source which was indisputably identified as arriving from the same source as the gravitational signal. This was the first time that a glow of a kilonova blast was observed. Kilonovas were predicted theoretically as events that occur when two neutron stars collide and merge, emitting electromagnetic radiation at all wavelengths. Measurements of the delay in gamma radiation from the kilonova GW170817 glow in relation to gravitational waves allowed us to determine the velocity of gravitation and light with an accuracy several orders of magnitude greater than any similar measurements made previously. This gave rise to yet another brand-new scientific discipline: multi-messenger astronomy.

This rough list of some of the greatest discoveries which have, in a sense, fallen out of the sky reveals that the close synergy between disciplines including cosmology, astronomy, high energy physics and elementary particle physics, practiced as astroparticle physics, has a bright and exciting future ahead.

A future full of discoveries

Twenty first-century physics, astrophysics and cosmology are facing some of the greatest challenges ever posed by nature and science. The mysteries include solving the physical nature of dark matter and dark energy – the enigmatic components of the Universe; the former is responsible for the formation of large-scale structure of the Universe and the galaxies it contains, and the latter drives the accelerated expansion of the Cosmos. Searching for elementary particles – the building blocks of dark matter and the products of its decay or annihilation – is one of the main aims of the research being carried out by astroparticle physicists and cosmologists. The new window onto the Universe, opened by the detection of gravitational waves and the research into the processes of the emission and variance of high-energy radiation of quasars and active galaxies, will help us conduct ever more precise measurements of cosmological parameters. These measurements should throw a new light on the dark energy problem, helping us elucidate its enigmatic nature. We can only speculate as to the new puzzles which will be uncovered by the new, dynamic disciplines of neutrino and hard gamma ray astronomy. Observations of cosmic neutrinos will help us explain the processes behind supernova explosions, such as the 1987A supernova which exploded in the Large Magellanic Cloud. Studies into high-energy gamma photons reveal the physics of exotic high-energy natural processes, such as kilonovas, collapsars and hypernovas. Analyses of primary and secondary air showers – cascades of particles and photons formed when high-energy cosmic ray particles enter the atmosphere – should help us gain a better understanding of distant sources of cosmic radiation and pave the way to devising further experiments and developing the standard model of elementary particles. The phenomena are usually accompanied by Cherenkov radiation, registered by terrestrial optical Cherenkov telescopes.

Our ongoing search for traces of double neutrinoless beta decay and gamma photons with energies on the TeV scale among air shower traces also show promise to bring further breakthroughs.



Computer simulations: formation of the Milky Way Halo using two different models of dark matter.

On p. 39:
The Virgo Observatory.

It's true that not everything that comes from the sky is pleasant or good for us. It wasn't so long ago that humankind lived in fear of comets or meteors crashing into the planet, and of course our concerns over the hole in the ozone layer and UV radiation are still valid. Perhaps not many of us admire hail or freezing rain. However, the history of great discoveries made by astroparticle physics and its future suggests that instead of gazing up at the sky in fear and trepidation, we should anticipate learning more about the Universe and its fascinating phenomena.

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Further reading:

Sownak B., Hellwing W. A., Frenk C. S., Jenkins A., Lovell M. R., Helly J. C., Li B., Gonzalez-Perez V., Gao L. (2017). Substructure and galaxy formation in the Copernicus Complexio warm dark matter simulations. *Mon. Not. Roy. Astron. Soc. 464 no.4*, 4520–4533.

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