International Particle
Physics Outreach Group

PASSPORT TO THE INFINITE

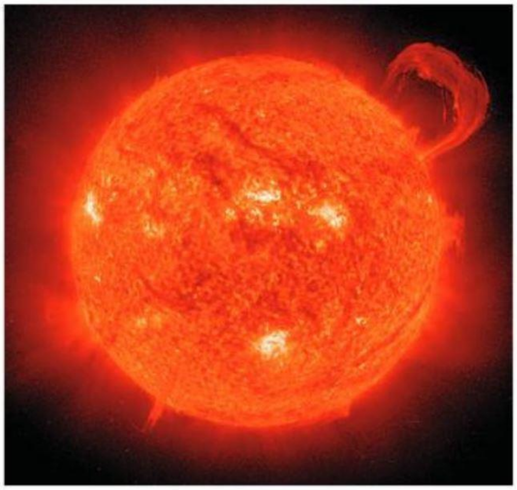
A Well-Known Formula: $E = Mc^2$

$E = Mc^2$ is the most famous formula in the world. This popularity, due to its simplicity and to the personality of its author, Albert Einstein, has resonated with physicists, who have made use of this relation and its consequences for more than a century.

The Sun,
$E = Mc^2$ at work

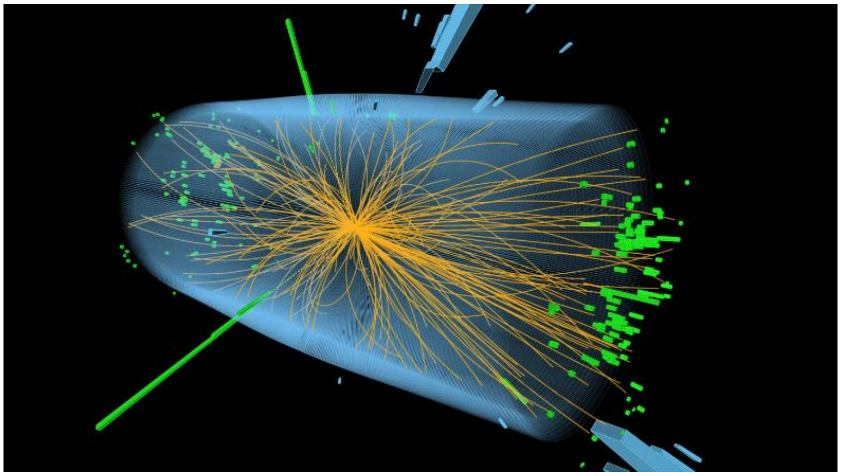
In the Sun, 620 million tonnes of hydrogen turn into 615 million tonnes of helium every second. The mass difference is released in the form of energy.

In September 1905 Albert Einstein, then 26 years old, wrote a mere three-page paper containing the $E = Mc^2$ equation. The paper was presented as an extension of the theory of relativity that the very same Einstein had just published. It demonstrated that a body emitting electromagnetic waves necessarily loses mass. The young man ascribed universal significance to this result: the mass of a body is a measure of its energy content. Consequently, if the body loses energy (in any form, electromagnetic or other), it also loses mass.



Credit: ESA/NASA/SOHO

Any massive body, even at rest, is given a ‘rest energy’ E, i.e. an energy owed to the mere fact of having a rest mass M. The two quantities are linked by the equation $E = Mc^2$, where c is the speed of light in vacuum, a constant equal to exactly 299,792,458 metres per second. Therefore, the mass-to-energy conversion factor is gigantic: almost ten million billion in the International System of Units. This observation explains why we generally cannot perceive the energy contained in the mass of a body. For example, take an 11-Watt low-energy lamp, connect it to a battery and suppose the whole system operates for a thousand years uninterruptedly. In the end, the system will have lost only a few micrograms, a tiny variation compared with its initial mass.



Credit: CERN-CMS

So how did Einstein's formula become the symbol of 20th-century physics? For since 1905, physicists have managed to explore, and sometimes industrially exploit, situations in which mass → energy or energy → mass transformations have tangible effects.

Let's start by transforming mass into energy. When a heavy Uranium-235 nucleus is hit by a neutron, it fissions and splits into two nuclei which are lighter together than the original nucleus. This mass loss corresponds to a large release of energy (for the same mass, the emission is a million times greater than in the case of coal). In nuclear power plants, energy is recovered as heat, part of which is converted into electrical energy.

The fusion of two light nuclei into a single nucleus induces the same result: the 'lost' mass is converted into energy. This reaction is what makes stars shine. Every second, our Sun turns 620 million tonnes of hydrogen into 615 million tonnes of helium, radiating the difference outwards. We receive only a very small fraction of this colossal amount of energy, but it is the source of life on Earth.

Finally, there are also situations in which energy transforms into mass rather than the other way round. Think of the extremely violent shocks that particles undergo in the colliders used by physicists to probe the structure of matter. Almost all the energy of the colliding particles is converted into mass, that is, into other particles which then travel through the detectors where they can be studied.

A high-energy collision of two photons in CMS

In a high-energy particle collision, energy is conserved but mass is not and the particles produced are not just fragments of the incident particles. They also come from the conversion of the collision energy. This 3D-image represents the central part of the CMS detector in the LHC in a simplified way (blue area). Each curved orange trace represents a charged particle. The green bars indicate two preferred directions for these particles, associated with energy deposits in the detector, represented by blue and green blocks.

Translated from 'Une formule célèbre : $E = mc^2$',* Passeport pour les deux infinis, *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG