The nine lives of Cosmic Rays in the Heliosphere

Into the physics of solar modulation

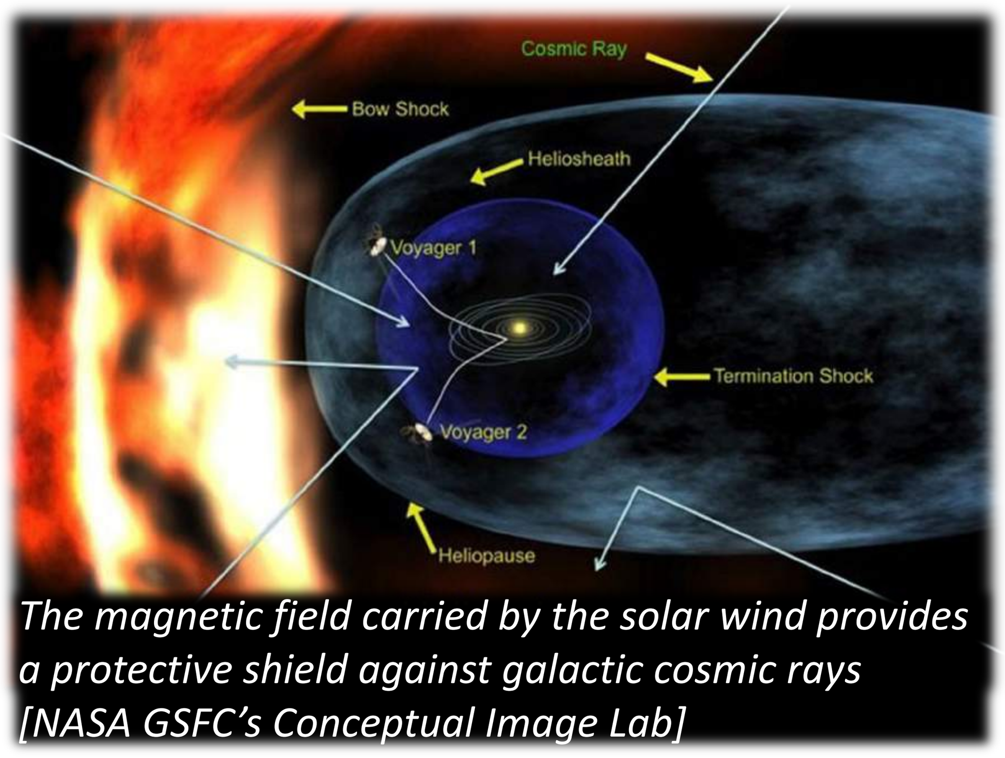
Cosmic rays, Galactic messengers

For a century now, we know that the Earth is bombarded by charged particles: electrons, protons, and nuclei that come in at nearly the speed of light. These particles are called **cosmic rays**, and before reaching our detectors near Earth, they have traveled millions of years throughout interstellar space. **Cosmic rays tell us a story about the Universe that we would not learn from light alone.**

Artist's impression of a cosmic.ray that hits Earth's atmosphere [J. Yang/NSF]

The Heliosphere: a bubble of splasma

In the last part of their journey toward our planet, cosmic rays encounter the **Heliosphere**: a giant bubble of plasma influenced by the Sun. It extends to about 120 astronomical units. The Heliosphere is created by the **solar wind**: a magnetized plasma made of particles and magnetic field that are continuously ejected from the Sun at supersonic speed. In this wind, the magnetic field lines and the plasma are tied to one another and move together with the flow of the plasma. Furthermore, because the Sun is spinning while ejecting the plasma, the large-scale structure of the solar wind has the form of a **rotating spiral**.



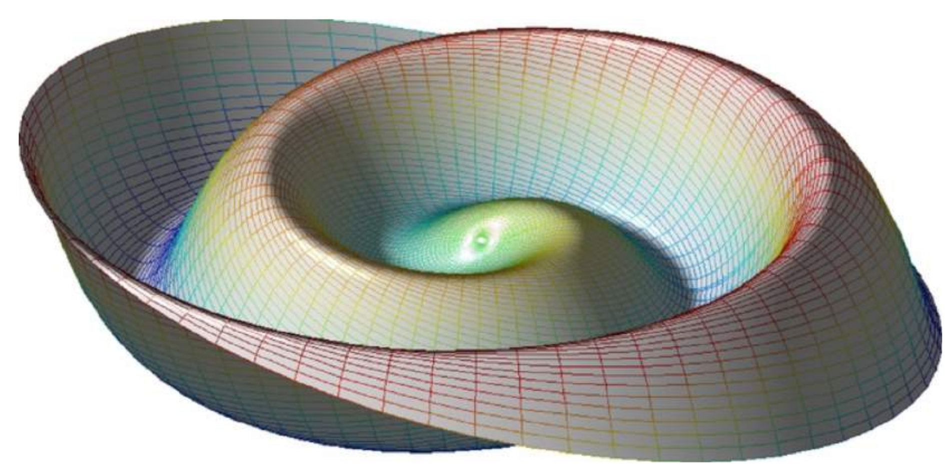
The magnetic field carried by the solar wind provides a protective shield against galactic cosmic rays [NASA GSFC's Conceptual Image Lab]

The solar modulation effect

When traveling in the Heliosphere, cosmic rays are deflected and decelerated by the turbulent **magnetic fields** of the Sun, dragged out by the **solar wind**. As a result, the intensity of the cosmic radiation at Earth is different from that in the **interstellar space**. Moreover, the change of their intensity is not a stationary effect: **it moves and changes** as the Sun's magnetic fields move and change. The change of the cosmic ray intensity caused by Sun's magnetic activity is known as **solar modulation effect.**

Why solar modulation is so important?

Because this effect limits our ability in understanding the physics of cosmic rays, to identify their sources, to search for dark matter signatures. Another reason to care about solar modulation is because the varying cosmic-ray flux can provide a significant challenge for interplanetary space missions.



The swinging «Parker spiral» of the solar magnetic field.

What do we know about it?

A general theory of solar modulation was established by Eugene Parker in the 60's. He developed complex mathematical equations describing the physical mechanisms of cosmic-ray transport in the Heliosphere.

The Parker evolution equation for the cosmic ray density

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K}\cdot\nabla f] - \mathbf{V}\cdot\nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

Eugene Parker and the Parker Solar Probe model

One is **diffusion**, that arises from the small-scale irregularities of the solar magnetic field. These irregularities make cosmic rays to move **randomly**, and to eventually spread out in all directions. Another important process is **convection**, a bulk motion of particles in the outflowing wind. Convection slows down cosmic rays that are directed toward the inner heliosphere, therefore protecting the Earth from the radiation.

Finally, charged particles experience **drift motion** due to the regular components of the large-scale magnetic field. The field lines guide the particles to make spiral trajectories around them. Due to drift, cosmic particles in the Heliosphere behave much di differently from their **antiparticles**. All these effects are also **time tependent** following the 11-year solar cycle. It is then very important, for understanding solar modulation, to analyze several types of observations: from the evolution of solar activity to the variations of the cosmic ray fluxes.

Multichannel Investigation of Solar Modulation Effects in Galactic Cosmic Rays
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