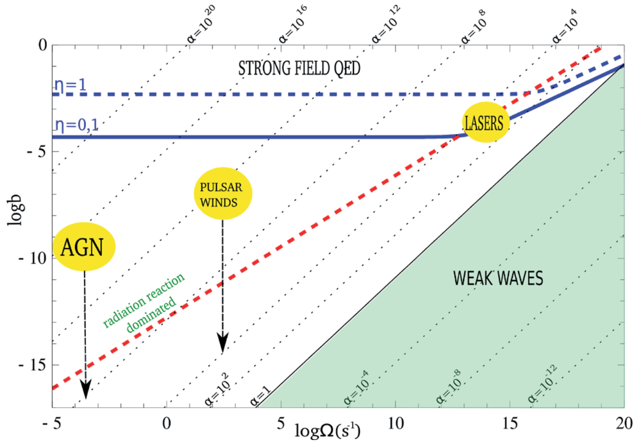
Materialisation of electrons and positrons

Both energetic electrons and energetic positrons bombard the Earth's upper atmosphere. Electrons can be taken from any atom by ionising it. But positrons are not so ubiquitous. A few of them are created in the decay of radioactive nuclei, but it's thought that the vast majority simply materialise together with an electron out of the vacuum. This is predicted to happen spontaneously when the electric field exceeds the critical or "Schwinger field" $E_c = 1.3 \times 10^{18}\ \mathrm{V\,cm^{-1}}$, but the process has never been observed. It can also happen when two gamma-ray photons collide, or when one gamma-ray photon enters a very intense magnetic field. Both processes are thought to occur in pulsar and black-hole magnetospheres, where the photons can be provided by electrons accelerated in a strong electromagnetic wave.



The physical parameters (frequency in Hz on the x-axis, amplitude b in units of E_c on the y-axis) of strong electromagnetic waves. Assuming counter-propagating vacuum waves, the regime of strong field QED, where the rest-frame electric field exceeds E_c is within reach of next generation optical lasers. In pulsar winds and jets from active galaxies, particles are strongly influenced by radiation reaction.

Ultra-intense, optical laser pulses from facilities such as the European project "Extreme Light Infrastructure" are expected to reach $10^{24}\ \mathrm{W\,cm^{-2}}$ in the next few years. This is powerful enough to reproduce the conditions for electron-positron creation found in pulsars and black-hole magnetospheres. Detailed calculations suggest that the energy in the laser beams can be dumped into electrons, positrons and gamma-rays once the intensity exceeds a few times $10^{23}\ \mathrm{W\,cm^{-2}}$.

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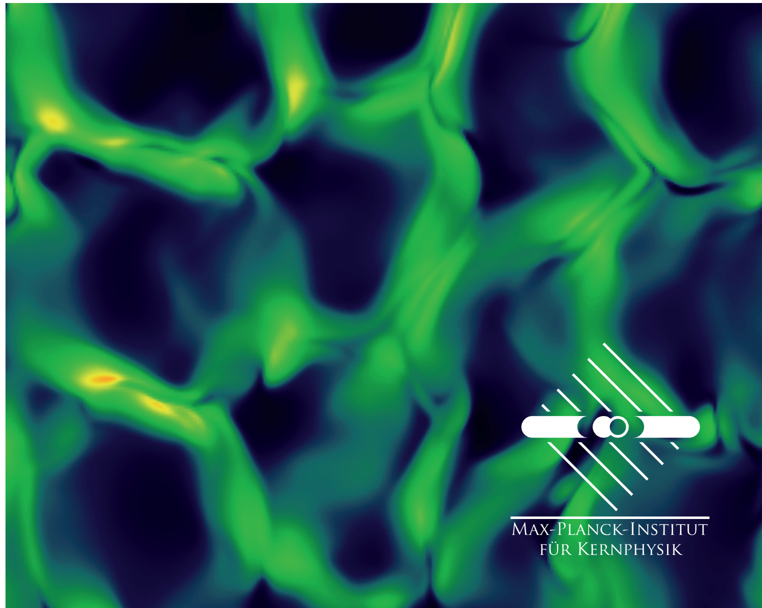
MAX-PLANCK-GESELLSCHAFT

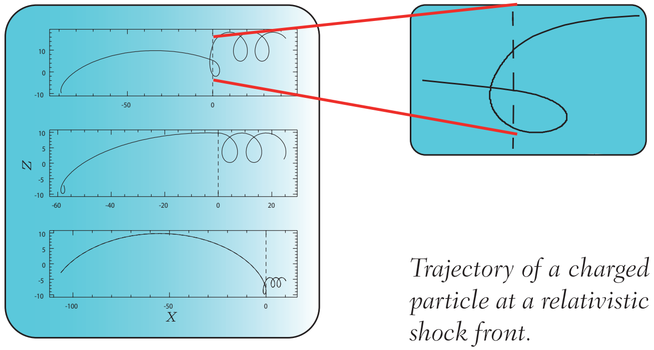
Theoretical Astrophysics



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

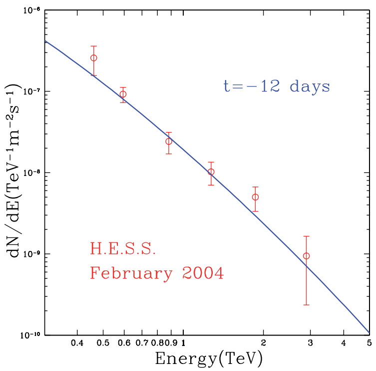
Theoretical Astrophysics

What accelerates the highest energy particles in the Universe? Do they emit a radiation signature? How do they affect the interstellar and intergalactic mediums?



Trajectory of a charged particle at a relativistic shock front.

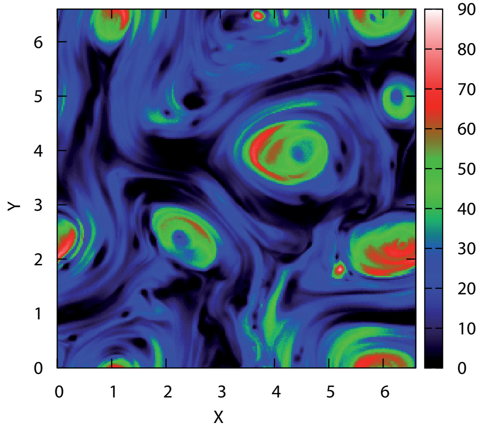
To answer these questions we study the physics of shock fronts and that of pair creation and radiation in strong electromagnetic waves. This is important not only in the extreme astrophysical conditions found near neutron stars and rotating black holes, but also under conditions that will be accessible in the laboratory using high-intensity, short-pulse lasers.
Predicting and modelling of the emission of sources such as the binary pulsar PSR B1259-63, supernova remnants, and active galaxies is also an important aspect of our research, enabling observations such as those made by the H.E.S.S. collaboration to be interpreted in a physically meaningful scenario.

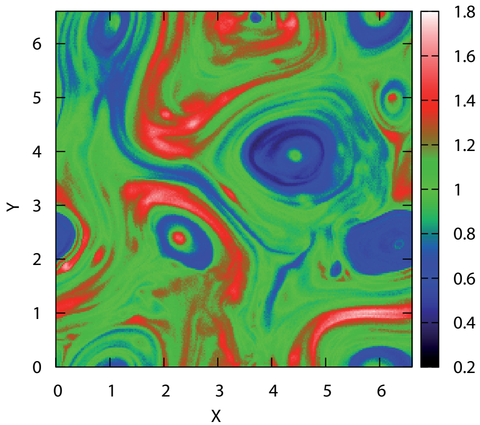


Prediction of the high-energy gamma-ray emission of the binary pulsar PSR 1259-63 made in 1999 (solid line), compared with measurements made in 2004. This was the first source discovered by the H.E.S.S. collaboration.

Cosmic-ray driven turbulence

Cosmic rays are accelerated at the blast waves sent out into space when a star ends its life in a supernova explosion. But for this process to be effective, the particles must be kept close to the wave for many years. Magnetic fields can do this, but only if they are very strong. Currently, it is thought that strong fields are generated by the cosmic rays themselves, in a kind of bootstrap process. To find out whether or not this can work, we study the plasma instabilities that occur when cosmic rays are accelerated, and make computer simulations of the magnetic turbulence that they drive (see the picture on the title page). Extensive "particle-in-cell" simulations are needed to determine at what level the turbulence will saturate, which sets the upper limit on the energy to which cosmic rays can be accelerated.

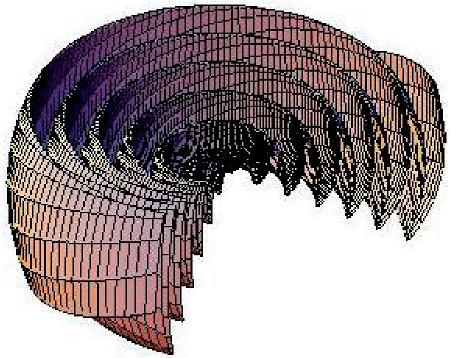




Results of a particle-in-cell simulation showing channels of low density and high magnetic field evacuated by streaming cosmic rays. The colour shading represents (top) the magnetic field strength, and (bottom) the plasma density.

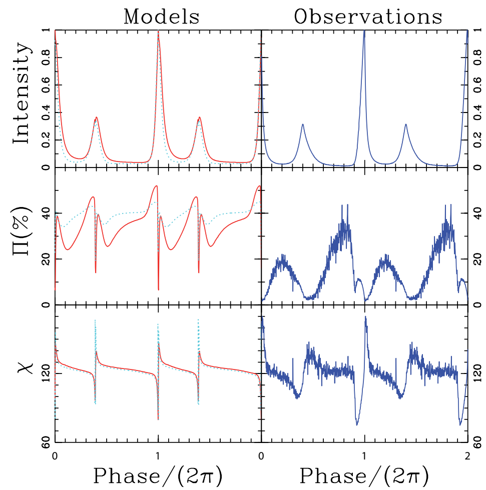
Pulsar Winds

Pulsars are rapidly rotating, magnetized neutron stars, and all those not in a binary star system are observed to be slowing down. Charged particles (most likely electrons and positrons) and magnetic fields carry the rotation energy away from the star in a relativistic wind, and deposit it in a "nebula" observed in the radio, optical, X-ray and gamma-ray wavebands around several pulsars.



Current sheet surrounding a pulsar. As the star rotates, the pattern moves outwards at the speed of light. Magnetic field dissipation leads to heating of the plasma in the sheet.

However, how the energy is released is unknown. One possibility is magnetic reconnection or annihilation. The pulsar wind carries a wave pattern imprinted on it at the rotation frequency of the star. Magnetic field lines from the two poles are folded into a striped pattern, separated by a current sheet. The alternating component of the field can be dissipated in the sheet, leading to heating and acceleration of the wind. If it occurs rapidly, dissipation will give pulsed high energy emission, similar to that observed.



Polarisation properties of light from the Crab pulsar as predicted in the striped-wind model (left) and as observed (right).