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Extreme Plasma Physics of Neutron Stars

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Neutron stars are extreme astrophysical objects that contain the strongest magnetic fields in the universe. The extreme electromagnetic and gravitational fields in the magnetospheres of neutron stars leads to a complex interplay of plasma physics, general relativity (GR), and quantum electrodynamics (QED) that produces spectacular multi-wavelength electromagnetic emission. In particular, electron-positron pairs and gamma-ray photons are produced in runaway QED particle showers --- the collective dynamics of the relativistic electron-positron pair plasma is poorly understood. The magnetospheres of neutron stars are also affected by their internal dynamics, including the evolution of ultra-strong magnetic fields in super-dense nuclear matter, and interacting hadronic quantum fluids.

One of the longstanding puzzles in this field is how neutron stars emit coherent radio waves from their magnetospheres. Recently, local first-principles plasma simulations have shown how collective dynamics of electron-positron pairs during QED particle showers can excite coherent electromagnetic waves [1]. In this talk I will present a global kinetic simulation of a neutron star magnetosphere that shows how and where radio waves are produced (Fig. 1) [2].

I will also discuss the magnetic field evolution of neutron star interiors, how it differs from the magnetohydrodynamics (MHD) of classical conducting fluids, and how the neutron star interior couples to the magnetosphere and its radiation. I will highlight the effects of proton superconductivity in neutron star cores, how it couples to the Hall drift in the crust (Fig 2), and how it may be observed in pulsar rotation and emission [3].

Lastly, I will discuss the magnetic field evolution of magnetars – very strongly magnetized neutron stars that emit powerful magnetic flares and bursts. They are also candidates for the engines of cosmological fast radio bursts. These objects likely contain magnetic fields strong enough to quench superconductivity, so the magnetic field evolves through a different channel of ambipolar diffusion: drift of the proton electron plasma relative to the neutrons. I will show that ambipolar diffusion can trigger powerful eruptions from the magnetar surface that could eject matter from the star and power a giant gamma-ray flares.

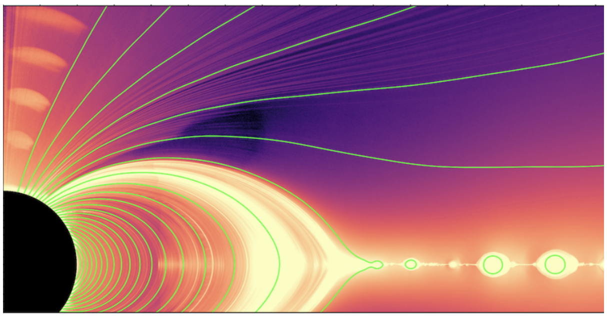

Fig 1. Global particle-in-cell simulation of a neutron star magnetosphere. Color shows density of electron-positron pair plasma, green curves show poloidal field lines.

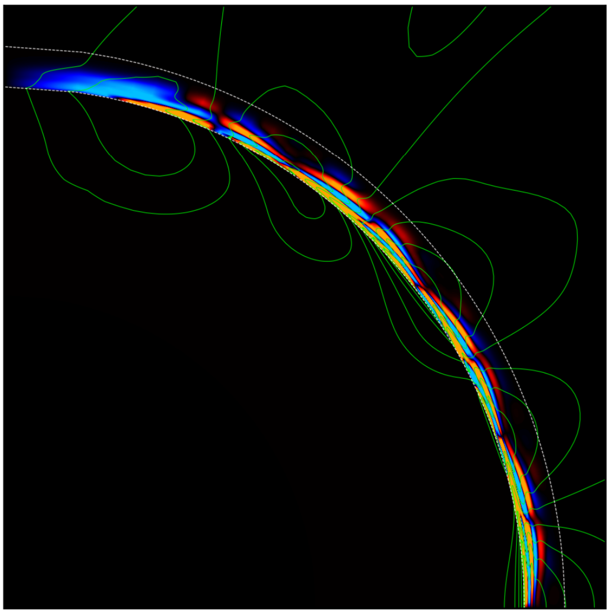

Fig 2. Magnetic field evolution inside a neutron star. The superconducting phase transition launches magnetic "Hall" waves into the solid neutron star crust. Color shows toroidal magnetic field, green curves show poloidal magnetic field lines.

References

[1] Philippov, A., Timokhin, A., & Spitkovsky, A. 2020, PRL, 124, 245101.
[2] Bransgrove, A., Beloborodov, A., Levin, Y., 2023 ApJL, 958, L9.
[3] Bransgrove A., Levin Y., Beloborodov A. M., 2025, ApJ, 979, 144.