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The Physics of Pulsar Magnetospheres

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Pulsars are rotating magnetized neutron stars that emit repeating pulses of radiation spanning all of the electromagnetic spectrum. 50 years after their discovery, more than 2000 pulsars are known, and they have been used as sensitive astronomical probes of diverse phenomena including the properties of interstellar medium and the predictions of general theory of relativity. Despite great observational successes, our theoretical understanding of how pulsar magnetospheres work and shine is woefully incomplete. Pulsars bring together aspects of classical and quantum electrodynamics, coupled with strongly magnetized plasma physics in curved rotating spacetimes of a massive compact object. The nonlinear interplay of these effects makes it a very difficult but rewarding problem to study. I will review the status and progress of pulsar magnetospheric modeling in various approximations, including force-free and relativistic magnetohydrodynamics, culminating with recent developments of fully kinetic simulations of pulsar magnetospheres. These simulations allow us to find the shape of the magnetosphere and the location and physics of particle acceleration regions, constraining the origin of high energy emission. The pulsar magnetosphere is a prototype for other strongly magnetized astrophysical objects, and I will discuss how the lessons from pulsar modeling can be useful in understanding the physics of black hole jets and in predicting electromagnetic counterparts to gravitational wave sources.