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Modeling Gravitational Waves via Post-Newtonian Expansion and Geometric Optics

Two complementary approximation frameworks are explored for modeling gravitational waves in general relativity. The first part develops the shortwave formalism, which treats gravitational radiation as high-frequency perturbations propagating on a slowly varying background spacetime. This approach enables the derivation of a gauge-invariant effective stress-energy tensor and allows for the study of energy and momentum transport in the far-field region. The second part focuses on the post-Newtonian (PN) expansion, a slow-motion approximation applicable in the near zone around compact sources. Using 1PN corrections to the two-body problem, expressions for periastron precession and orbital period decay are derived and evaluated. The predicted periastron shift for the binary PSR B1913+16, discovered by Taylor and Hulse in 1974, agrees closely with observations, and the theoretical orbital period decay rate matches the corrected observed value with high precision. Numerical modeling of the accumulated arrival time shift over several decades has been performed for both PSR B1913+16 and PSR J0737–3039A/B, yielding results that closely track the observed pulsar timing data. A central result is the accurate modeling of the double pulsar system PSR J0737–3039A/B, where numerical predictions from the PN expansion show excellent agreement with observed timing data. In this system, the deviation between the PN and weak-field predictions becomes clearly visible over time, demonstrating that relativistic corrections captured by the PN formalism are not only necessary, but critical for describing the dynamics of strongly gravitating binaries. Together, the PN and shortwave frameworks provide a coherent and effective approach for understanding both the generation and propagation of gravitational waves in curved spacetime.

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