Compact Objects and Binaries in Dense Star Clusters
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Modeling the Evolutionary Mechanisms of Pulsars and Millisecond Pulsars

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Abstract. This paper, the second in a series, examines the evolutionary processes shaping pulsars and millisecond pulsars (MSPs). It explores mechanisms such as accretion-driven spin-up, magnetic dipole braking, and binary interactions, presenting seven distinct evolutionary pathways. These include the formation of isolated pulsars, MSPs, and black holes through asymmetric collapse, recycling in low-mass X-ray binaries, dynamical interactions in globular clusters (GCs), and neutron star-neutron star mergers. Insights from observations by FAST, CHIME, and the Parkes Telescope, supported by initial simulation efforts, highlight the role of environmental factors, such as GC density compared to the Galactic field. Ongoing challenges in modeling magnetic field decay and binary dynamics suggest further investigation is warranted, through the accurate simulator, NBODY6++GPU.

1. Proceeding

Neutron stars, formed from the remnants of massive stars after a supernova, exhibit diverse behaviors, with pulsars emitting periodic radiation. Normal pulsars, with rotation periods between 0.1 and 10 seconds, evolve primarily through magnetic dipole radiation, whereas millisecond pulsars, with periods of 1 to 10 milliseconds, arise from recycling in binary systems where magnetic fields weaken to 1×10^8 Gauss to 1×10^9. Transitional pulsars, switching between X-ray and radio emissions, offer clues to this recycling. This study is the second in a series exploring pulsar evolution. The first article in this series provided a statistical analysis of pulsars and MSPs across different environments, such as globular clusters and the Galactic field, using multi-wavelength observations (radio, X-ray, gamma-ray) and simulations like NBODY6++GPU (Rah et al. 2024). It highlighted key advancements, identified gaps in understanding formation processes and magnetic field evolution, and underscored the need for improved modeling to address unresolved questions (Rah et al. 2024). The second article extended this work by modeling seven evolutionary scenarios using direct N-body simulations and observational data (Rah et al. 2025a). Building on these insights, the current work uses NBODY6++GPU simulations to explore the evolution of neutron stars, black holes, and pulsar transformations within globular clusters (Spurzem et al. 2023; Wang et al. 2015).

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Pulsar evolution is tracked using parameters such as spin period (P), period derivative ($\dot{P}$), surface magnetic field (B), and characteristic age ($\tau_c = P/(2\dot{P})$). For example, the Crab Pulsar rotates with a period of about 33 ms and a period derivative of 4.2×10^{-13} s/s, while the millisecond pulsar PSR J0437-4715 has a period of 5.75 ms and a derivative of 5.7×10^{-20} s/s. The magnetic field, estimated as $B \approx 3.2 \times 10^{19}\sqrt{P\dot{P}}$ Gauss, and the spin-down relationship $\dot{P} \propto B^2 P^{-1}$, are essential to understand evolutionary trends, often depicted in P-$\dot{P}$ diagrams (Zhang et al. 2022).

Pulsar rotation can increase through accretion in low-mass X-ray binaries, where a neutron star gains mass from a companion star, reducing its magnetic field and speeding up its rotation. Mergers of two neutron stars can also enhance rotation, potentially leading to a millisecond pulsar or a magnetar, while asymmetric collapse during supernova formation imparts an initial spin. Dynamical encounters in dense globular clusters can trigger spin-up by pairing a neutron star with a companion. Conversely, rotation slows due to magnetic dipole radiation, which dissipates energy in young pulsars, particle winds that form surrounding nebulae, gravitational waves from mass imbalances in fast rotating pulsars, magnetic field decay through Ohmic dissipation, and enhanced spin-down in globular clusters due to frequent interactions (Chattopadhyay et al. 2021).

Seven evolutionary pathways are identified: a massive star exceeding eight solar masses undergoes core collapse, followed by magnetic braking and field decay, forming an isolated pulsar with a mass of about 1.4 solar masses; a wide binary system with a neutron star evolves through magnetic radiation and orbital decay, resulting in gradual spin-down; an MSP forms when a neutron star in a binary accretes material from a lower-mass companion, passing through a common envelope phase and reducing its magnetic field, leaving an MSP paired with a white dwarf; an isolated MSP emerges after losing its companion, continuing with slow spin-down; dynamical interactions in globular clusters lead to MSP formation through companion capture and accretion; a merger of two neutron stars can produce an MSP or collapse into a black hole; and a neutron star merging with a black hole results in a more massive black hole. Current NBODY6++GPU simulations assess how pulsar evolution unfolds within these cluster environments alongside neutron stars and black holes (Spurzem et al. 2023).

Difficulties persist in modeling the decay of magnetic fields, the complex dynamics of binary systems, and interactions within globular clusters, partly due to limited knowledge of neutron star interiors and computational constraints. Future efforts will refine these models by incorporating detailed physical processes, with ongoing simulation work using NBODY6++GPU providing a foundation, enhanced by observations from FAST and LIGO (Wang et al. 2015; Zhang et al. 2022).

This study synthesizes the mechanisms and pathways of pulsar evolution, emphasizing the critical roles of environmental conditions and binary interactions. Ongoing simulation efforts are underway to explore these processes within globular clusters, offering preliminary insights into pulsar transformations alongside neutron stars and black holes, with further work anticipated to deepen understanding (Ye et al. 2019).

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