Gravity Tests with Radio Pulsars in Perturbative and Nonperturbative Regimes

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Searches for empirical clues beyond Einstein’s general relativity (GR) are crucial to understand gravitation and spacetime. Radio pulsars have been playing an important role in testing gravity theories since 1970s. Because radio timing of binary pulsars is very sensitive to changes in the orbital dynamics, small deviations from what GR predicts can be captured or constrained. In this sense, the gravity sector in the standard-model extension was constrained tightly with a set of pulsar systems. Moreover, compact objects like pulsars are possible to develop nonperturbative deviations from GR in some specific alternative gravity theories, thus radio pulsars also provide rather unique testbeds in the strong-gravity regime.

1. Introduction

Among the four fundamental forces in the Nature, gravity is rather unique as it is described in the language of differential geometry, while the other three forces are understood in terms of quantum field theory. Therefore, to go beyond the current paradigm of modern physics, which consists of Einstein’s general relativity (GR) and the standard model of particle physics, gravity might hold the key. Empirical studies of gravitation and spacetime are important to provide clues to a deep fundamental theory, probably the quantum gravity.\textsuperscript{1,2} In testing gravity theories, radio pulsars have been playing an important and unique role since the discovery of the Hulse-Taylor pulsar in 1970s. In this short proceedings, we will briefly review some interesting bounds from pulsar observations in a perturbative framework, called the standard-model extension (SME),\textsuperscript{3} as well as in some specific scalar-tensor gravity theories where nonperturbative strong-field phenomena might develop inside neutron stars. Pulsar timing puts remarkable limits in both perturbative and nonperturbative gravity regimes.
2. Perturbative weak-field expansion of gravity

As GR has been confronted with various kinds of experiments and observations for a century where all tests are passed with flying colors,\textsuperscript{1,2} one might only expect small deviations from it, at least in the weak-field limit. The gravity sector of SME is designed in the spirit of effective field theory, and it categorizes all kinds of operators beyond GR by introducing SME coefficients for Lorentz/CPT violation.\textsuperscript{3} In the pure gravity sector, the most generic Lagrangian for linearized gravity reads,

$$L_{\mathcal{K}^{(d)}} = \frac{1}{4} h_{\mu \nu} \mathcal{K}_{\mu \nu \rho \sigma}^{(d)} h_{\rho \sigma},$$

(1)

where $\mathcal{K}_{\mu \nu \rho \sigma}^{(d)} = \mathcal{K}_{\mu \nu \rho \sigma i_1 i_2 \ldots i_{d-2}} \partial_{i_1} \partial_{i_2} \ldots \partial_{i_{d-2}}$ is a complicated operator with derivatives contracted with SME coefficients $\mathcal{K}_{\mu \nu \rho \sigma i_1 i_2 \ldots i_{d-2}}^{(d)}$. The complete action (1) can be very cumbersome and contains an infinite number of field operators. However, in the sense of effective field theory, it is likely that terms of the lowest mass dimensions dominate in certain low-energy experiments.

In a modified gravity, a binary orbit is generally altered. This results in characteristic changes in the times of arrival, the main observables, for binary pulsars. In turn, dedicated long-term observations of radio pulsars can provide stringent limits to various types of modifications in the gravitational interaction. An updated list of gravity tests in the SME framework provided by pulsars includes tests of,\textsuperscript{4}

- the minimal gravity sector with operators of mass dimension four,
- CPT-violating operators of mass dimension five,
- nonlinear operators of mass dimension eight which violate the gravitational weak equivalence principle,
- matter-gravity couplings with operators of mass dimensions three and four, and
- abnormal spin behaviours caused by the Lorentz-violating neutron star structure, or due to gravity and matter-gravity couplings.

A summary of limits from pulsar timing experiments can be found in the Data Tables for Lorentz and CPT Violation,\textsuperscript{2} and for details readers are referred to original publication.

3. Nonperturbative strong-field gravity

The treatment in the SME has assumed the smallness of any kinds of deviations from GR. However, neutron stars are strongly self-gravitating objects.
As discovered by Damour and Esposito-Farèse in 1990s, a nonperturbative phenomena called “spontaneous scalarization” might happen for neutron stars in a class of scalar-tensor gravity theories. This behaviour introduces an extra dipolar channel for gravitational radiation in a binary and can be constrained by pulsar timing, via the orbital decay rate parameter, $\dot{P}_b$. There are a few variants of scalar-tensor gravity theories, including those with a massive scalar field and with a topological Gauss-Bonnet term. Scalarized neutron stars are illustrated in Fig. 1 for three representative massive scalar-tensor theories, including Damour-Esposito-Farèse theory, Mendes-Ortiz theory, and a $\xi$ theory from considerations in cosmology. As we can see, scalar hairs grow for neutron stars with certain masses as they are energetically favored. Current pulsar-timing observations of a handful of neutron-star white-dwarf binaries and asymmetric double neutron star binaries are able to put stringent constraints on theory parameters. Recently, gravitational waves also start to provide useful limits, and in many cases, depending on the specifics of theories under investigation, limits from pulsar timing and gravitational waves are complementary to each other.

4. Discussion

Neutron stars are superb testbeds for gravitation and spacetime. Thanks to the precision timing ability of large-area radio telescopes, gravity tests are
versatile with radio pulsars. A number of changes in the orbital dynamics of different types can be probed. In particular, it was demonstrated for a couple of times that, a set of carefully chosen binary pulsars are able to break degeneracy of theory parameters and put combined limits on the SME coefficients for Lorentz/CPT violations. These limits usually are very tight and provide important experimental results for the SME community. On the other hand, in some specific alternative theories of gravity, the perturbative treatment fails, and nonperturbative hairs grow for certain neutron stars. In such a case, pulsar timing appears even advantageous for empirical gravity tests, and provides remarkable constraints for gravity in the strong-field regimes, complementing the new tests brought by observations of gravitational waves and black hole shadows.

In a short summary, both perturbative and nonperturbative probes of the gravitational interaction are useful and might lead to clues for quantum gravity. Radio pulsars, whose timing results are extremely precise and improve over time, stand as a unique testbed for gravity. In the upcoming years, we can certainly expect improved tests from existing pulsar systems, as well as new tests from yet-to-be-discovered pulsars, for example, possibly from pulsars in binary with black holes.

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