The Double Pulsar: Timing and Strong-Field Gravity

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Abstract

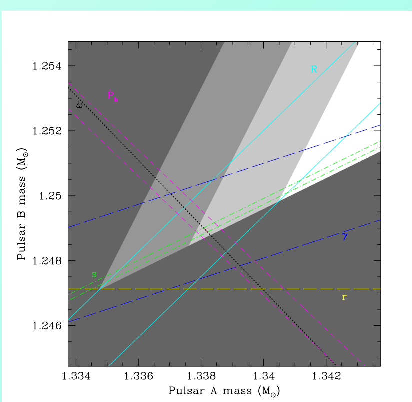
The double pulsar is a highly relativistic system in which both neutron stars are known to be radio pulsars. As expected from binary evolutionary theory, one pulsar is recycled and the other young. This binary provides the most stringent tests of strong-field relativistic gravity to date and offers the prospect of entirely new tests. We present updated timing results from this unique system, derived in large part from sensitive observations with the 100-m Green Bank Telescope (GBT).

Background

The double pulsar PSR J0737-3039A/B was discovered in 2003 (Burgay et al. 2003; Lyne et al 2004) and consists of a 22.7-msec pulsar ("A") and a 2.7-sec pulsar ("B") in a 2.4-hour, mildly eccentric orbit. The system's orbit is inclined nearly along the line of sight, making Shapiro delay accessible as well as other relativistic timing parameters. Uniquely among double-neutron-star systems, the mass ratio is measurable. Pulsar B has only ever been visible at certain orbital phases, due to interactions with A, and its emission cone precessed away from our line of sight several years ago (Perera et al. 2010). The system has already provided the most stringent test of general relativity (GR) in the strong-field regime (Kramer et al. 2006) and a precision measurement of the geodetic precession rate of B (Breton et al. 2008).

Observations and Timing

Observations have been carried out regularly with the Green Bank Telescope (GBT), Parkes, Lovell, Westerbork. Nancay and Effelsberg, using frequencies between 600 and 3000 MHz and backend instruments of both filterbank and coherent-dedispersion constructions. The combination of telescopes and time baselines provides both excellent snapshot sensitivity to the orbital parameters (particularly through the semi-annual GBT campaigns at 820 MHz) and high-precision measurement of astrometric parameters including proper motion and parallax. The 5 post-Keplerian (PK) parameters for A (advance of periastron $\dot{\omega}$, orbital period decay $\dot{P}_{\rm b}$, time dilation and gravitational redshift γ and Shapiro delay range r and shape s) are measured in a theory-independent manner (Damour & Deruelle 1985, 1986). The mass ratio is computed from the projected semi-major axes of both pulsar orbits, using the timing solution for B derived in Kramer et al. 2006. The updated timing solution will be published shortly (Kramer et al., in prep.).



Preliminary mass-mass diagram for the double pulsar system. The grey-shaded regions are those forbidden by the mass functions of the two pulsars, with the deepening values of grey illustrating the sizeable uncertainty in the mass function for pulsar B. Each of the 5 PK parameters measured for A, with uncertainties, produces an allowed region in the mass-mass plane under the assumption that general relativity is the correct theory of gravity (the upper r curve lies outside the boundaries of this plot). The mass ratio produces a 6th constraint. All 6 curves intersect in one small region, shown in red. This demonstrates that the description of the pulsar masses in GR is self-consistent to a high level of precision.

Features of the Timing Solution

The astrometry (position, proper motion and parallax) is broadly consistent with that obtained by VLBI (Deller et al. 2009), but the proper motion is measured to much higher precision. The orbital period decay is measured to 0.03% precision, already better than achieved for the Hulse-Taylor pulsar PSR B1913+16 (Weisberg et al. 2010). Furthermore, the pulsar's distance and transverse velocity are small enough that no kinematic correction (Damour & Taylor 1991) is as yet required to the observed $\dot{P}_{\rm b}$, whereas for B1913+16 the galactic parameters in the kinematic correction now form the limiting factor in the quality of the radiative-damping GR test.

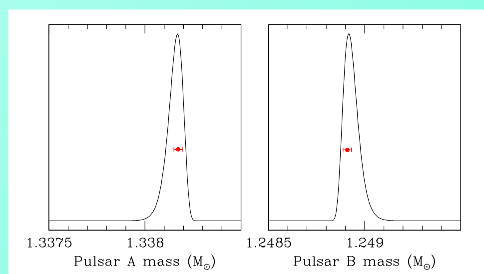
Test of General Relativity

The precision timing of PSR J0737-3039A/B can be used to constrain alternate theories of strong-field gravity such as generic tensor-scalar theories (e.g., Damour & Esposito-Farèse 1998) and TeVeS (Bekenstein 2004); full details of these constraints will be provided in the upcoming timing paper. Here we focus on the quality of agreement with GR. Taking the 5 PK parameters and their uncertainties (which have been measured in a theory-independent manner) as well as the mass-ratio and mass-function constraints to represent the data D, we write:

$$P(m_{\rm A,B}|D) \propto P(D|m_{\rm A,B})P(m_{\rm A,B})$$

We assume uniform priors on the masses $m_{\rm A,B}$ and use each pair to predict the values of the PK parameters within GR. We then use the measured parameter values and uncertainties to obtain the likelihood $P(D|m_{\rm A,B})$. This let us derive posterior probability density functions for the two masses, shown below. The resulting median masses (which are very close to the peaks of the pdfs) are:

$$m_A = 1.338160^{+0.000035}_{-0.000045}\,{\rm M}_\odot$$
$$m_B = 1.248930^{+0.000045}_{-0.000035}\,{\rm M}_\odot$$



In the figure above, the red points and uncertainties represent the masses derived from a timing solution ("DDGR") that assumes GR is the correct theory of gravity; these masses are:

$$m_A = 1.338173 \pm 0.000023\,{\rm M}_\odot$$
$$m_B = 1.248910 \pm 0.000022\,{\rm M}_\odot$$

A comparison between the two sets of masses yields an agreement to 0.004%, more than an order of magnitude better than previously achieved with this system (Kramer et al. 2006).

References

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