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THE DOUBLE PULSAR SYSTEM IN ITS 8TH ANNIVERSARY

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ABSTRACT

The double pulsar system J0737−3039A/B, discovered with the Parkes radio telescope in 2003, is one of the most intriguing pulsar findings of the last decade. This binary system, with an orbital period of only 2.4-hr and with the simultaneous presence of two radio pulsed signals, provides a truly unique laboratory for relativistic gravity and plasma physics. Moreover its discovery enhances of almost an order of magnitude the estimate of the merger rate of double neutron stars systems, opening new possibilities for the current generation of gravitational wave detectors. In this contribution we summarise the present results and look at the prospects of future observations.
Subject headings: Pulsars – individual: J0737-3039A/B

1. INTRODUCTION

The 22.7-ms binary pulsar PSR J0737-3039A (hereafter 'A') was discovered in April 2003 (Burgay et al. 2003) in the data of the Parkes High-Latitude Pulsar Survey (Burgay et al. 2006). Its short orbital period (P_b = 2.4 hrs), together with a remarkably high value of the periastron advance ($\dot{\omega}$ = 16.9 deg/yr) identified it soon as a member of the most extreme relativistic binary system ever discovered. The compactness of the system, combined with its short coalescence time (T_{coal} = 85 Myr) and low luminosity, increases the estimates on the double neutron star coalescence rate by almost an order of magnitude (Burgay et al. 2003; Kalogera et al. 2004b,a), boosting hopes to detect mergers of neutron stars (NSs) with ground based gravitational wave detectors.

Analysis of follow-up observations led, in October 2003 (almost exactly 8 years before the symposium for the Parkes radio telescope 50th anniversary) to the discovery of a second pulsar in the system (Lyne et al. 2004), the 2.8-s pulsar J0737-3039B (hereafter 'B'). The reason why the signal of pulsar B was not detected earlier is that this object is only bright in two short sections of the orbit; for the rest of the orbit the signal is very week or absent.

Upon closer inspection, the signals of both pulsar A and B revealed other intriguing characteristics: pulsar A is eclipsed for $\sim$ 30 s near superior conjunction and pulsar B shows variations in the pulse shape along the orbit (Lyne et al. 2004). Variations of the pulse shape on longer time scales and of the extent and location of B's bright phases have also been observed (Burgay et al. 2005; Perera et al. 2010). These phenomena are likely related to the geodetic precession of pulsar A and B that are changing the geometry of the system and hence our view towards it. This relativistic effect happens on such a short time scale on this system (75 years for pulsar B and 71 for pulsar A) that in 2008 pulsar B's beam went out of sight (Perera et al. 2010).

In this contributions, we will describe the binary system J0737-3039A/B focusing mainly on its current and future applications as a test-bed for relativistic theories.

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2. TESTING GRAVITY THEORIES WITH THE DOUBLE PULSAR

Because of their strong gravitational fields and rapid orbital motions, the binary systems containing two neutron stars can exhibit large relativistic effects (Damour & Deruelle 1986). If one (or two, as in this unique case) of the NSs emits clock-like radio pulsed signals it is possible, by measuring the delays in the time of arrival of the pulses, to measure directly not only the Keplerian parameters of the orbit, but also the relativistic corrections to the Keplerian description of an orbit, the so called "post-Keplerian" (PK) parameters, hence testing relativistic gravity. In each theory of gravity the PK parameters can be written as a function of the masses of the two stars and of the measurable Keplerian parameters. With the two masses as the only unknowns, the measurement of three or more PK parameters over-constrains the system hence providing tests for a given theory of gravity (Damour & Taylor 1992).

In General Relativity (GR) the post-Keplerian parameters can be written (at first post-Newtonian order, 1PN) as follows (Damour & Deruelle 1986):

$$\dot{\omega} = 3T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\,(M_A+M_B)^{2/3},$$

$$\gamma = T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\frac{M_B(M_A+2M_B)}{(M_A+M_B)^{4/3}},$$

$$\dot{P}_b = -\frac{192\pi}{5}T_{\odot}^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)}{(1-e^2)^{7/2}}\frac{M_A M_B}{(M_A+M_B)^{1/3}},$$

$$r = T_{\odot}M_B,$$

$$s = T_{\odot}^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\,\frac{(M_A+M_B)^{2/3}}{M_B},$$

where P_b is the orbital period, e the eccentricity and x the projected semi-major axis of the orbit measured in light-s. The masses M_A and M_B of A and B respectively (or, in general, of the pulsar and its companion), are expressed in solar masses. The constant $T_{\odot}$ is defined as $T_{\odot} = GM_{\odot}/c^3 = 4.925490947\mu$s where G is the Newtonian constant of gravity and c the speed of light. The first PK parameter, $\dot{\omega}$, describes the relativistic advance of periastron. The parameter γ denotes the amplitude

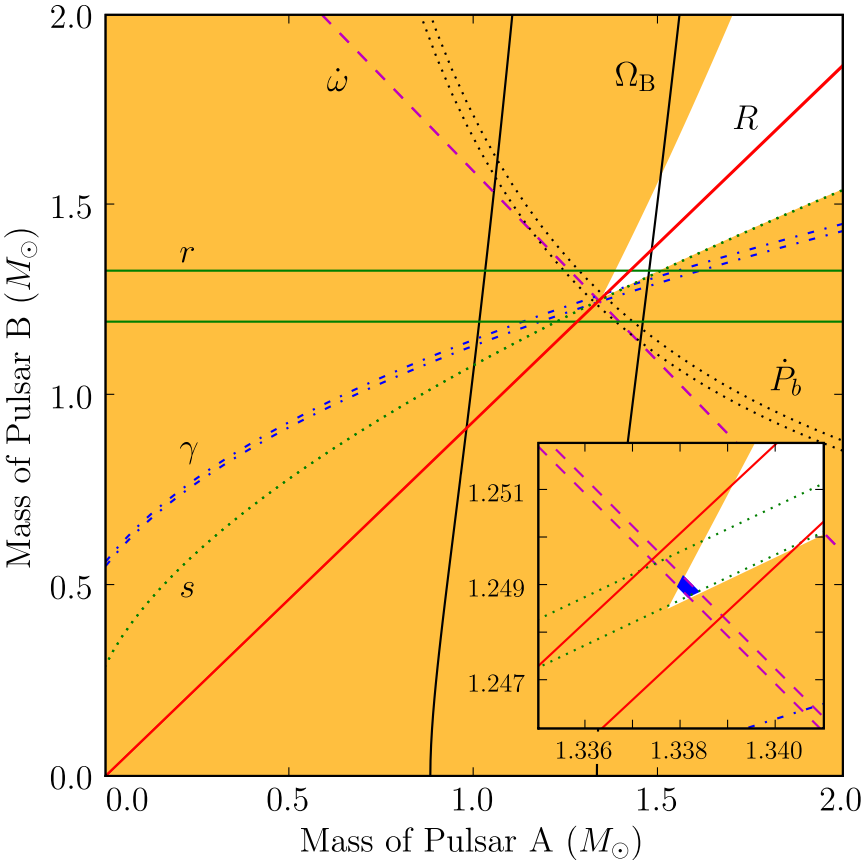

FIG. 1.— The observational constraints on the masses of the two pulsars in the double pulsar system, M_A and M_B. The coloured regions are those which are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as predicted by general relativity: (a) the measurement of the advance of periastron $\dot{\omega}$ (dashed lines); (b) the measurement of the mass ratio R (solid lines); (c) the measurement of the gravitational red-shift/time dilation parameter γ (dot-dash lines); (d) the measurement of Shapiro parameter r (solid horizontal lines) and Shapiro parameter s (dotted lines); (e) the measurement of the orbital decay (dotted lines); (f) the measurement of the relativistic spin precession (solid dark lines). Inset is an enlarged view of the small square which encompasses the intersection of the three tightest constraints. The permitted regions are those between the pairs of parallel lines and we see that an area exists which is compatible with all constraints. From Breton et al. (2008).

of delays in arrival times caused by the varying effects of the gravitational redshift and time dilation as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. The decay of the orbit due to gravitational wave damping is expressed by the change in orbital period, $\dot{P}_b$. The other two parameters, r (rate) and s (shape), are related to the Shapiro delay caused by the gravitational field of the companion.

The PK parameter can be plotted on a mass-mas diagram (see e.g. Fig. 1) and, if the theory tested is correct, the curves on the plane must intersect in a single point.

In this context, PSR J0737-3039A/B, with its two clock-like signal and its relativistic orbital motion, promises to be the most powerful instrument to test GR (and other theories). Measurements of the times of arrival (*timing*) of pulsar A, in fact, have provided all 5 post-Keplerian parameters with high accuracy after only 3 years of observations and precision on their measurement increases with time as we continue monitoring this system. Moreover, with the knowledge of the projected semimajor-axes for both A and B, possible only in this system, we obtain a precise measurement of the mass ratio R of the two stars:

$$R \equiv M_A/M_B = x_B/x_A \tag{1}$$

For every realistic theory of gravity, we can expect the mass ratio, R, to follow this simple relation (Damour & Taylor 1992), at least to 1PN order. The R value is not only theory-independent, but also independent of strong-field (self-field) effects which is not the case for PK-parameters. This provides a stringent and new constraint for tests of gravitational theories as any combination of masses derived from the PK-parameters *must* be consistent with the mass ratio.

Another effect predicted by relativistic theories is the relativistic spin precession which, for General Relativity, can be written (for pulsar A, for instance) as:

$$\Omega_s = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{M_B(4M_A + 3M_B)}{2(M_A + M_B)^{4/3}} \frac{1}{1-e^2} \tag{2}$$

For the two pulsars in the double pulsar system this implies a period for the relativistic spin precession of 75 years for A and 71 years for B. Given these small numbers one would expect to see a rapid variability in the observed pulse profiles caused by the change in the line of sight through the radio beam as the latter precesses around the total angular momentum vector (as observed e.g. in pulsar B1534+12 (Arzoumanian et al. 1999; Stairs

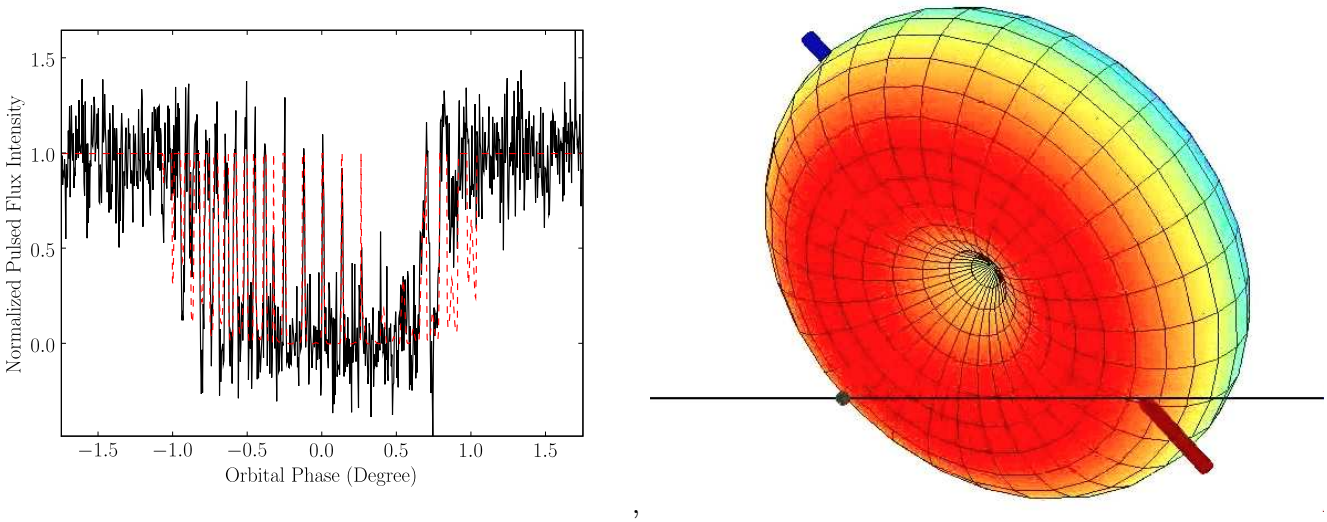

FIG. 2.— Left: average eclipse profile of pulsar A at 820 MHz over a five-day period around April 11, 2007 (black solid line) along with a model eclipse profile (red dashed line). Near orbital phase 0.0 the spikes are separated by the spin period of pulsar B while at eclipse ingress and egress at twice B's period (Breton et al. 2008). Right: geometric model for B's magnetosphere eclipsing A (black circle) along its orbit (horizontal line).

et al. 2000). In the case of pulsar A no such changes have been seen in the past 8 years (Manchester et al. 2005) suggesting that the spin axis has a very small misalignment with respect to the total angular momentum vector (Ferdman et al. 2007). Pulsar B, on the contrary shows variations on the shape of pulse profile and on the extent of the bright visibility phases over different time scales, at rates comparable with that of the relativistic spin precession (Burgay et al. 2005) and in 2008 its radio beam has gone outside our line of sight (Perera et al. 2010). With B's pulse profile variation, anyway, only a qualitative assessment of the effects of the precession can be done. The double pulsar system, however, shows another very peculiar characteristic: pulsar A is eclipsed for about 30 s around superior conjunction and the light curve in the eclipsed region shows a clear modulation with the spin period of pulsar B (or twice the period, depending on the exact orbital phases; see Fig. 2). Describing this eclipse of pulsar A as due to absorption occurring in the magnetosphere of pulsar B, Breton et al. (2008) successfully use a simple geometric model to characterize the observed changing of the eclipse morphology with time and hence to measure the relativistic precession of pulsar B.

With five PK parameters already available, and the mass ratio measurement, this additional constraint makes the double pulsar the most overdetermined system to date providing five possible tests for relativistic theories, the most stringent of which, given by the measurements of R, $\dot{\omega}$ and s, tests General relativity at the 0.02% level (see Fig. 1.

3. AN NEW ESTIMATE OF DOUBLE NEUTRON STARS COALESCENCE RATE

As mentioned above, for the double pulsar it has been possible to measure all 5 PK parameters in just 3 years of timing observations. The last measured, and one of the most interesting for its implications, is the decay of the orbit $\dot{P}_b$ which, according to General relativity, is due to emission of gravitational waves. At the measured rate of -1.24×10^{-12}, the orbit should shrink by 7 mm per day, implying that the NSs in the double pulsar system will coalesce in only 85 Myr. Such a merger event should produce a burst of gravitational waves detectable from current generation ground based interferometers.

A reliable estimate of the double neutron star (DNS) merger rate in the Galaxy is crucial in order to predict whether these gravity wave detectors will be successful in detecting such bursts in a reasonable timescale. Before the discovery of the Double pulsar the estimates of this rate were rather low (Curran & Lorimer 1995; Arzoumanian et al. 1999; Kalogera et al. 2001; Kim et al. 2003), because only a few DNss with merger times less than the age of the Universe were known. With the discovery of this system, with a lifetime two times shorter than the shortest known before (that of PSR B1913+19), a radio luminosity 6 times smaller and a very short orbital period, making it more difficult to detect in a blind survey, the estimate rates have increased by a factor of 6 (Burgay et al. 2003; Kalogera et al. 2004b,a).

Thanks to the discovery of the double pulsar, hence, the estimated merger rates and, by consequence, the detection rates for ground based gravitational wave detectors, fall for the frst time in a human time scale.

4. FUTURE EXPERIMENTS

The double pulsar system J0737-3039A/B has already proven to be an excellent laboratory for relativistic gravity providing new and more stringent tests for General Relativity and boosting hopes for the gravitational wave community. The future promises to be even brighter. Thanks to the fact that the precision with which the measured parameters (rotational, positional, orbital - classic and relativistic) increases with time (see e.g. Kramer & Wex (2009)) as we proceed with the timing observations, we will soon need to include the second post-newtonian order (2PN) in some of the equation adopted. At 2PN the expression for General Relativity of the periastron advance $\dot{\omega}$ depends on the geometry of the system, constrained, for pulsar A, by the lack of changes in the pulse

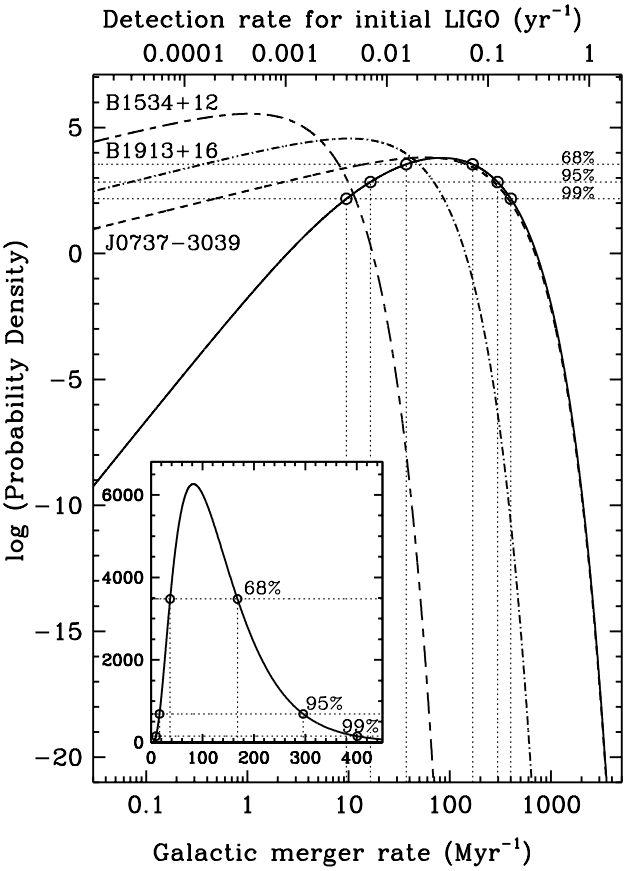

FIG. 3.— Probability density function representing the expectation that the actual DNS binary merger rate in the Galaxy (bottom axis) and the predicted initial LIGO detector rate (top axis) take on particular values, given the observations. The curves shown are calculated assuming the parameters of the reference model in Kalogera et al. (2004b). The solid line shows the total probability density, along with those obtained for each of the three known binary systems (dashed lines) coalescing within a Hubble time. Inset: Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale. From Kalogera et al. (2004a)

shape and for B by the shape of the light curve of A during eclipse, and on the moment of inertia I of the NSs (Damour & Schäfer 1988). Measuring $\dot{\omega}$ at 2PN should allow us to measure I hence to tightly constrain the equation of state of a NS (Kramer & Wex 2009).

Another intriguing possibility is to constrain not only GR but also alternative theories of gravity: Esposito-Farèse (2004) shows, for instance, that a measurement with a 1% precision of the orbital decay in the double pulsar system would constrain the α_0 and β_0 parameters for scalar tensor theories better than the current solar system tests. Also, Wex & Kramer (2007) show that measuring a correlation in the change of the eccentricity and the periastron advance in a relativistic binary pulsar should be the signature of the existence of a preferred reference frame with respect to which the orbit is varying in time.

5. THE ITALIAN PULSAR CONNECTION

In this final section, on behalf of Nichi DAmico and the rest of the Italian pulsar group, Id like to briefly summarize the 30-years long story of the Italian-pulsar connection that tightly links us to the Parkes radio telescope. After having visited Parkes for the first time in 1979, Nichi started a collaboration with Dick Manchester in 1981, by building a prototype filter bank (Fig. 4) designed for pulsar searches a 21cm. The experiment was called "Sample4", as 4 frequency channels only were sampled at 21cm in order to remove dispersion and interstellar scattering. That experiment represents the first attempt to ex- ploit relatively high frequencies to search pulsars hidden in the most dense and dispersed regions of the Galaxy, and put the basis for a boom of pulsar discoveries which was achieved at Parkes in the following years. Indeed, since then, larger and more ambitious experiments were continuously setup at Parkes by the Italians, the British, and the other international collaborators (Fig. 5), in a fruitful collaboration with Parkes staff, which ultimately led to the multibeam surveys and the discovery of the Double Pulsar and many other interesting systems. Nichi managed to get many Italian students and post-docs to get involved in these experiments. An overall figure of more than 100 visits to Australia by the Italian pulsar group was registered in the last 30 years (Fig. 6), which represents for all of us an unforgettable testimony of the professional skills and the human passion of Parkes staff.

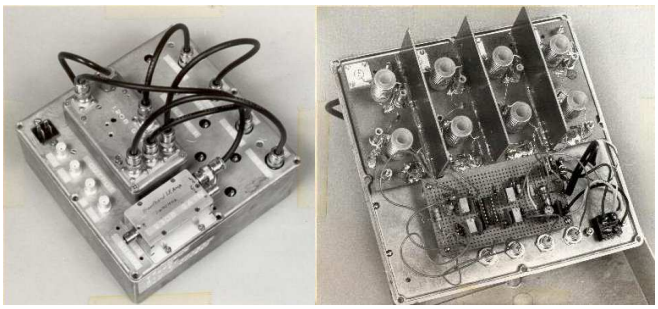

FIG. 4.— The hand-made filterbank built for the Sample4 experiment.

FIG. 5.— Some of the racks of the Parkes old control room. The red stars mark various pieces of hardware, including parts of the 21-cm analogue filterbank, built at the Bologna Astronomical Observatory and the IRA-Medicina radio telscope (Italy).

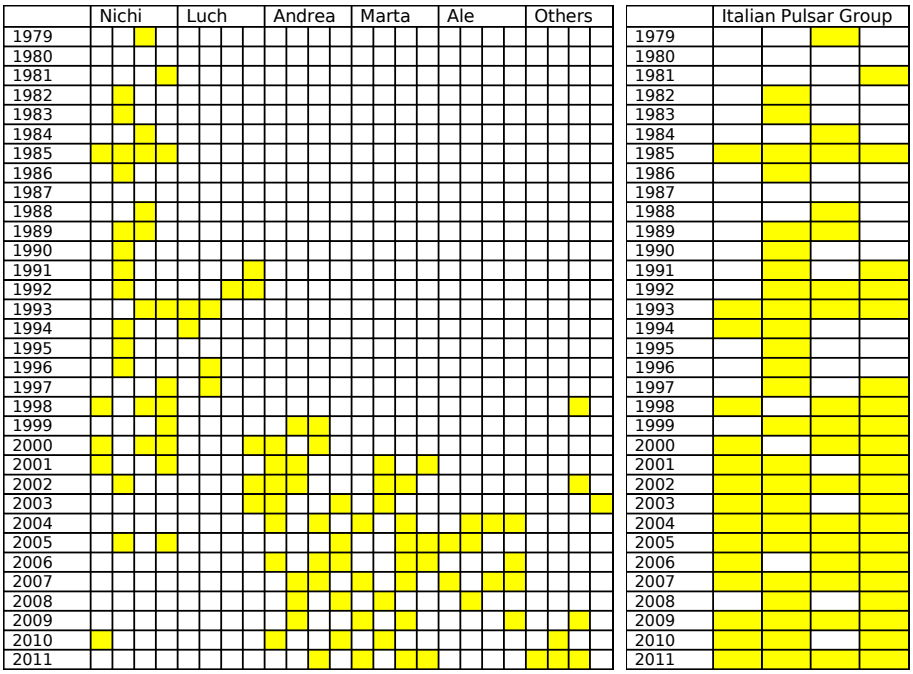

FIG. 6.— Schematic view of the italian presence at the Parkes Observatory. In the left part of the grid, a yelow square marks a visit of a member of the group (whose name is specified in the first row) during a given quadrimester. On the right, the overrall presence of all members of Prof. DAmicos team at Parkes is summarised (we never leave the telescope alone!).

Thanks to the Parkes Radio Telescope and its wonderful staff. In these last 10 years I spent quite a bit of time down-under observing (not only the double pulsar): I learnt a lot and I enjoyed every moment (even the 4 AM shifts)!

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