# PSR J0337+1715

## Millisecond pulsar in a triple system

Tasha Gautam[1]

[1] Max Planck Institute for Radioastronomy

5 December 2018

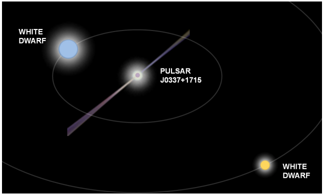


FIGURE – Credit : Thomas Tauris

# Outline

# Discovery

- First discovered in a 350MHz drift scan survey with Green Bank Telescope(GBT) at DM=21.3162(3)pc$cm^{-3}$

## A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14], K. Stovall[15,16]

**Gravitationally bound three-body systems have been studied for hundreds of years[1,2] and are common in our Galaxy[3,4]. They show complex orbital interactions, which can constrain the compositions, masses, and interior structures of the bodies[5] and test theories of gravity[6], if sufficiently precise measurements are available. A triple system containing a radio pulsar could provide such measurements, but the only previously known such system, B1620−26[7,8] (with a millisecond pulsar, a white dwarf, and a planetary-mass object in an orbit of several decades), shows only weak interactions. Here we report precision timing and multiwavelength observations of PSR J0337+1715, a millisecond pulsar in a hierarchical triple system with two other stars. Strong gravitational interactions are apparent and provide the masses of the pulsar (1.4378(13) $M_\odot$, where $M_\odot$ is the solar mass and the parentheses contain the uncertainty in the final decimal places) and the two white dwarf companions (0.19751(15) $M_\odot$ and 0.4101(3) $M_\odot$), as well as the inclinations of the orbits (both $\sim 39.2^\circ$). The unexpectedly coplanar and nearly circular orbits indicate a complex and exotic evolutionary past that differs from those of known stellar systems. The gravitational field of the outer white dwarf strongly accelerates the inner binary containing the neutron star, and the system will thus provide an ideal laboratory in which to test the strong equivalence principle of general relativity.**

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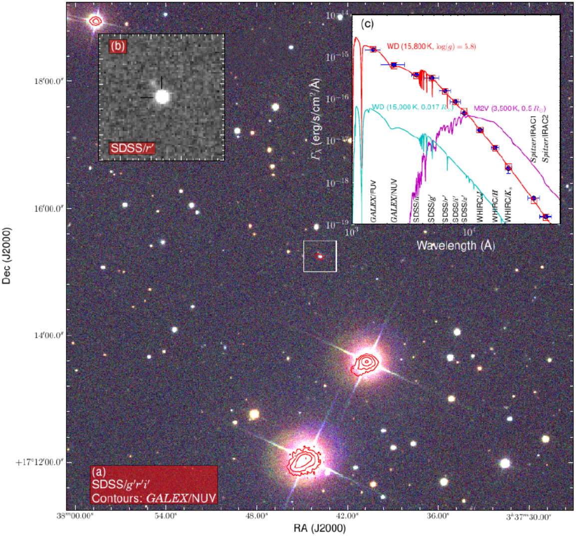
- Multi-frequency radio timing campaign was done using GBT, Arecibo and Westerbork Synthesis Radio Telescopes(1.4/1.5GHz) with $\sim$ 0.8$\mu$s timing precision for 10s of data

# Cool video !

FIGURE – NRAO outreach

# Optical, Infrared and UV observations



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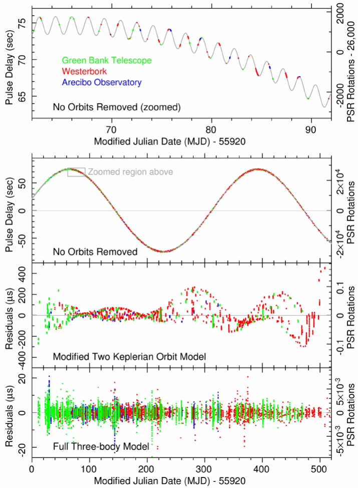
- The time delay due to transverse Doppler effect coming from the cross velocity of inner and outer orbits is also taken into account for the fitting.
- Used Monte Carlo techniques to find parameters accounting for three-body integrations

# Timing Residuals



# Fitted parameters

| Inferred or derived values | | |
|---|---|---|
| **Pulsar properties** | | |
| Pulsar period | $P$ | $2.73258863244(9)$ ms |
| Pulsar period derivative | $\dot{P}$ | $1.7666(9) \times 10^{-20}$ |
| Inferred surface dipole magnetic field | $B$ | $2.2 \times 10^{8}$ G |
| Spin-down power | $\dot{E}$ | $3.4 \times 10^{34}$ erg s$^{-1}$ |
| Characteristic age | $\tau$ | $2.5 \times 10^{9}$ y |
| **Orbital geometry** | | |
| Pulsar semimajor axis (inner) | $a_I$ | $1.9242(4)$ lt-s |
| Eccentricity (inner) | $e_I$ | $6.9178(2) \times 10^{-4}$ |
| Longitude of periastron (inner) | $\omega_I$ | $97.6182(19)$ ° |
| Pulsar semimajor axis (outer) | $a_O$ | $118.04(3)$ lt-s |
| Eccentricity (outer) | $e_O$ | $3.53561955(17) \times 10^{-2}$ |
| Longitude of periastron (outer) | $\omega_O$ | $95.619493(19)$ ° |
| Inclination of invariant plane | $i$ | $39.243(11)$ ° |
| Inclination of inner orbit | $i_I$ | $39.254(10)$ ° |
| Angle between orbital planes | $\delta_i$ | $1.20(17) \times 10^{-2}$ ° |
| Angle between eccentricity vectors | $\delta_\omega \sim \omega_O - \omega_I$ | $-1.9987(19)$ ° |
| **Masses** | | |
| Pulsar mass | $m_p$ | $1.4378(13)\ M_\odot$ |
| Inner companion mass | $m_{cI}$ | $0.19751(15)\ M_\odot$ |
| Outer companion mass | $m_{cO}$ | $0.4101(3)\ M_\odot$ |

8

# Formation Mechanism-I



## FORMATION OF THE GALACTIC MILLISECOND PULSAR TRIPLE SYSTEM PSR J0337+1715 – A NEUTRON STAR WITH TWO ORBITING WHITE DWARFS

T. M. Tauris[1,2] and E. P. J. van den Heuvel[3]

*Submitted to ApJL October 31, 2013; Accepted November 29, 2013*

ABSTRACT

The millisecond pulsar in a triple system (PSR J0337+1715, recently discovered by Ransom et al.) is an unusual neutron star with two orbiting white dwarfs. The existence of such a system in the Galactic field poses new challenges to stellar astrophysics for understanding evolution, interactions and mass-transfer in close multiple stellar systems. In addition, this system provides the first precise confirmation for a very wide-orbit system of the white dwarf mass–orbital period relation. Here we present a self-consistent, semi-analytical solution to the formation of PSR J0337+1715. Our model constrains the peculiar velocity of the system to be less than 160 km $s^{-1}$ and brings novel insight to, for example, common envelope evolution in a triple system, for which we find evidence for in-spiral of both outer stars. Finally, we briefly discuss our scenario in relation to alternative models.

*Subject headings:* pulsars: individual (PSR J0337+1715) — binaries: close — X-rays: binaries — stars: mass-loss — supernovae: general — stars: neutron

# Formation Mechanism-I

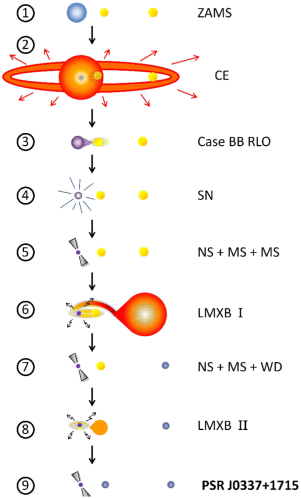



FIGURE – FORMATION OF THE GALACTIC MILLISECOND PULSAR TRIPLE SYSTEM PSR J0337+1715 – A NEUTRON STAR WITH TWO ORBITING WHITE DWARFS T. M. Tauris and E. P. J. van den Heuvel

# Problems with this model

- Reduced orbital period of tertiary star !

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- Reduced orbital period of tertiary star !
- Coplanar system !

# Formation Mechanism-II

## A formation scenario for the triple pulsar PSR J0337+1715: breaking a binary system inside a common envelope

Efrat Sabach★ and Noam Soker★

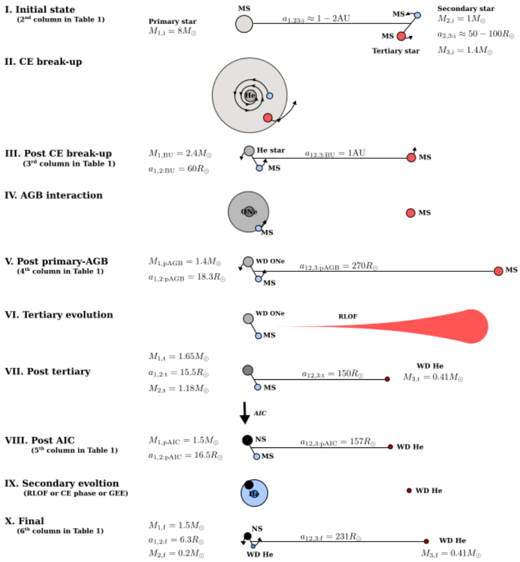
*Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel*

Accepted 2015 March 26. Received 2015 March 26; in original form 2015 January 27

**ABSTRACT**

We propose a scenario for the formation of the pulsar with two white dwarfs (WDs) triple system PSR J0337+1715. In our scenario, a close binary system is tidally and frictionally destroyed inside the envelope of a massive star that later goes through an accretion-induced collapse (AIC) and forms the neutron star (NS). The proposed scenario includes a new ingredient of a binary system that breaks up inside a common envelope. We use the BINARY_C software to calculate the post-break-up evolution of the system, and show that both low-mass stars end as helium WDs. One of the two lower mass stars that ends further out, the tertiary star, transfers mass to the ONeMg WD remnant of the massive star, and triggers the AIC. The inner low-mass main-sequence star evolves later, induces AIC if the tertiary had not done it already, and spins-up the NS to form a millisecond pulsar. This scenario is not extremely sensitive to many of the parameters, such as the eccentricity of the tertiary star and the orbital separation of the secondary star after the low-mass binary system breaks loose inside the envelope, and to the initial masses of these stars. The proposed scenario employs an efficient envelope removal by jets launched by the compact object immersed in the giant envelope, and the newly proposed grazing envelope evolution.

# Formation Mechanism-II



# Further research

Submitted to ApJ
Preprint typeset using LaTeX style emulateapj v. 01/23/15

ORDINARY X-RAYS FROM THREE EXTRAORDINARY MILLISECOND PULSARS: XMM-NEWTON OBSERVATIONS OF PSRS J0337+1715, J0636+5129, AND J0645+5158

Renée Spiewak[1], David L. Kaplan[1], Anne Archibald[2], Peter Gentile[4], Jason Hessels[2,3], Duncan Lorimer[4], Ryan Lynch[5], Maura McLaughlin[4], Scott Ransom[5], Ingrid Stairs[6,7], and Kevin Stovall[8]

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We present the first X-ray observations of three recently discovered millisecond pulsars (MSPs) with interesting characteristics: PSR J0337+1715, PSR J0636+5129, and PSR J0645+5158. PSR J0337+1715 is a fast-spinning, bright, and so-far unique MSP in a hierarchical triple system with two white dwarf (WD) companions. PSR J0636+5129 is a MSP in a very tight 96-min orbit with a low-mass, $8\,M_J$ companion. PSR J0645+5158 is a nearby, isolated MSP with a very small duty cycle (1-2%), which has led to its inclusion in high-precision pulsar timing programs. Using data from *XMM-Newton*, we have analyzed X-ray spectroscopy for these three objects, as well as optical/ultraviolet photometry for PSR J0337+1715. The X-ray data for each are largely consistent with expectations for most MSPs with regards to the ratios of thermal and non-thermal emission. We discuss the implications of these data on the pulsar population, and prospects for future observations of these pulsars.

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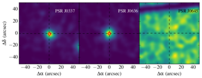


FIG. 1.— X-ray images of PSR J0337+1715 (left panel), PSR J0636+5129 (middle panel), and PSR J0645+5158 (right panel). Data limited to events with PATTERN ≤ 4 (singles and doubles), with energies between 0.2 and 2.0 keV. The black dashed lines indicate the radio positions (Ransom et al. 2014; Stovall et al. 2014), and the red circles indicate the 2″ uncertainty in the X-ray positions.

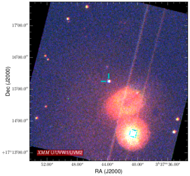


FIG. 4.— 3-color composite image of *XMM-Newton* OM data on PSR J0337+1715. The counterpart is indicated by the tick marks at the center. The image is 5′ on each side, with north up and east to the left. The composite is made from $U$ (3440 Å), $UVW1$ (2910 Å), and $UVM2$ (2310 Å) observations. The linear streaks are readout trails from the bright star, the diffuse circular region is internally-reflected light from that star, and the square box indicates a saturated region.

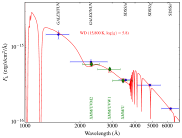


FIG. 5.— Spectral-energy distribution (SED) of the optical counterpart to PSR J0337+1715. We show the optical/ultraviolet portion of the SED presented in Ransom et al. (2014) (data shown as blue circles) with the new *XMM-Newton* OM data shown as the green diamonds. The OM photometric points from each filter are shown, and the red squares are the best-fit model atmosphere (including extinction) integrated over the filter passband.

# Further research

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## Testing the strong equivalence principle with the triple pulsar PSR J0337+1715

Lijing Shao*
*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, D-14476 Potsdam-Golm, Germany*
(Dated: March 16, 2016)



Three conceptually different masses appear in equations of motion for objects under gravity, namely, the inertial mass, $m_{\mathcal{I}}$, the passive gravitational mass, $m_{\mathcal{P}}$, and the active gravitational mass, $m_{\mathcal{A}}$. It is assumed that, for any objects, $m_{\mathcal{I}} = m_{\mathcal{P}} = m_{\mathcal{A}}$ in the Newtonian gravity, and $m_{\mathcal{I}} = m_{\mathcal{P}}$ in the Einsteinian gravity, oblivious to objects' sophisticated internal structure. Empirical examination of the equivalence probes deep into gravity theories. We study the possibility of carrying out new tests based on pulsar timing of the stellar triple system, PSR J0337+1715. Various machine-precision three-body simulations are performed, from which, the equivalence-violating parameters are extracted with Markov chain Monte Carlo sampling that takes full correlations into account. We show that the difference in masses could be probed to $3 \times 10^{-8}$, improving the current constraints from lunar laser ranging on the post-Newtonian parameters that govern violations of $m_{\mathcal{P}} = m_{\mathcal{I}}$ and $m_{\mathcal{A}} = m_{\mathcal{P}}$ by thousands and millions, respectively. The test of $m_{\mathcal{P}} = m_{\mathcal{A}}$ would represent the first test of Newton's third law with compact objects.

### I. INTRODUCTION

Mass is an important concept whose notion has evolved dramatically during several important paradigm shifts in

showed that there is only one mass for an isolated body when the gravitational energy is taken into account [13].

The importance of experimental examination of equivalence of masses was realized early in Newton's era [14].

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*Subject h...*

HE] 14 Mar 2016

## Universality of free fall from the orbital motion of a pulsar in a stellar triple system

Anne M. Archibald, Nina V. Gusinskaia, Jason W. T. Hessels, Adam T. Deller, David L. Kaplan, Duncan R. Lorimer, Ryan S. Lynch, Scott M. Ransom & Ingrid H. Stairs

*Nature* **559**, 73–76 (2018) | Download Citation

### Abstract

Einstein's theory of gravity—the general theory of relativity[1]—is based on the universality of free fall, which specifies that all objects accelerate identically in an external gravitational field. In contrast to almost all alternative theories of gravity[2], the strong equivalence principle of general relativity requires universality of free fall to apply even to bodies with strong self-gravity. Direct tests of this principle using Solar System bodies[3,4] are limited by the weak self-gravity of the bodies, and tests using pulsar–white-dwarf binaries[5,6] have been limited by the weak gravitational pull of the Milky Way. PSR J0337+1715 is a hierarchical system of three stars (a stellar triple system) in which a binary consisting of a millisecond radio pulsar and a white dwarf in a 1.6-day orbit is itself in a 327-day orbit with another white dwarf. This system permits a test that compares how the gravitational pull of the outer white dwarf affects the pulsar, which has strong self-gravity, and the inner white dwarf. Here we report that the accelerations of the pulsar and its nearby white-dwarf companion differ fractionally by no more than $2.6 \times 10^{-6}$. For a rough comparison, our limit on the strong-field Nordtvedt parameter, which measures violation of the universality of free fall, is a factor of ten smaller than that obtained from (weak-field) Solar System tests[3,4] and a factor of almost a thousand smaller than that obtained from other strong-field tests[5,6].

**...equivalence principle with the triple pulsar PSR J0337+1715**

Lijing Shao
*...Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, D-14476 Potsdam-Golm, Germany*
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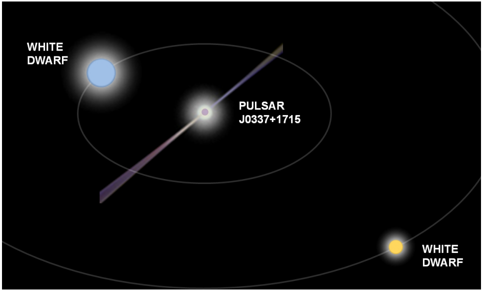


FIGURE – Credit : Thomas Tauris