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Hulse Taylor Pair Revisited in Primary-centric Frame-work

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Abstract: This paper describes the Primary-centric Framework conceived by the Author for describing first order binaries or higher order binaries. This paper gives the formation and evolution process of the Pulsar-Neutron Star System by common envelope evolution and by dynamical coupling. The discovery of the Hulse-Taylor Pair is described. Its impact in terms of universal orbital decay, periastron advance and its effect on astrophysical landscape is described. The Binary Neutron Stars discovered till date are tabulated. The underlying physics of Gravitational Wave Radiation is unveiled and the impact it has on the Binary System in terms of inspiral, ringdown,chirp signal and final merger is described and the aftermath of merger is also described. This study points to the possibility of using Binary Neutron Star (BNS) as a probe for extreme gravity and quantum gravity.

Keywords: dipole radiation; quadrupolar radiation: inspiral: chirp signal: merger; gamma bursters.

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Introduction:

This paper will be discussing the Hulse-Taylor Pair in Primari centric Frame-Work [1]. Primary centric formalism is conveyed in Figure 1. In brief it states that every system or subsystem can be represented as a first order binary or higher order binary. Every binary has two Geo-synchronous orbits in the Earth-Moon system and two Clarke's orbits (named in honour of Sir Arthur C. Clarke who proposed a system of three geo-synchronous satellites for world wide communication). These two orbits are designated as a_{G1} and a_{G2} . These two orbits are true Keplerian Orbits where centripetal force due to gravitational attraction and centrifugal force due to tangential orbital velocity of the secondary of the binary are exactly balanced and hence these two orbits are true Keplerian equilibrium orbits but if analyzed from total energy consideration [2] the inner Clarke's orbit is Energy Maxima hence unstable equilibrium and outer Clarke's orbit is Energy Minima hence stable equilibrium orbit. Figure 1 gives the architectural layout of the binary system for different mass ratios 'q'. These two Clarke's orbits are triple synchrony orbits where the following conditions are satisfied:

$T_{spin.primary} = T_{spin.secondary} = T_{orbit}$……………………relation 1

In these two orbits, the two components of the binary are axially aligned, interlocked and orbiting around the barycenter (center of mass) of the binary system as a single body. In these two orbits there is no tidal stretching and squeezing of the two components hence in these two orbits the binary is in conservative state. In any other orbit tidal dissipation takes place and the secondary is radially moving inward if secondary tumbles into sub-synchronous orbit and the secondary is receding from the primary if secondary tumbles into super synchronous orbit. In super synchronous orbit the secondary is receding from the primary until it reaches the outer Clark's Orbit where it again gets interlocked with the Primary component. The secondary component cannot go beyond a_{G2}. The secondary either remains stayput at a_{G2} or gets deflected inward. Thus a_{G2} defines the Gravitational Sphere of Influence (GSI) of the primary.

The outer Geosynchronous Orbit defines the sphere of gravitational influence of Earth in much the same way as Hill Radius [2A] does for Earth in presence of the Sun.

Hill Radius $=R_H$ = $R\times(\frac{M_+}{3M_\odot})^{1/3}$ ………………………………………………….relation 2

R = 1AU=1.49598×10^{11}m.; M_+=mass of Earth; $M_\odot$ = solar mass;

Substituting the mass of Earth and Sun in relation 2 we get:

R_H= 1.49× 10^9 m and a_{G2} = 5.527× 10^8 m which are approximately equal at astrophysical scale.

In sub-synchronous orbit secondary spirals in towards the primary to its doom hence this spiral path is known as "death spiral". On this death spiral, as secondary enters the Roche's Limit of the binary system it gets pulverized and it spreads as a ring of debris around the primary. But if the secondary is stiff enough to withstand the tidal stress of the primary then the secondary will make a glancing angle collision with the primary and get broken into pieces leaving ellipsoidal craters on the primary surface.

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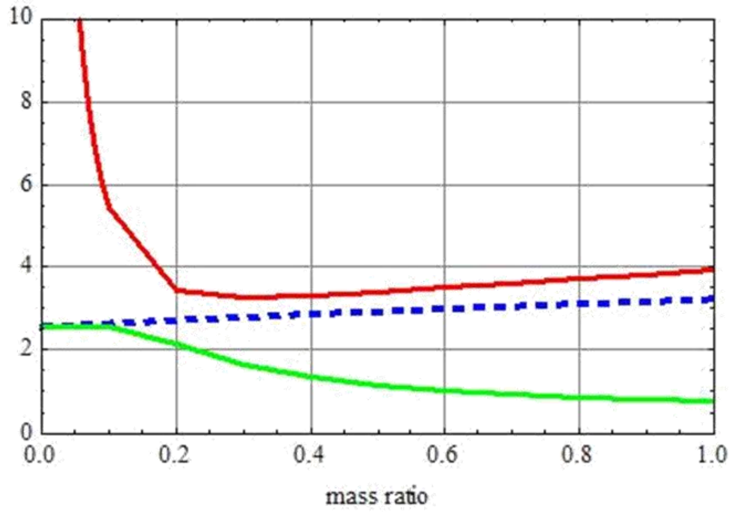

Figure 1. Plot of asynSS (×RIap)[Dashed Blue], aG1 (×RIap)[Thick Green] and aG2 (×RIap)[Thick Red] as a function of 'q'=mass ratio. Y-axis is a semi-major axis as a multiple of Iapetus Globe Radius. [Courtesy: Author]

Inspection of Figure 1., tells us that at infinitesimal values of 'q' , asynSS is the same as aG1 and only one Clarke's Orbit is perceptible. But at larger mass ratios the two (classical and kinematic formalism for aG1) rapidly diverge. Author's analysis till now has confirmed that aG1 is the correct formalism for predicting the inner triple synchrony orbit in a binary system at $q < 0.2$.

At mass ratios greater than 0.2, aG1 is physically untenable and only aG2 is perceptible. Outer Triple Synchrony Orbit seems to converge but does not actually converge to the classical formalism but remains offsetted right till the limit of $q = 1$. Here again only outer Clarke's Orbit is perceptible. The actual Star pairs satisfy the Kinematic formalism and not the classical formalism.

So Kinematic Formalism, though satisfies the correspondence principle at $q \sim 0$, is a theory in its own right. Till date there exists no formalism for two triple synchrony orbits in Classical Newtonian Mechanics. In the mass ratio range 0.0001 to 0.2 through total energy analysis as shown in reference 2, the two triple synchrony orbits can be derived.

For mass ratio less than 0.0001, binaries remain in inner Clarke's Configuration stably which is predicted by Classical Newtonian Formalism also.

At mass ratios greater than 0.2 right up to unity, star pairs remain in outer Clarke's Configuration stably and its magnitude is more than Classical Newtonian prediction.

For mass ratios $0.0001 < q < 0.2$, Outer Clarkes configuration is the only stable orbit and the secondary is catapulted from aG1 by Gravitational Slingshot mechanism and it spirals out of that configuration. If it is at $a > aG1$ the pair spirals out with a time constant of evolution and if $a < aG1$ then the pair spirals-in on a collision course again with a characteristic time constant of evolution.

Time Constant of Evolution is in inverse proportion of some power of mass ratio (Sharma 2011) [1].

For $q = 0.0001$, it is Gy and as q increases , time-constant decreases from Gy to My to kY to years. This is valid for mass scales encountered in Solar and Exo-Solar Systems. Between 0.2 to 1, a solar nebula falls into outer Clarke's Configuration by hydro-dynamic instability within months/years.

For q being vanishingly small, the calculation of the man-made Geo-synchronous Satellite's orbit of 36,000Km above the equator has been done by Kinematic Formalism. This calculation has been done by the Author in his personal communication:

http;//arXiv.org/abs/0805.0100

2. Comparative Study of different binaries.

Table 1. Comparative Study of Triple Synchrony Orbits of Earth-Moon, Mars-Phobos-Deimos , Pluto-Charon Systems, Sun-Jupiter and two stellar binaries (NN-Serpentis and RW Lac) from Classical Newtonian Mechanics and Kinematic Model.[The Globe-Orbit Parameters based on which the calculations have been made are given in NASA fact sheet]

Planet-Sat	Mass-ratio (q)	a(present) (m)	B($m^{3/2}$/s)	aG1 (m)	aG2 (m)	async* (m)
Earth-Moon	1/81	3.84400×10^8	2.00811×10^7	1.46×10^7	5.53×10^8	4.234×10^7
Mars-Phobos	10^{-8}	9.378×10^6	6.54×10^6	2.04×10^7	7.46×10^{18}	2.04×10^7
Mars-Deimos	10^{-9}	23.459×10^6	6.54×10^6	2.04×10^7	1.69×10^{20}	2.04×10^7
Pluto-Charon	1/8	19.600×10^6	9.88×10^5	1.37672×10^6	1.95579×10^7	1.96133×10^7
Sun-Jupiter	9.55×10^{-4}	778.3×10^9	1.15256×10^{10}	1.06889×10^9	7.92465×10^{11}	2.53×10^{10}
Star Binaries NN-Serpentis	0.2074	6.49597×10^8	9.25989×10^9	4.44958×10^7	6.4986×10^8	6.49514×10^8
RW-Lac	0.9375	1.69267×10^{10}	1.54426×10^{10}	4.08908×10^8	1.69314×10^{10}	1.69252×10^{10}

$$*a_{sync}^{3/2}\Omega_{orb} = a_{sync}^{3/2}\omega_{primary}$$

In Table 1, all cases are consistent with Kinematic Formalism except Pluto-Charon (case no.4). This exception is due to large uncertainty in the Globe-Orbit parameters of Pluto-Charon.

Case 1: Moon is a significant fraction of Earth (1/81) hence our Moon has a definite Tidal Evolution History. It started its journey about 4.467Gya (The birth of the Solar System is the time when the condensation of the first solid took place from the Solar Nebula. This is taken as

4.567Gya. The last giant impact on Earth formed the Moon and initiated the final phase of core formation by melting the mantle of the Earth. The date of this last impact decides the birth date of the Moon which was completed in a few hundred years by the accretion of the impact generated debris. The age of the Moon was 30 My after the birth of the Solar System. A younger Moon formed after 50 to 100 My after the first solid condensed. The concentration of highly siderophile elements (HSEs) in Earth's mantle constrains the mass of chondritic material added to Earth during Late Accretion. Using HSE abundance measurements, a Moon-formation age of 95± 32 Myr after the solar-system condensation. This method is invariant of the geo-chemistry chronometer adopted by earlier researchers.So it will be realistic to take the age of Moon as 4.467Gva since its birth just beyond Roche's Limit 15,000Km

By gravitational slingshot it was launched on an expanding spiral orbit from inner geo-synchronous orbit of 15,000Km orbital radius towards the outer geo-synchronous orbit of 5.53×10^8 m = 553,000Km. At the inner geo-synchronous orbit, the length of day = length of month = 5 hours and at the outer geo-synchronous orbit, the length of day = length of month = 47 days. Presently the lunar orbital radius is 384,400Km with sidereal length of day = 23.9344 hours and length of Sidereal Month = 27.32 Earth days. Earth-Moon started from geo-synchrony and will end in geo-synchrony. As predicted in Figure 1, for mass ratio = 1/81 the classical synchronous orbit is less than the outer geo-synchronous orbit.

Case 2 and 3: In case of Mars-Phobos-Deimos, since the mass ratio is insignificant hence Deimos launched on an orbit long of inner Clarke's Orbit has hardly evolved from its point of inception which is inner Clarke's Orbit. But Phobos is launched on an orbit short of inner Clarke's orbit hence it is on a gravitational runaway orbit, trapped in a death spiral. Deimos is stay-put in its orbit of inception which is 20,400Km but Phobos has lost altitude from its point of inception of 20,400Km to the present altitude of 9,378Km. Since the mass ratio is insignificant hence the classical synchronous orbit is the same for both Phobos and Deimos equal to 20,400Km same as the inner Clarke's Orbit. This is in exact correspondence with Figure 1.

Case 4. Pluto-Charon's classical synchronous orbit should be smaller than Outer Clarke's Orbit as required by Kinematic Analysis but the former is 0.28% larger. This is due to the uncertainty in Globe-Orbit parameters of Pluto-Charon.

Case 5. Mass ratio of Jupiter to Sun is 10^{-3} hence according to KM analysis Jupiter-Sun has a tidal evolutionary history with a rapid Time-constant of evolution of 4.275My. It has evolved from inner Clarke's Orbit 3.7859×10^9m to the present orbit of 778.3×10^9m where its evolution factor is 0.893 and eventually it will lock into second triple-synchrony state in the outer Clarke's Orbit of 871.161×10^9m. The classical synchronous orbit is at 25.3×10^9m, 97% of outer Clarke's Orbit, as predicted by Figure 1 also.

In Paper No. B0.3-0011-12 Iapetus hypothetical sub-satellite re-visited and it reveals celestial body formation process in the KM Framework. presented at 39th COSPAR Scientific Assembly, Mysore, India from 14th July to 20th July 2012, the correspondence between Newtonian Formalism of Synchronous Orbit and Kinematic Case 6 and Case 7: These are stellar non-relativistic binaries. Author calls them non-relativistic because the mean apsidal motion or periastron advance per year is negligible. Here since the mass ratio is greater than 0.2, hence the original molecular cloud settles into a binary in Months-Years and gets locked-into outer Clarke's Orbit. In both cases the synchronous orbit is shorter than the Outer Clarke's Orbit by 0.05% and 0.04% respectively. This is consistent with Kinematic Analysis.

3. What is a Neutron Star?

Collapse of the iron core of a massive star greater than 1.4 and less than 3 at the end of the life cycle leads to a Neutron Star (NS)[3]. In a binary system of two massive stars, one undergoes a supernova explosion and becomes a Neutron Star. The Neutron Star and the secondary main sequence star evolve in a 'common envelope', NS keeps orbiting around in the extended envelope of the secondary star. At the end of this common envelope stage the secondary star also undergoes a supernova explosion .If after this second supernova explosion the binary system remains connected then a Binary Neutron Star (BNS) is born. This is a compact binary of Neutron Stars. Two isolated NSs through dynamical capture in a dense stellar regime such as Globular Clusters can form BNS[4,5,6]. In principle any orbiting mass in a non-circular orbit around another mass emits gravitational waves due to the time varying mass quadrupole moment – this is the central prediction of the General Theory of Relativity (GTR). As a result of gravitational wave radiation, rotational energy of the binary system is dissipated and the two NS's are set on an in-spiral path, ring down, chirp signal and final merger. In Hubble Time the two NS's merge.

4. Discovery of First Neutron Star-Pulsar Binary PSR 1913+16 on July 2,1974.[7]

Russell Alan Hulse and Joseph Hooten Taylor Jr, at MIT, Amherst,USA, using the Arecibo Radio Telescope on July 2, 1974, discovered the first Neutron Star-Pulsar Binary which was christened as PSR 1913-16. On 28th November 1967, Jocelyn Bell Burnell and her supervisor Antony Hewish discovered an isolated Pulsar PSR B1919+21 pulsing at 1.3373sec and pulse width 0.04sec at Mullard Radio Observatory, Cambridge,UK, vindicating S. Chandrashekhar who in 1935 in his PhD thesis at Cambridge University , England, had predicted the existence of compact objects at the end of the life cycle of stars heavier than $1,4M_{\odot}$. These Pulsars emitted high intensity Radio Waves from their magnetic Poles. The Pulsars are like LightHouse Beacon sweeping the surrounding sea with regularity. In a Pulsar, the geographical polar axis or the spin axis and magnetic dipole are misaligned. Hence in the spinning Neutron Star the synchrotron radiation emanating from the magnetic poles are sweeping the Universe around with a regularity and if Earth happens to fall in their sweeping path then the radio waves sweeps us with a regularity of 1.3373 second at a rate of 0.707Hz in case of PSR B1919+21.Pulsars have extremely strong magnetic fields (10^8 - 10^{15} $Gauss$) . Electrons and Positrons spiral along the magnetic field lines by Lorentz force. These particles move at relativistic speed and emit synchrotron radiation (non-thermal radiation in Radio spectrum but also in X-Ray and gamma-Ray part of the spectrum and it is strongly polarised - a signature of synchrotron origin) also called curvature radiation. The radiation is highly directional emitted in a narrow cone tangent to the particle's path as shown in Figure 3.

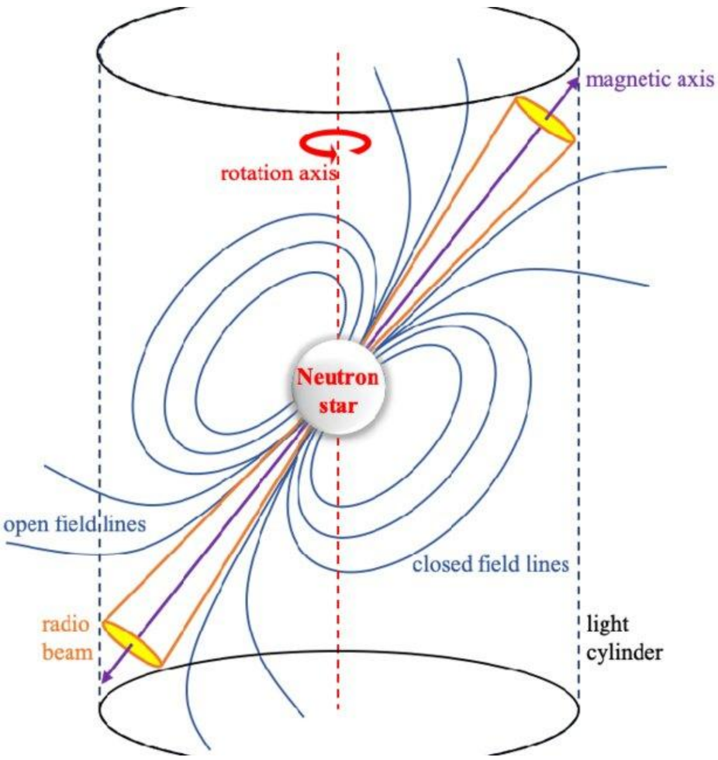

Figure 2. Schematic of a Pulsar.Magnetic Dipole is misaligned with the spin axis of the pulsar hence the radio beam emanating from the North and South Pole due to synchrotron radiation is sweeping the space around as LightHouse Beacon. [Credit: researchgate net]

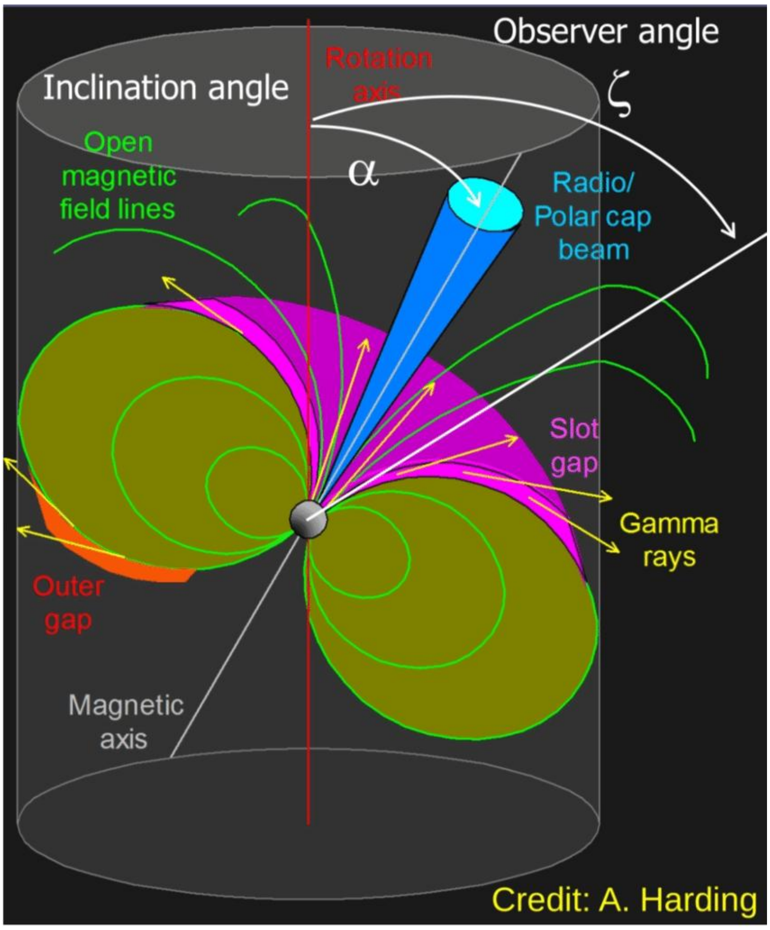

Figure 3. Schematic of the synchrotron radiation which is highly directional emitted in a narrow cone tangent to the particle path. [Credit: A.Harding]

Hulse-Taylor closely monitored the Pulsar-Neutron Star Binary from 1981 to 2001 and discovered the orbital decay shown in Figure 4 confirming the Gravitational Wave emission as a result of orbital motion of the two binary components in eccentric orbit.

In 1993 Nobel Prize in Physics was awarded to Hulse and Taylor "for the discovery of a new type of Pulsar - it has opened new possibilities for the study of gravitation" .

The orbital decay of Hulse-Taylor Pair is shown in Figure 4.

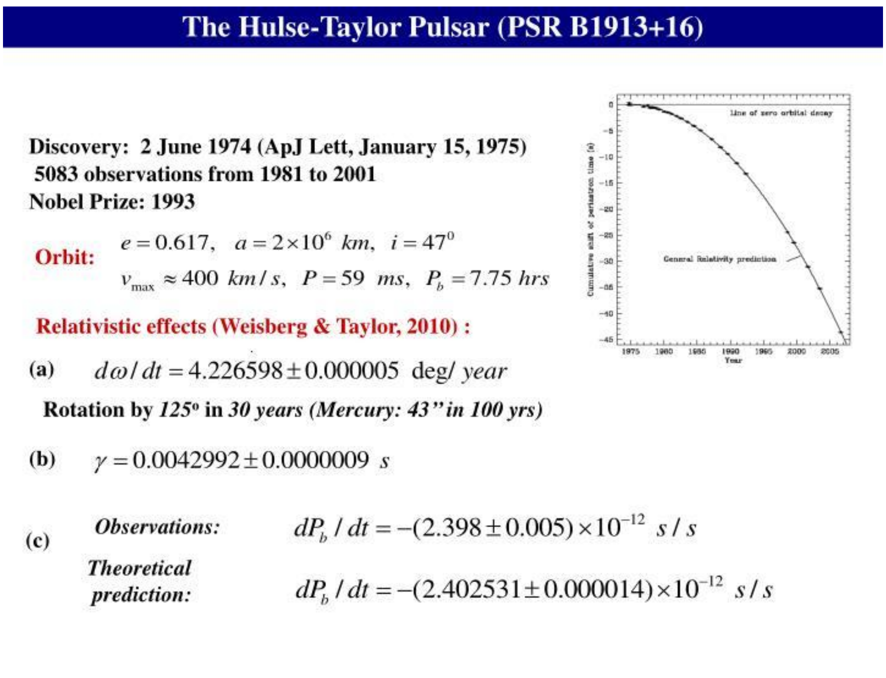

Figure 4. The Orbital Decay of PSR 1913+16.[Credit: reference 7]

4.1. Relativistic Effects exhibited by Hulse-Taylor Pair:

The Neutron Star Binary configuration provides us with a nearly ideal relativity laboratory including an accurate astrophysical clock in a high speed eccentric orbit and a strong gravitational field.

Variation of $\frac{v^2}{c^2}$ and $\frac{GM}{c^2 r}$ in the following situations ;

1. In tight eccentric orbit of BNS, v (tangential velocity) and r (the separation between the two components) change significantly during the entire orbit.This leads to measurable variations

*in the special relativistic Doppler Shift due to change in the line of sight and orbital velocity;

*in the General Relativistic Gravitational Red Shift also known as Einstein Delay due to the variation in gravitational potential;

These two combine to modulate the Pulse Arrival Time by several microseconds which is measurable by Modern Radio Telescopes.

2. Periastron Advance: The orbit's ellipticity at Periastron Point advances by 4.2∘per year due to General Relativistic Correction. As of 2025 CE, this is one of the most precisely measured relativistic parameters of any BNS system.

3. Utility of these measurements:

- The timing model includes five Post-Keplerian (PK) parameters, which encode relativistic effects such as :
  ώ : periastron advance
  - **ϒ:** Einstein delay (gravitational redshift + time dilation)
  - $\boldsymbol{P_{\dot{b}}}$ **:** orbital period decay due to gravitational wave emission
  - **r,s,:** Shapiro delay parameters (range and shape, used for edge-on systems)

  The combination of these parameters allows:
- Estimation of orbital inclination: from the amplitude of the relativistic effects.
- Individual neutron star masses: by solving the PK parameter equations with Keplerian constraints.

  Significance of Spectroscopic vs Pulsar Binaries
- In spectroscopic binaries, we are often limited to **mass functions** due to lack of inclination knowledge.
- In pulsar binaries, the timing precision enables:
  - Direct measurement of inclination.
  - Full solution of the two-body problem with relativistic corrections.
  - No need to rely on spectral Doppler curves—timing of pulse arrival does it all.

  Post-Keplerian Parameters in Pulsar Timing:

Table 2, Post Keplerian Parameters.

Parameters	Symbols	Physical Meaning	What it constrains
Periastron Advance	ώ	Rate of rotation of periastron due to gravitational wave emission	$total\ mass\ M$
Einstein Delay	ϒ	Time Dilation And gravitational Redshift near periastron	Combination of m1 , m2 and e;
Orbital period decay	$P_{\dot{b}}$	Shrinkage of orbit due to gravity wave emission (quadrupolar radiation)	Energy loss rate -direct measure of gravitational radiation
Shapiro Delay Range	r	Extra delay due to space-time curvature	
Shapiro Delay Shape	s		Orbital inclination

Shapiro Delay And Shape (r and s) are used for edge on systems.

How are these used:

ώ (periastron advance) $=3(\frac{2\pi}{P_b})^{5/3}(\frac{GM}{c^3})^{2/3}$ $\frac{1}{1-e^2}$ ……………….relation 1

ϒ gives a second constraint between m1 and m2;

$P_{\dot{b}}$ test of Gravitational Wave emission- supports General Relativity;

If system is favourably oriented for edge on view then r and s - Shapiro Delay range and shape allow direct measurement of companion mass and inclination;

- the estimate of orbital inclination from the amplitude of relativistic effects;
- Individual neutron star mass can be determined by solving PK parameter equation with Keplerian constraints

Changes of $\frac{v^2}{c^2}$ and $\frac{GM}{c^2 r}$ during its orbit are sufficient to cause changes in the observed period of the order of several parts in a million. Therefore both the relativistic Doppler Shift and Gravitational Red Shift will be easily measurable. For Hulse Taylor NS-Pulsar Binary the General Relativistic Advance of Periastron is 4 degrees per year and has been detected and extensively studied by 2025 CE.. The measurement of these effects not observable in spectroscopic binaries allow the orbit inclination and the individual masses to be obtained.

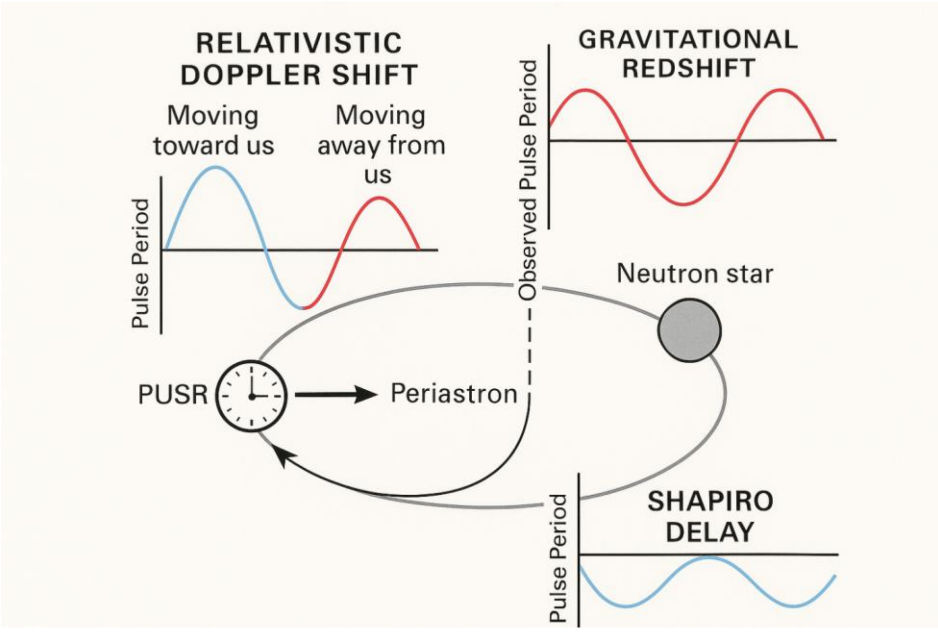

Figure 5. Relativistic Doppler Shift, Gravitational Redshift and Shapiro Delay.[Credit:OpenAI(2025) Diagram generated by ChatGPT . Retrieved from ChatGPT May 10,2025]

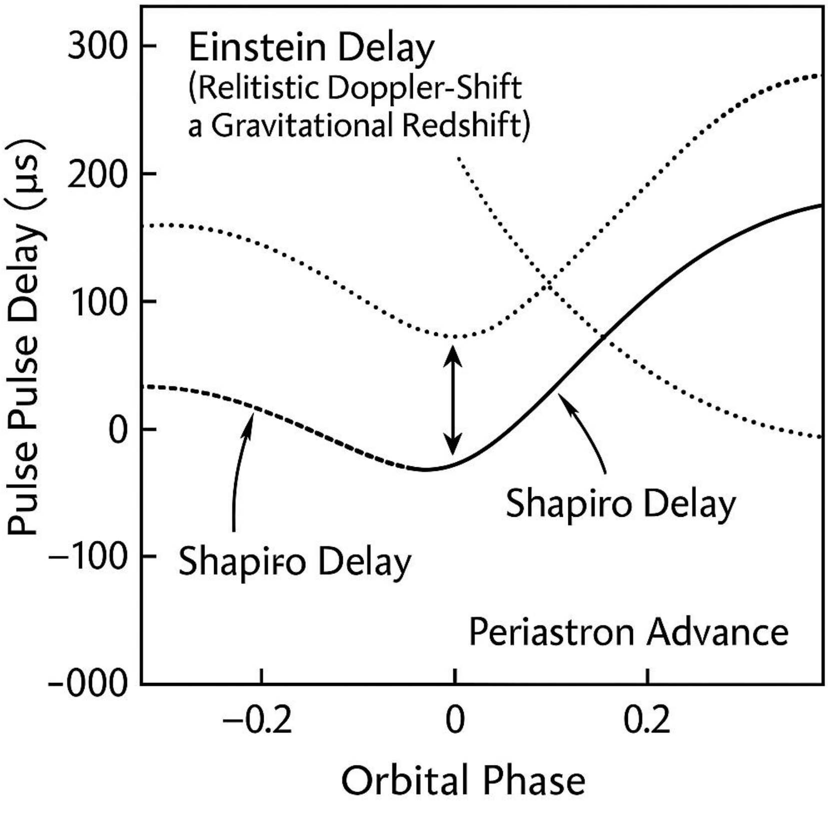

Figure 6. Annotated Timing Diagram showing Einstein Delay, Shapiro Delay and Periastron Advance. [Credit:OpenAI(2025) Diagram generated by ChatGPT . Retrieved from ChatGPT May 16, 2025]

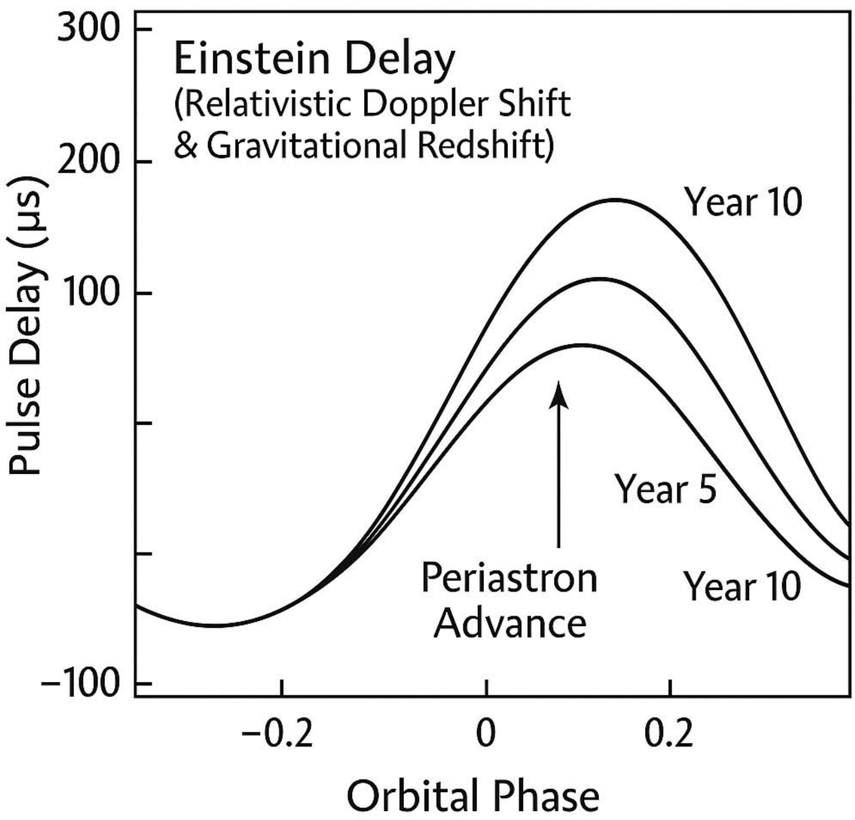

Figure 7. Periastron advances through the Einstein Delay Curve across years.[Credit:OpenAI(2025) Diagram generated by ChatGPT . Retrieved from ChatGPT May 16,2025]

PSR B1913+16 promised to be a clean system. Hulse-Taylor is an isolated system. It has no additional gravitational perturbation or orbital disturbance from external masses. There is no mass transfer hence orbital dynamics is governed purely by gravity. There are highly regular pulses from the pulsar. The Hulse-Taylor pair emit highly regular radio pulses. And it acts as a precise natural clock. Pulse arrival time is measured with microsecond precision which is essential to detect small relativistic effects such as periastron advance and gravitational redshift. It has a high orbital eccentricity e = 0.67. This enhanced the detectability of relativistic effects over the orbit. The Hulse-Taylor pair provides a strong gravitational field regime. With an orbital speed of 300Km/s and a few solar radii separation, the binary system is firmly in a strong gravitational field regime. It has provided clean data measured over 40 years. This enabled the measurement of orbital decay with remarkable precision This enabled a precise match with Peter-Mathew Model predictions (see section 6). The orbital decay is an indirect confirmation of gravitational wave emission much earlier than the detection of gravitational waves by LIGO on 14th September 2015.

4.1. The Impact of Hulse-Taylor binary:

i. The first impact is the secular decrease in the orbital period: $\frac{dP_b}{dt}$ would constitute a test for the existence of gravitational radiation;

ii. The orbital period decay rate = negative $\frac{dP_b}{dt}$ is a sensitive test of alternative relativistic theory of gravity and notable form of tensors- scalar theories such as Jordan-Brans-Dicke theory. Emission of dipole gravitational radiation in theory contains scalar excitations . This would generally be much larger than the usual quadrupolar emission.

However, in alternative relativistic theories of gravity—particularly scalar-tensor theories such as the **Jordan-Brans-Dicke (JBD)** theory—additional scalar degrees of freedom can lead to **dipolar gravitational radiation**. This dipole component arises from the coupling of matter to a scalar field, typically denoted ϕ, which complements the usual metric tensor gμν. The resulting scalar field excitations can carry away energy more efficiently than the quadrupole radiation of GR, especially in systems with components of unequal gravitational binding energies (i.e., different self-gravitational structures), such as a neutron star–white dwarf binary.

The emission of dipolar radiation leads to an **enhanced orbital period decay**, typically of the form:

$(\frac{dP_b}{dt})_{dipole}$ proportional to $\frac{1}{\omega_{BD}} \times \Delta s^2$;

where:

- ω_{BD} is the Brans–Dicke coupling constant,
- Δs=s1−s2 is the difference in **sensitivities** (a measure of how the gravitational binding energy contributes to the mass) of the two bodies.

In systems like the Hulse-Taylor pulsar, composed of two neutron stars with similar internal structure, Δs is small, so dipolar emission is suppressed. However, in mixed binaries (e.g., neutron star–white dwarf), dipolar contributions can be substantial and measurable, making them key laboratories to constrain or rule out scalar-tensor theories.

The **absence of excess orbital period decay** in precision-timed pulsar binaries has therefore placed **stringent bounds on the strength of scalar couplings**, and hence on parameters like ω_{BD}.

For example, current limits from pulsar–white dwarf systems suggest $\omega_{BD} \geq 40{,}000$, far exceeding solar-system limits like those from the Cassini experiment.

iii. Spin-period precession of the pulsar spin axis (of a few degree per year) will test General Theory of Relativity and also it will enable us to observe for the first time the pulsar emission process at varying angle;

iv. Gravity propagates as predicted by General Theory Of Relativity;

v. Gravitational Radiation damping in binary systems;

vi. Negative value of $(\frac{dP_b}{dt})$ has been measured;

vii. Hulse-Taylor pulsar binary provides a direct observable proof that gravity propagates at velocity of light and has a quadrupolar structure;

4.2. Binary Pulsar and Astro-Physics:

i. Enabled the measurement of masses of the two components;

ii. Co-evolution of stars began to be studied with the launch of Uhuru Satellite which enabled us to study the X-Ray emission from binary star system;

iii. The study of Binary Radio Pulsars began:

iv. The discovery of binary pulsars and discovery of millisecond isolated pulsars has given impetus to the development of astrophysical scenario for the co-evolution of binary stars;

v. The later life of Binary Neutron Stars; Radio Pulsars have limited life but there is a population of BNS which will emit gravitational waves for hundreds of millions of years[7A, 7B]. The gravitational waves from late inspiral will give useful constraints on the equation of state of nuclear matter. The final coalescence will give rise to catastrophic events leading to the emission of the whole range of Electro-Magnetic Waves and neutrinos. This may be related to short gamma ray bursts;

vi. As a binary neutron star system nears its merger, the two components orbit each other faster and closer radiating more energy in the form of gravitational waves.The intense emission during the ringdown and merger peaks into chirp signal (see Figure 9) just before merger.Hence these systems have been the prime target of gravitational wave Observatory.and was presciently described by Freeman Dyson (a British-American Theoretical Physicist and gifted Mathematician) decades before we had tools for observing the gravitational waves. See Figure 8 and Figure 9.

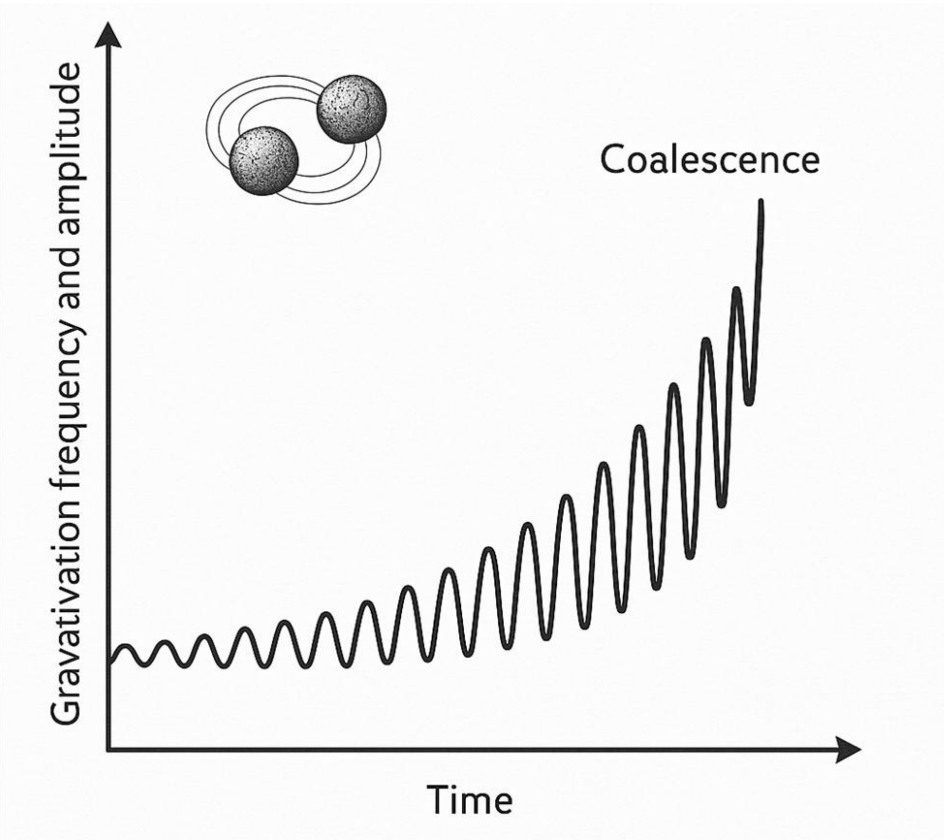

Figure 8. The Inspiral , Ringdown and Merger of Neutron Stars in a Binary Neutron Stars System due to Gravitational Wave Radiation. [Credit: OpenAI(2025) Diagram generated by ChatGPT on Binary Neutron Stars Gravitational Waves . Retrieved from ChatGPT May 10,2025]

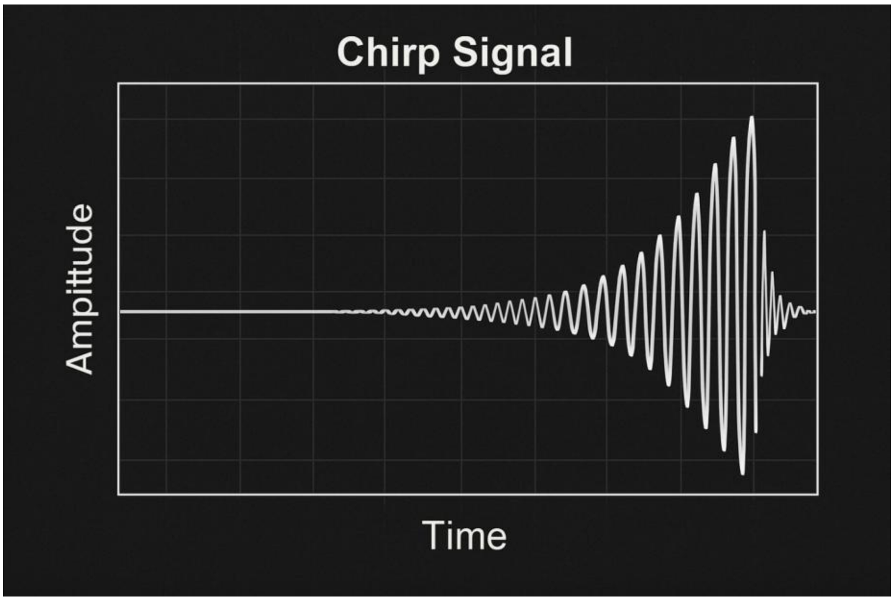

Figure 9. In-spiral, ring-down and chirp signal just before the merger of BNS.[Credit: "Chirp Signal- Gravitational Waves Amplitude vs Time" created by Open AI's Chat GPT (2025),generated using DALL E retrieved from Chat GBT on 12th May 2025]

5. The ensemble of Neutron Star Binary Discovered till date.

Table 2. Observational data of Neutron Star in Binary Neutron Star System containing at least 1 Pulsar , masses are M_A, M_B and $\frac{M_A}{M_B}$ = q and q < 1, (orbital period), the projected semi-major axis of the orbit (projection on the line of sight) , (the orbital eccentricity), distance from the Earth (D kpc), the barycentric rotation frequency (Hz), the inferred surface magnetic dipole field is B_{SURF}(G). The DATA is truncated to 4 significant digits for masses and to 2 significant digits for the rest. J0737-3039 is the only known Double-Pulsar System The magnetic field of the second Pulsar is 1.59× 10^{12} G.

Name	$\mathbf{M_{Total}}$($\times M_\odot$)	M_A($\times M_\odot$)	M_B($\times M_\odot$)	q	T_{ORB} (days)	R(l-s)	e_{ORB}	D(kpc)	(Hz)	(G)
J0453+1559[8]	2.734	1.559	1.174	0.75	4.1	14	0.11	1.8	22	9.3×
J0737-3039[9]	2.587	1.338	1.249	0.93	0.10	1.4	0.088	1.1	44	6.4×
J1518+4904 [10]	2.718	<1.776	>0.951	>0.54	8.6	20	0.25	0.7	24	9.6×
J1534+12 [11]	2.678	1.333	1.345	0.99	0.42	3.7	0.27	1.0	26	9.6×
J1753-2240 [12,13]	-	-	-	-	14	18	0.30	3.5	10	9.7×
J1756-2251 [14]	2.577	1.341	1.23	0.92	0.32	2.8	0.18	0.73	35	5.4×
J1807-2500 [14A]	2.571	1.344	1.21	0.89	1	29	0.75	-	239	< 9.8×
J1811-1736 [15]	2.571	<1.478	>1.002	>0.68	19	35	0.83	5.9	9.6	9.8×
J1829+2456 [16]	2.59	<1.298	>1.273	>0.98	1.2	7.2	0.14	0.74	24	1.5×
J1906+0746 [17]	2.613	1.291	1.322	0.98	0.17	1.4	0.085	7.4	6.9	1.7×
J1913+1102 [18]	2.875	<1.84	>1.04	>0.56	0.21	1.8	0.090	13	1.1	2.1×
J0*:(Hulse-Taylor)PSR 1913+16 [7B]	2.828	1.449	1.389	0.96	0.32	2.3	0.62	7.1	17	2.3×
J1930-1852 [19]	2.59	<1.199	>1.363	>0.88	45	87	0.40	2.3	5.4	6×
B2127+11C[20]	2.713	1.358	1.354	1	0.34	2.5	0.68	13	33	1.2×

6. Physics of Orbital Decay and Gravitational Wave Radiation Formulation:

Peters- Mathew Formalism:[21,22]

The Peter-Marhew Model will be referred to as PM Mode. PM Model comprises of weak field, slow motion, point mass, quadrupole radiation, an insular sample (non-interacting), double compact binaries evolving under gravitational wave emission with special reference to the characterization of binary stars gravitational wave sources in ELF & LF band which can be observed by LISA future space based gravitational wave interferometry observatories. Here there is adiabatic evolution (negligible change in orbital parameters over each orbit).

The PM Model starts with steady state binaries in non-circular orbits, with several spectral lines with comparable intensities emitted. Circular orbits don't give the harmonics hence loss in signal power also loss in Signal to Noise level deterioration which can spoil the performance of gravity wave detectors. For steady state binaries periastron advance have significant effects on gravitational wave form. Orbital eccentricities must not be neglected in detecting gravitational waves from steady state binaries. The standard PM Model for binary star orbital damping under gravitational wave emission is completely solved in analytic form for any value of insular orbital eccentricity resulting in Universal Decay Scenario.

The PM Model was introduced 30 years ago under the point mass weak-field, slow motion and quadrupole radiation approximation. The whole General Relativistic Two-Body problem was reconsidered.

- A well founded and rigorous description of General Relativistic Orbital Damping under Gravitational Wave Emission became available;
- This gave a firm support to the first indirect observational evidence of gravitational radiation based on the observed orbital damping of Binary Pulsar PSR 1913+16;

Extensive numerical simulations of binary star coalescence were performed by Nakamua et.al.[23] first in Newtonian Framework and then in relativistic hydrodynamic framework [24]. Pierro and Pinto give the general solution of PM orbital damping equations- a general solution in analytic form is obtained. Universal Decay Scenario is deduced and the limit of validity is well defined. In late evolution stages a binary orbit becomes nearly circular by the emission of gravitational radiation.

Gravitational Wave Radiation rate:

$$< \frac{dE}{dt} > = \frac{32}{5} \times \frac{G^4}{c^5} \times \frac{m_1^2 m_2^2 (m_1+m_2)}{a^5(1-e^2)^{7/2}} \times (1+ \frac{73}{24}e^2 + \frac{37}{96}e^4) \frac{Joules}{second}$$ …………………relation 1

M= $(m_1 + m_2)$

where m_1 *primary component of the binary*, $m_2 =$ *secondary component of the binary* ; reduced mass $\mu = \frac{m_1 m_2}{M}$; G = gravitational constant, c = velocity of light;e =eccentricity of the orbit NSB; a = semi-major axis of the orbit of the binary;

Orbital decay rate =

$$< \frac{da}{dt} > = \frac{64}{5} \times \frac{G^3}{c^5} \times \frac{m_1 m_2 (m_1+m_2)}{a^3(1-e^2)^{7/2}} \times (1+ \frac{73}{24}e^2 + \frac{37}{96}e^4) \frac{m}{second}$$ …………………relation 2

Decay of eccentricity =

$$< \frac{de}{dt} > =- \frac{304}{15} \times \frac{G^3}{c^5} \times \frac{m_1 m_2 (m_1+m_2)}{a^4(1-e^2)^{5/2}} \times e(1+ \frac{121}{304}e^2) \frac{1}{second}$$ …………………relation 3

Energy loss and orbital decay rate are higher for closer, more eccentric and massive binaries.

System Parameters of Hulse-Taylor Binary (Pulsar-Neutron Star Binary):

The two components of the binary system follow an elliptical path.

Rotation period of each component = 59.02999792988 ms;

Orbital period is 7.75 hours;

Estimated mass is 1.4411$M_{\odot}$ + 1.3879$M_{\odot}$ = 2.828378(7) $M_{\odot}$;

Separation of preistran =1.1$R_{\odot}$ = 746,600 Km;

Separation of apstron 4.8$R_{\odot}$ = 3,153,600 Km;

The plane of orbit is inclined at 47.233∘ with respect to line of sight from Earth;

Semi-major axis a = $a_A + a_B$= 1.949261860344882× 10^9m= 1,950,100 Km

Orbital velocity at periastron = 450 Km/s ;

Orbital velocity at apstron = 11 Km/s;

D (distance from Earth) =21,000ly =6,400 pc;

Orientation of periastron changes by 4.2∘per year in the direction of the orbital motion. This is the relativistic precession of periastron also known as apsidal motion;

In January 1975, periastron occurred perpendicular to the line of sight from Earth;

At the time of periastron passage in January 1975, the periastron of the Hulse–Taylor binary system (PSR B1913+16) lay nearly in the plane of the sky—that is, the line connecting the pulsar and its companion at closest approach was oriented perpendicular to our line of sight. Although the orbital plane is significantly inclined to the line of sight (as evidenced by measurable Doppler shifts), this particular periastron orientation provided a highly favorable geometry for pulsar timing measurements. It enabled a clearer disentanglement of relativistic effects such as the periastron advance, gravitational redshift, and second-order Doppler shift, facilitating precise determination of the system's post-Keplerian parameters and contributing to early empirical confirmations of general relativity.

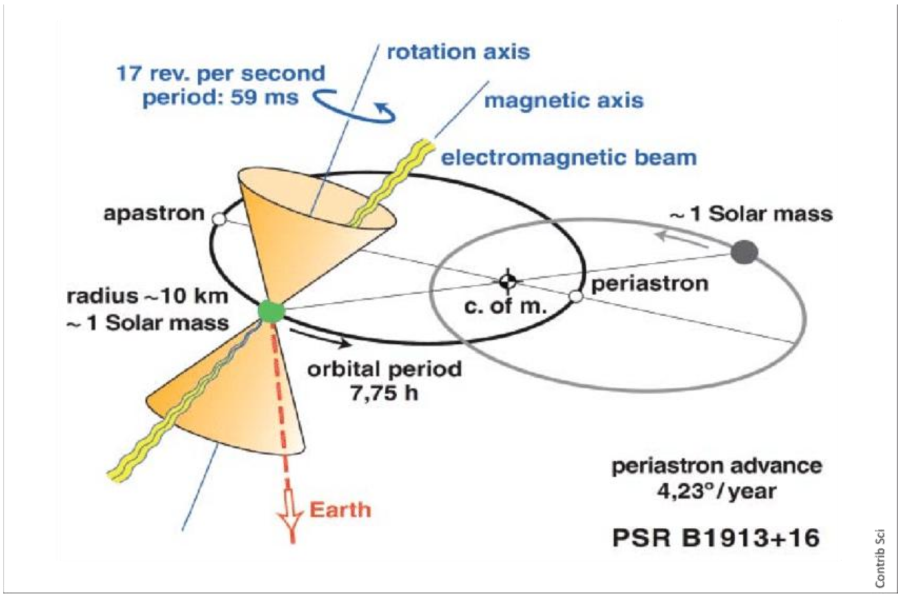

Figure 6. The Orbital Plane and Inclination of Hulse-Taylor Pair in January1975. [Credit: created by Open AI's Chat GPT (2025),generated using DALL E retrieved from Chat GBT on 14th May 2025]

Key Features of the Diagram:

- Orbital Plane and Inclination: The diagram shows the elliptical orbit of the pulsar and its companion neutron star around their common center of mass. The orbital plane is inclined at approximately 45° to our line of sight, which is crucial for observing Doppler shifts in the pulsar's signals.
- Periastron Orientation: In January 1975, the periastron—the point of closest approach in the orbit—was oriented such that it lay nearly in the plane of the sky, meaning the line connecting the two stars at periastron was perpendicular to our line of sight. This orientation minimized certain relativistic effects along our line of sight, aiding in precise measurements.
- Relativistic Effects: The diagram highlights the advance of periastron, a relativistic effect where the point of closest approach shifts over time due to spacetime curvature. For PSR B1913+16, this advance is about 4.2° per year.
- Pulsar Beam and Rotation: The pulsar emits a beam of electromagnetic radiation due to its rapid rotation. As it orbits its companion, the timing of these pulses varies due to relativistic effects, which can be precisely measured to test predictions of general relativity.

This visualization helps in understanding how the unique orientation and relativistic dynamics of the Hulse–Taylor binary pulsar system make it an excellent laboratory for testing gravitational theories.

6.1. Physics of Orbital Decay:

Total Energy = T (Kinetic Energy) + U (Potential Energy)……………………relation 4.

T = $\frac{1}{2}\mu v^2$ where μ= $\frac{m_1 m_2}{(m_1+m_2)}$ and v =relative orbital velocity;

U = -2$\frac{G m_1 m_2}{a}$ where G = Universal Gravitational Constant.

E = T+U = -$\frac{G m_1 m_2}{2a}$ ……………………………………………………………relation 5

Negative Total Energy means bound elliptical orbit. Here energy will have to be added to bring the two masses apart to infinity. That is energy will have to be added to make it unbound.

6.1.1. The consequences of Gravitational Wave Emission:

Gravitational wave emission means loss of Rotational Kinetic Energy:

This means tighter orbit and 'a' shrinks.

Gravitational Wave Radiation launches the two binary components on an in-spiral path.

From relation 5 we get: a = -Gm1.m2/(2E)............relation 6…

Differentiating relation 6 with respect to time one obtains:

..da/dt = (Gm1.m2)/(2E^2) dEdt …………………………relation 7

Since dE/dt < 0 therefore da/dt < 0;

We use Peters- Mathew Formalism for orbital decay.

Orbital decay rate for Hulse-Taylor Pair = -3.42 m per year ;

Orbital period for Hulse-Taylor becomes shorter = -76.5 microsecond per year

7. Detection of BNS by Gravitational Wave Observatory.

The first direct detection of BlackHoles merger was done by LIGO in 2015. LIGO detected Gravitational Wave Emissions due to inspiral, ring down and merger of the two Black Holes [25,26,28,29] Few months later, detection of Black Holes merger came from VIRGO in Italy [27]. Advanced detectors called VIRGO [34], KARGA in Japan [35] and LIGO India [30] will soon become operational. We have detected signals from the inspiral and merger of BNS and NS-BH binary [31, 32,] and stellar BH merger [33].

From an analysis of Earth-Moon System [personal communication: http://arXiv.org/abs/0805.0100] and Iapetus (a moon of Saturn) and its Sub-satellite[36] it has been discovered that in any binary system of a given mass ratio 'q', binary rapidly falls into the outer Clarke's configuration at a time scale of months/years with a perfect score of evolution factor (€) equal to Unity for $0.2 < q < 1$, provided the tidal locking time scale is within the age of the binary. Otherwise the system reaches near-outer Clarke's Orbit but never quite settles to the triple synchrony state [$T_{spin\_A} = T_{spin\_B} = T_b$ (orbital period)]. This is defined as the Kinematic Model (KM) Framework of Binaries. In this paper Keplerian Binaries such as Main Sequence Star Binary RW Lacertae, M Dwarf-White Dwarf pre-cataclysmic NN Serpentis and Relativistic Binaries such as 6 Double Neutron Star Binaries (DNSBs) namely PSR J1811-1736, PSR J1518+4904, PSR B1534+12, PSR B1913+16(Hulse-Taylor Pair), PSR 2127+11C and PSR J0737-3039 are tested for KM prediction of Unity Evolution Factor. Main Sequence Star Binary RW Lacertae and M Dwarf-White Dwarf pre-cataclysmic NN Serpentis are found to be in outer Clarke's Configuration with triple synchrony state achieved as predicted. On the other hand all the above six DNSBs are found to be offsetted from the Unity Evolution Factor due to gravitational radiation induced spiral-in. This off-set is in proportion to the relativistic strength of the DNSB measured by apsidal motion or rate of periastron advance. Hence this study clearly vindicates the central tenant of KM Framework and establishes it as the pivotal physical process in shaping this evolving Universe.

8. Binary Neutron Stars merger are unique in the Landscape of Relativistic Astrophysics:

Binary Neutron Stars are unique in several ways:

i Binary Neutron Stars are source of Gravitational Waves during the inspiral and merger but also post-merger;

ii. Possible progenitors of Short Gamma Ray Bursts (SGRB);

iii. Possible source of other Electro-magnetic messengers and neutrino emissions;

iv. Responsible for nucleosynthesis of a good portion of heavy elements in our Universe;

Thus BNS mergers become the richest Einstein's laboratory where highly non-linear gravitational effects blend with complex micro-physical processes and yield astonishing astrophysical phenomena.

Discussion:

The discovery of Hulse-Taylor Pair on July 2, 1974, was a major breakthrough comparable to the discovery of an isolated Pulsar byJocelyn Bell and her supervisor in 1967. Orbital Decay matched the energy loss as predicted by the PM Model. This was the first indirect evidence of Gravitational Wave emission. These are natural laboratories for studying strong gravity fields..This laid the theoretical foundation of LIGO and Virgo and first detection of gravitational waves from Black Holes merger came in 2015. This is key in mapping the distribution of compact binaries in the Galaxy. These help understand the stellar deaths, supernova kicks and the evolutionary pathways leading to Neutron Stars merger. These mergers are the sites of heavy elements nucleosynthesis such as Gold and Platinum and are the beacons shining throughout the Cosmic Web.. This discovery has heralded the age of gravitational wave astronomy.

Conclusions:

Merger of Binary Neutron Stars combines in a single process: extreme gravity, copious emission of gravitational waves, complex microphysics and electromagnetic processes that can lead to astrophysical signatures observable at the largest red shift. This is Einstein's richest laboratory. Here considerable amount of significant events occur post merger namely Black Hole formation as a result of merger of in-spiraling Neutron Stars/Pulsar, torus accretion on the merged compact object, connection with gamma ray burst engine , ejected material and its nucleosynthesis.

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Conflict of Interest:

There is no conflict of interest financial or otherwise with anybody

Declaration of generative AI and AI assisted technologies in the writing process: During the preparation of this work the Author used ChatGPT and deepseek in order to reason. After using this service the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

"Ethics, Consent to Participate and Consent to Publish Declaration" not applicable.

Author's contribution:

Author collected data regarding LOD (Length of Earth Day) from popular science books by Isaac Asimov, George Gamow and Carl Sagan (COSMOS). After receiving the Press Release of NASA on Silver Jubilee Anniversary of Man's landing on Moon on 20th July 1994 that Moon has receded by 1m in last 25 years, author redid the Earth-Moon analysis and presented at 82nd Session of Indian Science Congress at Jadavpur University, Kolkata, in 1995. The Author further elaborated the analysis of the E-M system and presented the Kinematic Model of the E-M System at World Science Congress, Houston, in 2002. In 2004, at the 35th Scientific assembly of COSPAR, Author presented the New Perspective on Birth and Evolution of our Solar System and exo-planetary systems. In 2012, at the 39th Scientific Assembly at Mysore,India, paper B03- 0011-12, "Iapetus sub-satellite revisited and it reveals the celestial body formation in Primary Centric Framework. In 2017,at CELMEC VII, Rome, the Advanced Kinematic Model of Earth-Moon System was presented and finally published in Journal Of Geography And Natural Disasters where the perfect match between the Observed LOD curve and Theoretical LOD curve was achieved. A sequential paper on the Past, Present and Future of Earth-Moon Globe Orbit Dynamics and its habitability was published in JMTCM. The present paper is a paper in the same series where the author is trying to study different binary systems in Primary-Centric Framework.

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