Milisecond Pulsars and Gravitational Radiation

Luis Padilla González

Universidad de Valparaíso

February 28, 2023

Overview

Introduction

- 1967 First observed **puls**ating **r**adio source by Jocelyn Bell.
- periods between 0.25 s and 1.3 s
- Emits beams of electromagnetic radiation out of its magnetic poles. ▸ Link

Up until 1982, most of the ~ 300 known pulsars had similar periods. But ...

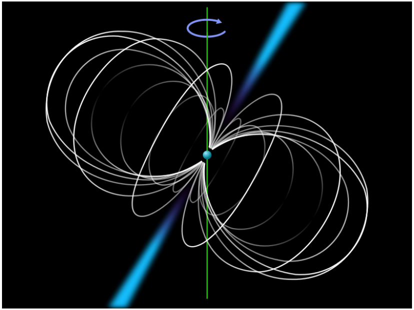


Figure 1: Schematic view of a pulsar

Pulsars

Exceptions:

- Crab pulsar (1054A.D). period 33 ms
- Vela pulsar. period 89 ms
- Hulse-Taylor binary pulsar. period 59 ms

Crab and Vela pulsars had rapid slow-down rates.
Pulsars are rotating neutron stars, born in supernova explosions with periods 10-20 ms and gradually slowing down to periods of 1 s over million years.

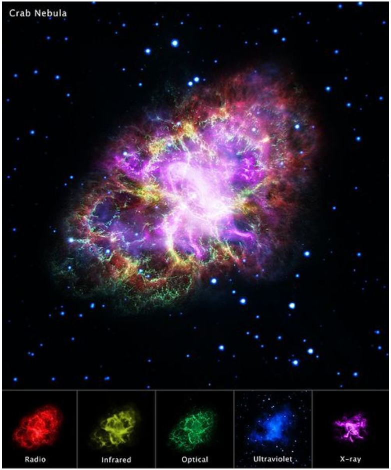


Figure 2: The Crab Nebula - five observatories (2017)

Milisecond Pulsars

Milisecond Pulsar (MSP) 1937+21:

- period 1.558 ms (642 times per second)
- resulted from "recycling" of an old, slowly rotating neutron star through accretion from a low-mass companion.
- Mass transferred from the companion also carries angular momentum from the orbit to the neutron star, spinning it up and reactivating the pulsar emission process.

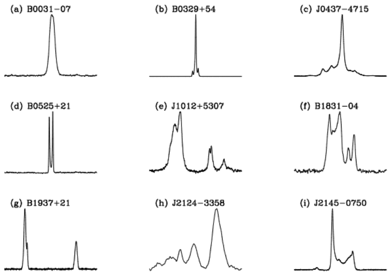


Figure 3: pulse profiles. Lorimer 2005

Milisecond Pulsars

Abscence of binary companion:

- Disruption of the binary by asymmetric mass loss in acretion-induced collapse of likely WD remnant of companion star → Ablation of companion
- "Black widow" pulsar PSR B1957+20

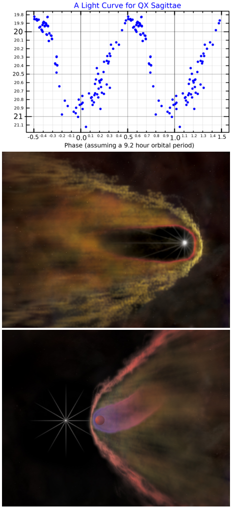


Figure 4: PSR B1957+20

$P - \dot{P}$ diagram

- over 1500 pulsars
- differences in magnetic fields and ages.
- magnetic field strengths $B \propto (P\dot{P})^{0.5}$
- characteristic age $\tau_c = P/(2\dot{P})$

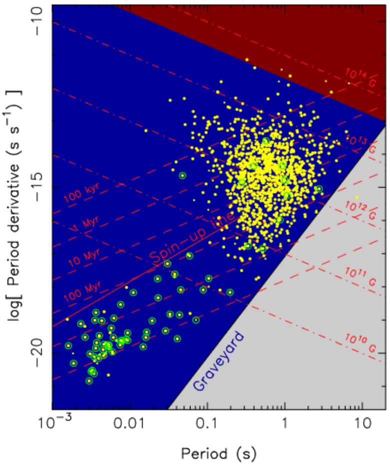


Figure 5: $P - \dot{P}$ diagram, M. Kramer

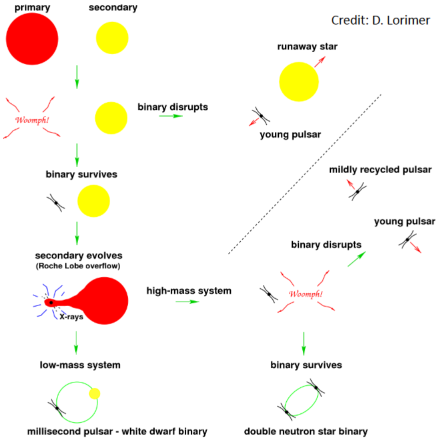


Figure 6: evolutionary scenarios

Pulsars:

1. Mildly recycled pulsars ($P > 20$ ms) with heavy companion (neutron star).
2. Fully recycled pulsars ($P < 20$ ms). MSPs, with light companion (white dwarf)
3. Pulsar-black hole possible

Companion of binary pulsars found so far: white dwarf, neutron star, pulsar, main-sequence star, planet.

Binary evolution tree

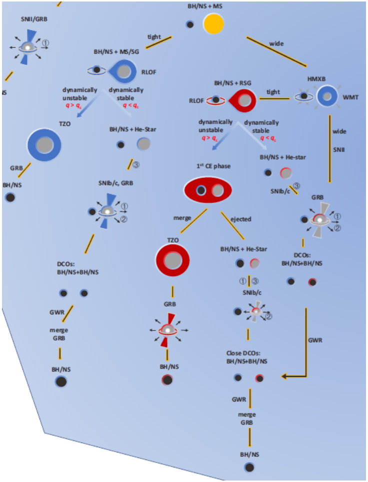


Figure 7: Binary evolution tree. Han, et al.

Timing binary Pulsars

5 post-Keplerian (PK) parameters. (Pb, x, e, w and T0)

Constraints on the masses of the pulsar $m_{\rm p}$ and the orbiting companion $m_{\rm c}$ can be placed by combining x and $P_{\rm b}$ to obtain the mass function

$$f_{\rm mass} = \frac{4\pi^2}{G}\frac{x^3}{P_{\rm b}^2} = \frac{(m_{\rm c}\sin i)^3}{(m_{\rm p}+m_{\rm c})^2}, \tag{11}$$

relativity (GR) the PK formalism gives the relativistic advance of periastron

$$\dot{\omega} = 3\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}, \tag{12}$$

the time dilation and gravitational redshift parameter

$$\gamma = e\left(\frac{P_{\rm b}}{2\pi}\right)^{1/3}T_\odot^{2/3}M^{-4/3}m_{\rm c}(m_{\rm p}+2m_{\rm c}), \tag{13}$$

the rate of orbital decay due to gravitational radiation

$$\dot{P}_{\rm b} = -\frac{192\pi}{5}\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}T_\odot^{5/3}m_{\rm p}m_{\rm c}M^{-1/3} \tag{14}$$

key point: given precisely measured Keplerian parameter, the only two unknows are the masses of pulsar and companion.

Testing General Relativity

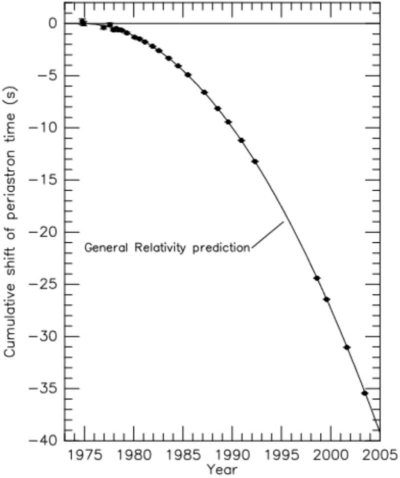


Figure 8: Orbital decay in binary pulsar B1913+16

- Hulse & Taylor 1974.
- comparing third PK parameter with predicted value based on masses of other two.
- Measurments within 0.2% of GR prediction.
- First indirect evidence of gravitational waves.

EM waves and GW contrasted

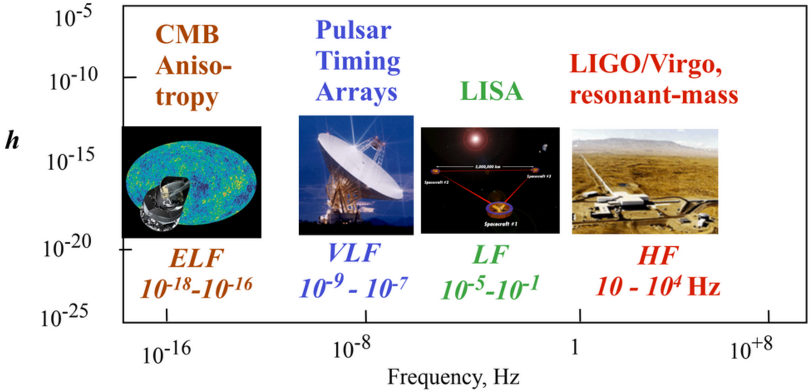
Electromagnetic waves

- Oscillations of EM field propagating through spacetime
- Incoherent superposition of waves
- easily absorbed and scattered
- Most detectors very large compared to wavelength. Narrow field of view. Good angular resolution

Gravitational waves

- Oscillations of “fabric” of spacetime itself.
- Coherent emission by bulk motion of matter.
- Never significantly absorbed or scattered.
- Most detectors small compared to wavelength . See entire sky at once. Poor angular resolution.

Frecuency Bands and detectors



Gravitational Waves

- The gravitational-wave field, h_{jk}^{GW}

  Symmetric, transverse, traceless (TT);
  two polarizations: +, x

- + Polarization

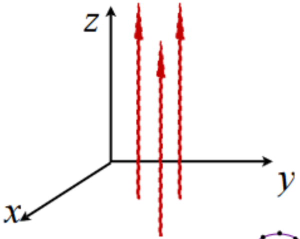
$$h_{xx}^{\mathrm{GW}} = h_+(t - z/c) = h_+(t - z)$$
$$h_{yy}^{\mathrm{GW}} = -h_+(t - z)$$

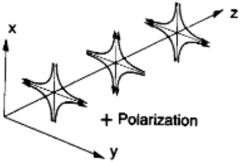
Lines of force

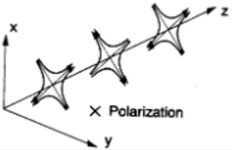
$$\ddot{x}_j = \frac{1}{2}\ddot{h}_{jk}^{\mathrm{GW}} x_k \qquad \ddot{x} = \ddot{h}_+ x \qquad \ddot{y} = -\ddot{h}_+ y$$

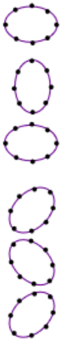
- x Polarization

$$h_{xy}^{\mathrm{GW}} = h_{yx}^{\mathrm{GW}} = h_\times(t - z)$$





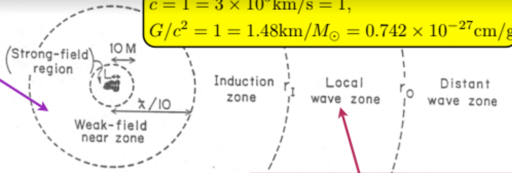




GW Generation

$$\boxed{\Phi = -\frac{M}{r} - \frac{3}{2}\frac{\mathcal{I}_{jk} n_j n_k}{r^3} + \dots}$$

quadrupole moment



$$\boxed{c = 1 = 3 \times 10^5 \mathrm{km/s} = 1, \quad G/c^2 = 1 = 1.48 \mathrm{km}/M_\odot = 0.742 \times 10^{-27} \mathrm{cm/g}}$$

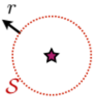
for Newtonian source $\mathcal{I}^{\rm GW}_{jk} = \int \rho \left(x^j x^k - \frac{1}{3} r^2 \delta_{jk} \right) d^3x$

$$\boxed{h^{\rm GW}_{jk} = 2 \left(\frac{\ddot{\mathcal{I}}_{jk}(t-r)}{r} \right)^{TT}}$$

$$\boxed{h^{\rm GW}_{jk} \sim h_+ \sim h_\times \sim \frac{E^{\rm quad}_{\rm kin}/c^2}{r} \sim 10^{-21} \left(\frac{E^{\rm quad}_{\rm kin}}{M_\odot c^2} \right) \left(\frac{100 \mathrm{Mpc}}{r} \right)}$$

$$\boxed{h_+ = \frac{\ddot{\mathcal{I}}_{\theta\theta} - \ddot{\mathcal{I}}_{\varphi\varphi}}{r}, \quad h_\times = \frac{2\ddot{\mathcal{I}}_{\theta\varphi}}{r}}$$

$$\frac{dM}{dt} = -\frac{dE_{\rm GW}}{dt} = -\oint_S T^{tr}_{\rm GW} dA = -\frac{1}{16\pi} \oint_S \langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle dA$$



$$\boxed{\frac{dE_{\rm GW}}{dt} = \frac{1}{5} \dddot{\mathcal{I}}_{jk} \dddot{\mathcal{I}}_{jk}}$$

$$\boxed{\frac{dE_{\rm GW}}{dt} \sim \mathcal{P}_o \left(\frac{\mathcal{P}^{\rm quad}}{\mathcal{P}_o} \right)^2}$$

Internal power flow in quadrupolar motions

$$\mathcal{P}_o = \frac{c^5}{G} = 3.6 \times 10^{52} \mathrm{W} = 3.6 \times 10^{59} \mathrm{erg/s} \sim 10^{27} L_\odot \sim 10^7 L_{\rm EM\ universe}$$

- **Me waving my arms**

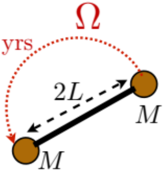
$$\mathcal{P}^{\rm quad} \sim \frac{(10\ {\rm kg})(5\ {\rm m/s})^2}{1/3\ {\rm s}} \sim 100{\rm W}$$

$$\frac{dE_{\rm GW}}{dt} \sim 4\times 10^{52}\ {\rm W}\left(\frac{100\ {\rm W}}{4\times 10^{52}\ {\rm W}}\right)^2 \sim 10^{-49}\ {\rm W}$$

Each graviton carries an energy

$$\hbar\omega = (7\times 10^{-34}{\rm joule\ s})(2Hz) \sim 10^{-33}{\rm joule}$$

I emit 10^{-16}gravitons s^{-1} $\sim$ 3 gravitons each 1 billion yrs



- **A rotating two tonne dumb bell**

$$M = 10^3{\rm kg}, \quad L = 5{\rm m}, \quad \Omega = 2\pi\times 10/s$$

$$\mathcal{P}^{\rm quad} \sim \Omega\, M(L\Omega)^2 \sim 10^{10}\ {\rm W}$$

$$\frac{dE_{\rm GW}}{dt} \sim 4\times 10^{52}\ {\rm W}\left(\frac{10^{10}\ {\rm W}}{4\times 10^{52}\ {\rm W}}\right)^2 \sim 10^{-33}\ {\rm W} \quad \hbar\,(2\Omega) \sim 10^{-32}{\rm joule}$$

$\boxed{\text{1 graviton emitted each 10 s}}$ $\boxed{\text{At } r = (1\text{ wavelength}) = 10^4\text{ km, } h_+ \sim h_\times \sim 10^{-43}}$

Generation and detection of GWs in lab is hopeless

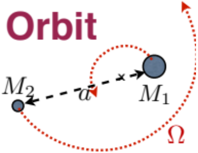
Binary Star System: Circular Orbit

$$I_{jk} = \int \rho x_j x_k d^3x \qquad \text{trace} = \mu a^2 = \text{const}$$

$$I_{xx} = \mu a^2 \cos^2 \Omega t, \; I_{yy} = \mu a^2 \sin^2 \Omega t, \; I_{xy} = \mu a^2 \cos \Omega t \sin \Omega t$$

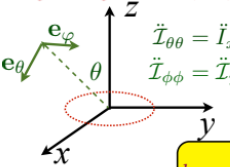
$$\ddot{\mathcal{I}}_{xx} = \ddot{I}_{xx} = -2\mu(a\Omega)^2 \cos 2\Omega t, \; \ddot{\mathcal{I}}_{yy} = \ddot{I}_{yy} = 2\mu(a\Omega)^2 \cos 2\Omega t$$

$$\ddot{\mathcal{I}}_{xy} = \ddot{I}_{xy} = -2\mu(a\Omega)^2 \sin 2\Omega t$$



$$M = M_1 + M_2$$

$$\mu = \frac{M_1 M_2}{M}, \Omega = \sqrt{M/a^3}$$



$$\ddot{\mathcal{I}}_{\theta\theta} = \ddot{\mathcal{I}}_{xx} \cos^2 \theta + \overset{0}{\ddot{\mathcal{I}}_{zz}} \sin^2 \theta$$

$$\ddot{\mathcal{I}}_{\phi\phi} = \ddot{\mathcal{I}}_{yy}, \; \ddot{\mathcal{I}}_{\theta\phi} = \ddot{\mathcal{I}}_{xy} \cos \theta$$

$$f = \frac{2\Omega}{2\pi} = \frac{1}{\pi}\sqrt{\frac{M}{a^3}} = 200\text{Hz} \left(\frac{10 M_\odot}{M}\right) \left(\frac{10M}{a}\right)^{3/2}$$

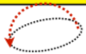
$= 10^{-4}$ to 10^{-3} Hz for EM-observed compact binaries

$= 30$ to 3000 Hz for final stages of NS/NS, BH/BH

$$h_+ = 2\frac{\ddot{\mathcal{I}}^{TT}_{\theta\theta}}{r} = \frac{(\ddot{\mathcal{I}}_{\theta\theta} - \ddot{\mathcal{I}}_{\varphi\varphi})}{r} = -2(1+\cos^2\theta)\frac{\mu(a\Omega)^2}{r} \cos 2\Omega(t-r)$$

$$h_\times = 2\frac{\ddot{\mathcal{I}}^{TT}_{\theta\phi}}{r} = -4\cos\theta \frac{\mu(a\Omega)^2}{r} \sin 2\Omega(t-r)$$

- Angular dependence comes from TT projection



- As seen from above, θ=0, circular polarized: $h_+ = A\cos 2\Omega t, \; h_\times = A \sin 2\Omega$
- As seen edge on, θ=π/2, linear polarized: $h_+ = A\cos 2\Omega t, \; h_\times = 0$

Binary Star System

- **Energy Loss ⇒Inspiral; frequency increase: "Chirp"**

$$\frac{dE_{\rm GW}}{dt} = \frac{1}{5}\left[(\dddot{\mathcal{I}}_{xx})^2 + (\dddot{\mathcal{I}}_{yy})^2 + 2(\dddot{\mathcal{I}}_{xy})^2\right] = \frac{32}{5}\mu^2 a^4 \Omega^6 = \frac{32}{5}\frac{\mu^2 M^3}{a^5}$$

$$\frac{dE_{\rm binary}}{dt} = \frac{d}{dt}\left(\frac{-\mu M}{2a}\right) = -\frac{32}{5}\frac{\mu^2 M^3}{a^5}$$

$$a = a_o(1 - t/\tau)^{1/4}, \qquad \tau_o = \frac{5}{256}\frac{a_o^4}{\mu M^2} = \frac{5\mathcal{M}}{256(\mathcal{M}\Omega)^{8/3}} \qquad \boxed{\mathcal{M} = \text{chirp mass} = \mu^{3/5}M^{2/5}}$$

- **Observables:**
  - from h_+ & $h_\times \sim \cos(2\Omega t + \text{phase})$: **GW frequency f=Ω/π**
  - from df/dt = -3f/8τ_o: **Time to merger τ_o and chirp mass $\mathcal{M}$**
  - from GW amplitudes $h_+^{\rm amp} = -2(1+\cos\theta)\frac{\mu(a\Omega)^2}{r} = -2(1+\cos\theta)\frac{\mathcal{M}(\pi\mathcal{M}f)^{2/3}}{r}$ and $h_\times^{\rm amp} = -4\cos\theta\frac{\mathcal{M}(\pi\mathcal{M}f)^{2/3}}{r}$: **Orbital inclination angle θ and distance to source *r***
- **At Cosmological Distances:** $\mathcal{M}(1+z)$, **Luminosity distance**
  - complementary to EM astronomy, where z is the observable

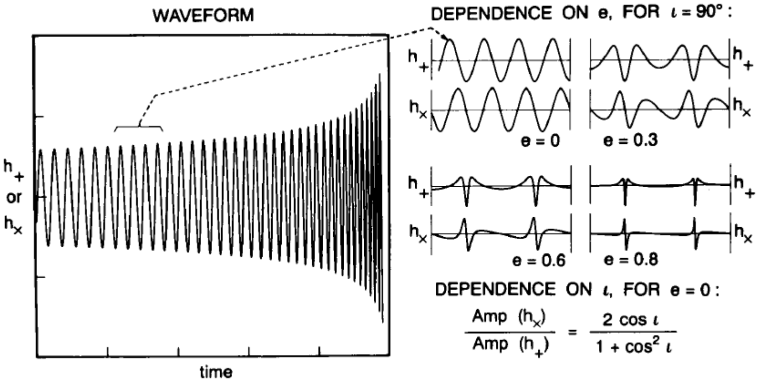


Figure 9: Waveforms from the inspiral of compact binary. Newtonian Gravity for orbital evolution. Quadpole-moment approximation for wave generation.

High-Spin High-Mass Xray Binaries

DRAFT VERSION JULY 29, 2022
Typeset using LaTeX **twocolumn** style in AASTeX63

Do high-spin high mass X-ray binaries contribute to the population of merging binary black holes?

MONICA GALLEGOS-GARCIA,[1,2] MAYA FISHBACH,[2] VICKY KALOGERA,[1,2] CHRISTOPHER P L BERRY,[3,2] AND ZOHEYR DOCTOR[2]

[1] *Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA*
[2] *Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA),1800 Sherman, Evanston, IL 60201, USA*
[3] *SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK*

ABSTRACT

Gravitational-wave observations of binary black hole (BBH) systems point to black hole spin magnitudes being relatively low. These measurements appear in tension with high spin measurements for high-mass X-ray binaries (HMXBs). We use grids of `MESA` simulations combined with the rapid population-synthesis code `COSMIC` to examine the origin of these two binary populations. It has been suggested that Case-A mass transfer while both stars are on the main sequence can form high-spin BHs in HMXBs. Assuming this formation channel, we show that depending on critical mass ratios for the stability of mass transfer, 48–100% of these Case-A HMXBs merge during the common-envelope phase and up to 42% result in binaries too wide to merge within a Hubble time. Both `MESA` and `COSMIC` show that high-spin HMXBs formed through Case-A mass transfer can only form merging BBHs within a small parameter space where mass transfer can lead to enough orbital shrinkage to merge within a Hubble time. We find that only up to 11% of these Case-A HMXBs result in BBH mergers, and at most 20% of BBH mergers came from Case-A HMXBs. Therefore, it is not surprising that these two spin distributions are observed to be different.

High-Spin High-Mass Xray Binaries

Our main conclusions are:

1. Case-A HMXBs do not tend to form BBHs. When using only `COSMIC` simulations to model the full binary evolution, we find that at most 2% of Case-A HMXBs result in BBHs. When combining the `COSMIC` population with grids of BH–H-rich star `MESA` simulations, we find at most 12% form BBHs.

2. Case-A HMXBs contribute only a small fraction to the total merging BBH population. When considering all the BBHs for the range of masses investigated here, only 7% had a Case-A HMXB progenitor. When considering the individual mass ranges, the most massive H-rich donor, $M_{\rm donor} = (45 \pm 2.5) M_\odot$, had the largest fraction with at most 20% of BBHs having a Case-A HMXB progenitor.

3. The scenario of Case-A MT while both stars are on the MS allows for the formation of high-spin HMXBs while forming a minority of BBHs, such that the expected population of GW sources would contain primarily low-spin BHs.

Referencias

Duncan Lorimer
Binary and Milisecond Pulsars
Max Planck Institute for Gravitational Physics

Kip S. Thorne
Gravitational Radiation: A New Window Onto the Universe
California Institute of Technology, Pasadena, CA 91125 USA

Thanks for your attention