Compact Binaries as Gravitational-Wave Sources

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Extreme Astrophysics for All
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Outline

Introduction

Double-neutron-star systems = NS-NS binaries

Neutron star – white dwarf binaries = NS-WD binaries

Black hole binaries (e.g. NS-BH, BH-BH binaries)

this work is to be done in Lund with Melvyn Davies

Collaborators: Vicky Kalogera (Northwestern), Richard O’Shaughnessy (PSU),
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Compact binaries as GW sources

Gravitational-wave detectors based on laser interferometry: ground-based (LIGO,GEO,VIRGO,TAMA), and space-borne (LISA)

Detection freq ~ 100 - 1000 Hz
NS-NS, NS-BH binaries

Detection freq ~ 0.0001 - 0.1 Hz
NS-WD binaries
Pulsar binaries and the detection of gravitational waves

Consider merging binaries \((m_{\text{rg}} < \text{Hubble time})\)

Source merger rate

GW detection rate for LIGO

PSR B1913+16

Weisberg & Taylor (2003)
Consider merging binaries ($\tau_{\text{mrg}} < \text{Hubble time}$)

Source merger rate $R$

$GW$ detection rate for LIGO
Merger Rate $R$

$$R = \frac{\text{Population size (} N_{\text{pop}} \text{)} \times \text{PSR beaming correction factor (} f_b \text{)}}{\text{Lifetime of a system (} \tau_{\text{life}} \text{)}}$$

- $N_{\text{pop}}$ : number of pulsars in ‘merging’ binaries in disk

- $\tau_{\text{life}} = \text{current age} + \text{merging time}$
  - of a pulsar
  - of a system

Merging binaries: merging timescale $< \text{age of the Universe}$
(e.g., PSR J0737-3039; merging timescale $= 85 \text{ Myr}$)

$\tau_{\text{life}}$ and $f_b$ can be estimated from observations.
We calculate $N_{\text{pop}}$ using a Monte-Carlo method.
Detected or Not?

Fix spin period, pulse width, and orbital period of model binaries in order to mimic one of the known system (e.g. J0737-3039A)

Calculate \( S_{\text{PSR}} = \frac{L}{d^2} \) (flux density) a model pulsar

for a pulsar \( i \) \((x,y,z,L)_i\)

\[
d = (x^2+y^2+z^2)^{1/2}
\]

Calculate a survey sensitivity using a “radiometer equation”

\[
S_{\text{min}} = \frac{S/N_{\text{min}}}{\eta \sqrt{n_{\text{pol}}}} \left( \frac{T_{\text{rec}} + T_{\text{sky}}}{K} \right) \left( \frac{G}{K \text{ Jy}^{-1}} \right)^{-1} \left( \frac{\Delta \nu}{\text{MHz}} \right)^{-1/2} \left( \frac{t_{\text{int}}}{s} \right)^{-1/2} \left( \frac{W}{P-W} \right)^{1/2} \text{ mJy,}
\]

\( S_{\text{min}} \): Minimum detectable flux of a survey

**Compare** \( S_{\text{PSR}} \) and \( S_{\text{min}} \)

A model pulsar is considered to be “detected”, if \( S_{\text{PSR}} > S_{\text{min}} \)
Detected or Not?

PSR B1913+16 like pulsars with different (x,y,z,L)
calculate $N_{PSR}$ that is consistent with "1 detection"

$P_i(N_{pop})$  \[\text{chain rule}\]  $P_i(R)$

$R \propto \frac{N_{pop}}{\text{lifetime}}$
Probability density function of $R$
Galactic merger rate of NS-NS binaries

As of 2009 February, there are 5 merging NS-NS binaries known in the Galactic disk.

PSRs B1913+16, B1534+12, J0737-3039, and J1906+0731 (PSR J1756-2251 is ignored in this work)

\[ P_i(R) = C_i^2 R \exp(-C_i R) \] and \( i = 1, 2, 3, 4 \)

\[ P(R_{tot}) = \int dR_1 dR_2 dR_3 dR_4 \delta(R_{tot} - R_1 - R_2 - R_3 - R_4) \times P_1(R_1) P_2(R_2) P_3(R_3) P_4(R_4) \]
$P(R) = \text{PSR}1913 + \text{PSR}1534 + \text{PSR}0737 + \text{PSR}1906$

Galactic NS-NS merger rate (Myr$^{-1}$)

$N_{J1534} \sim 400$
$N_{J1913} \sim 600$
$N_{J1906} \sim 300$
$N_{J0737} \sim 1800$

Lifetime \sim 82\text{ Myr}
Lifetime \sim 230\text{ Myr}
$R_{\text{peak}} = 120 \text{ per}$

Galactic NS-NS merger rate (Myr$^{-1}$)
Detection rate of NS-NS inspirals for LIGO

\[ R_{\text{det}} \sim R_{\text{NS-NS}} \times \text{detection volume} \]

Max. detection distance (ini. LIGO) \(= 20 \text{ Mpc} \)
(adv. LIGO) \(= 350 \text{ Mpc} \) \(\text{(Finn 2001)}\)

Reference model @ peak:

\[ R_{\text{det}} \text{ (ini. LIGO)} \sim 1 \text{ event per century} \]
\[ R_{\text{det}} \text{ (adv. LIGO)} \sim 270 \text{ events per yr (\sim 20 events per month)} \]

Reference model @ 95% upper limit

\[ R_{\text{det}} \text{ (ini. LIGO)} \sim 1 \text{ event per 10 yr} \]
\[ R_{\text{det}} \text{ (adv. LIGO)} \sim 660 \text{ events per yr (\sim 2 events per day)} \]
NS-WD binaries as GW sources for LISA

• The GW background
due to the large number of sources
limits the detectability of weak sources
in GW frequencies below 3 mHz

\[ h_{\text{rms}}(f) \approx 1.7 \times 10^{-26} \left( \frac{M}{M_\odot} \right)^{5/6} \left( \frac{f}{\text{mHz}} \right)^{-7/6} \left( \frac{N_0}{\text{Mpc}^{-3}} \right)^{1/2} \left( \frac{T_{\text{obs}}}{\text{yr}} \right)^{-1/2} \]

GW amplitude chirp mass GW freq. source number density observation time

We calculate \( N_0 \) relevant to NS-WD binaries (up to \( z = 5 \))
considering, PSRs J0751+1807, J1757-5322, and J1141-6545
GW signals from NS-WD binaries

The contribution from NS-WD binaries to the GW background would be negligible.

Detection distance for advanced LIGO:
NS-NS (1.4 $M_{\text{sun}}$) $\sim$ up to 350 Mpc
NS-BH (10 $M_{\text{sun}}$) $\sim$ up to 740 Mpc
(almost an order of magnitude increase in $V_{\text{det}}$)

$h \sim \frac{M_{\text{chirp}} f^2}{d}$

h: GW amplitude
f: GW frequency $= 2/P_{\text{orb}}$
d: distance to the source
$M_{\text{chirp}}$: chirp mass

NS-BH binaries
**NS-BH binaries**

\[ h \sim \frac{M_{\text{chirp}} f^2}{d} \]

- \( h \): GW amplitude
- \( f \): GW frequency = \( 2/P_{\text{orb}} \)
- \( d \): distance to the source
- \( M_{\text{chirp}} \): chirp mass

BH binaries (BH-BH, BH-NS) are even stronger GW sources than NS binaries. However, they have not yet been observed.
Constraining theoretical models (to be done with M Davies)


More than 92% models are ruled out by Galactic NS-NS merger rate

Detection rates for BH-NS binaries:
~ 1 event per decade to 1000 years (initial LIGO)
~ 100 event per year (Advanced LIGO/Virgo)

Use only these models to explore BH binaries

Parameter space used in theoretical models for a binary evolution

Accepted range of parameters
Summary

• Compact binaries are strong sources of gravitational waves.

• Pulsar binaries provide indirect evidence of GWs.

• NS-NS binaries are prime targets for the GW detectors.

• The Galactic merger rate of NS-NS binaries is most likely to be ~120 per Myr.
The next generation of GW detectors will be able to detect GW signals from NS-NS inspirals in next decade!

• NS-WD binaries emit GW in low frequencies (~mHz) that is within a LISA frequency band. The GW background formed by cosmic NS-WD binaries are negligible comparing with that of WD-WD binaries in our Galaxy.
Future Work in Lund

• Developing a realistic Galactic pulsar model & pulsar survey model

• Obtaining the “best” empirical rate estimates for known pulsar populations in our Galaxy (e.g. globular cluster pulsars vs disk pulsars)

• Constraining theoretical models by applying empirical merger rates as well as known properties of pulsar binaries. This work will be useful to calculate GW detection rates relevant to BH binaries.