Theory of Gamma-Ray Burst

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Understanding Nature’s High-Energy Particles and Radiation
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Physical Picture: A Sketch

Increasingly difficult to diagnose with electromagnetic signals
Open Questions in GRB Physics

• **Progenitor** (massive star core collapse vs. compact star mergers)
• **Central engine** (black hole vs millisecond magnetar)
• **Ejecta composition** (fireball vs. Poynting flux)
• **Energy dissipation mechanism** (shock vs. magnetic reconnection)
• **Particle acceleration & radiation mechanisms** (synchrotron, inverse Compton, quasi-thermal)
• **Afterglow**
Progenitors
Two Progenitor Models

Massive Star Core Collapse
(Eichler et al. 89; Narayan et al. 92 ...)

NS-NS or BH-NS Merger
(Woosley 93; Paczynsky 98 ...)

Massive Star Core Collapse
(Woosley 93; Paczynsky 98 ...)
Gehrels Question:  
(Nov. 10, 2016)

“Are short GRBs made from NS-NS or BH-NS mergers?”

Cornelis A Gehrels  
GW170817 – GRB 170817A

The 90% credible intervals (Veitch et al. 2015; Abbott et al. 2017e) for the component masses (in the mm\textsubscript{12} convention) are \(m_{1} = 1.36, 2.26\) and \(m_{2} = 0.86, 1.36\), with total mass \(M = 2.82_{-0.09}^{+0.47}\). When considering dimensionless spin with magnitudes up to 0.89 (high-spin prior, hereafter), when the dimensionless spin prior is restricted to 0.05 (low-spin prior, hereafter), the measured component masses are \(m_{1} = 1.36, 1\) and \(m_{2} = 1.17, 1.36\), and the total mass is \(M = 1.60\).

At least some NS-NS mergers can make some low-L short GRBs!

Intriguing GRB 170817A

- An otherwise normal short GRB
  - Nothing special if not coinciding with GW 170817
- Many similar sGRBs in GBM archives

B.-B. Zhang et al. arXiv: 1710.05851
Intriguing GRB 170817A

- Extremely low luminosity: $1.7 \times 10^{47}$ erg/s
- Short GRB luminosity covers 7 orders of magnitude!
- Luminosity function is consistent with one simple power law!

B.-B. Zhang et al. arXiv: 1710.05851
Event rate densities of sGRBs & NS-NS mergers

- A factor of ~6 lower
- There might be several more low-luminosity sGRBs in the GBM archives?
- But not many (limited by the NS-NS merger event rate density)

METHODS

sGRB event rate density: The anomalously low luminosity and extremely small distance of GRB 170817A suggest that the event rate density of short GRBs is large. With one detection, we can estimate the event rate density $\rho_{\text{sGRB}}$ of short GRBs through

$$N_{\text{GRB}} = \frac{\Omega_{\text{GBM}} T_{\text{GBM}}}{4\pi} \rho_{\text{sGRB}} V_{\text{max}} \geq 1$$

The field of view of GBM is approximately taken as full sky with $\Omega_{\text{GBM}} \approx 4\pi$. The working time of GBM is taken since 2008 with a duty cycle of ~50%, so that $T_{\text{GBM}} \approx 4.5$ yrs. The maximum volume a telescope can detect for this low luminosity event is $V_{\text{max}} = 4\pi D_{\text{L,max}}^2/3$. We simulate a set of pseudo-GRBs by placing GRB 170817A to progressively larger distances, and find that the signal would not be detectable at 65 Mpc (Supplementary Information). Taking this distance as $D_{\text{L,max}}$, we derive the event rate density of GRBs [6]

$$\rho_{\text{sGRB}}(L_{\text{iso}} > 1.7 \times 10^{50} \text{erg s}^{-1}) \geq 190^{+145}_{-22} \text{Gpc}^{-3} \text{yr}^{-1}.$$  

The event rate density of NS-NS mergers may also be estimated based on one detection by aLIGO during O1 and O2. Since only one NS-NS merger event was detected [8], one may write

$$N_{\text{NS-NS}} = \frac{\Omega_{\text{LIGO}}}{4\pi} \rho_{\text{NS-NS}} (V_{\text{max,O1}} T_{\text{O1}} + V_{\text{max,O2}} T_{\text{O2}}) = 1.$$  

Noticing $\Omega = 4\pi$ for GW detectors, taking NS-NS merger horizon ~ 60 Mpc and ~ 80 Mpc for O1 and O2, respectively, and adopting a duty cycle of ~40% for both O1 and O2, we estimate

$$\rho_{\text{NS-NS}} = 1100^{+280}_{-150} \text{Gpc}^{-3} \text{yr}^{-1}.$$  

This is consistent with the NS-NS merger event rate density derived by the LIGO team using more sophisticated simulations [8]. This rate is greater than the event rate density of GRB 170817A-like events. This either suggests that there might be even less luminous sGRBs than GRB 170817A, or there might be similar sGRBs hidden in the GBM archives that are associated with NS-NS mergers. The number of these events is at most a few.

B.-B. Zhang et al. arXiv: 1710.05851
Why low luminosity?

- A large angle
  - uniform jet viewed from outside?
  - Structured jet viewed from a large angle?
  - Cocoon? (luminosity function? Delay time and duration?)

B.-B. Zhang et al. arXiv: 1710.05851

\[
\frac{t(\text{off} - \text{beam})}{t(\text{on} - \text{beam})} = \frac{D(\theta = 0)}{D(\theta = \theta_v - \theta_j)} = \frac{1 - \beta \cos(\theta_v - \theta_j)}{1 - \beta},
\]

LIGO-Virgo-GBM-INTEGRAL arXiv: 1710.05834
• Delay time: ~1.7 s
• Duration: ~2 s

• Total mass: $2.74 \pm 0.04 - 0.01$
• Merger product: cannot be constrained, but likely a BH
  • Mass is too large
  • No strong evidence of magnetar emission from sGRB & kilonova

• Disfavor the photosphere origin of the GRB: predicted delay time ~ ms (B. B. Zhang et al. arXiv: 1710.05834)
• Disfavor the cocoon shock breakout origin of GRB: delay time should be $R/(0.1 \, c)$, much longer than the duration ($R/ \Gamma^2 \, c$)

• A magnetic bubble (structured jet) squeezed out from the surrounding wind viewed off axis.
Central engine
GRB central engine requirements

- Energetic and luminous ($E_{\text{iso}} \sim 10^{50}-10^{55}$ erg, $L_{\text{iso}} \sim 10^{49}-10^{53}$ erg/s)
- Clean - relativistic ejecta ($\Gamma > 100$)
- Rapid variability, diverse temporal behavior
- Intermittent, delayed activity with reducing amplitudes
- A possible long-lasting steady component in some GRBs (due to spindown?)
Hyper-Accreting Black Hole vs. Millisecond magnetar

Neutrino annihilation

Spindown
Magnetic bubble eruption
Accretion?
How to tell a magnetar from a BH?

- Energy injection with constant luminosity
  - External plateau
  - Internal plateau

\[
L(t) = L_0 \frac{1}{(1 + t/T)^2} \approx \begin{cases} L_0, & t \ll \tau, \\ L_0(t/\tau)^{-2}, & t \gg \tau. \end{cases}
\]

\[
E_{\text{rot}} = \frac{1}{2} I \Omega_0^2 \approx 2 \times 10^{52} \text{ erg } M_{1.4} R_6^2 P_{0.3}^{-2},
\]

\[
L_0 = 1.0 \times 10^{49} \text{ erg s}^{-1} (B_{p,15}^2 P_{0.3}^{-4} R_6^6)
\]

\[
\tau = 2.05 \times 10^3 s (I_{45} B_{p,15}^{-2} P_{0.3}^2 R_6^{-6})
\]
How to tell a magnetar from a BH?

- Anti-correlation between plateau luminosity & break time
- Maximum (collimation-corrected energy)

\[ L(t) = L_0 \frac{1}{(1 + t/\tau)^2} \simeq \begin{cases} L_0, & t \ll \tau, \\ L_0(t/\tau)^{-2}, & t \gg \tau. \end{cases} \]

\[ E_{\text{rot}} = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52} \text{ erg} M_{1.4} R_6^2 P_0^{-2}, \]

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\[ \tau = 2.05 \times 10^3 s \left( I_{45} B_{p,15}^{-2} P_0^{-2} R_6^{-6} \right) \]

Lü & Zhang (2014)
Millisecond magnetars in short GRBs

- Some short GRBs have extended emission (EE) in gamma-rays
- Some others have internal plateaus.
- They are actually the same thing!
Origin of Prompt Emission

Jet Composition (matter vs. magnetic)
Energy dissipation (shock vs. reconnection)
Radiation Mechanisms (thermal, synchrotron, inverse Compton)
Prompt GRB Emission: Still a Mystery

What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, Compton scattering, thermal)?
Basic Theoretical Framework

Fig. 7.5: An energy flow chart for GRBs.

- Early on, a relativistic shock propagates into the jet itself and crosses the jet in a short duration of time.
- If the central engine is long-lived or if the ejecta has a Lorentz factor "stratification" (a wide distribution of $\Gamma$), the reverse shock can be long lived.
- Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

• The spatial range between the photosphere (included) and the external forward/reverse shocks (excluded) is called an internal emission site of a GRB.

GRB prompt emission likely originates from one or more internal emission regions. The radiation mechanism of prompt emission is an open question. The leading candidates include synchrotron radiation from an optically thin region, and a quasi-thermal, Comptonized emission near the photosphere. Synchrotron self-Compton (SSC), external inverse Compton (EIC), and hadronic cascade have been also discussed in the literature to account for (part of) the prompt emission spectra.

• The main radiation mechanism of afterglow emission has been identified as synchrotron radiation from the external shocks.

Figure 7.4 is a cartoon picture of the evolution of a GRB jet within this general theoretical framework. Figure 7.5 outlines the energy flow in a GRB jet, describing how various forms of energy convert from one to another and give rise to the observed radiation from GRBs.

**Energy Flow in GRBs**

![Energy Flow Diagram](energy_flow_diagram.png)
Basic Theoretical Framework

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**Energy Flow in GRBs**

- Gravitational
  - Thermal
    - Magnetic dissipation
    - Thermal acceleration
    - Photosphere emission
  - Kinetic
    - Magnetic acceleration
    - Magnetic dissipation
  - Radiation
- Spin (kinetic)
  - Poynting flux

**Fireball model**
Basic Theoretical Framework

Fig. 7.5: An energy flow chart for GRBs.

• Medium and a relativistic shock propagates into the medium. Early on a reverse shock propagates into the jet itself and crosses the jet in a short duration of time. If the central engine is long-lived or if the ejecta has a Lorentz factor “stratification” (a wide distribution of $\Gamma$), the reverse shock can be long lived. Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

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Energy Flow in GRBs

Magnetic photosphere model
Energy Flow in GRBs

Initially magnetized internal shock model
Energy Flow in GRBs

- Gravitational
- Thermal
- Spiral (kinetic)
- Poynting flux
- Kinetic
- Radiation
- Photopshere emission

Magnetic dissipation

ICMART

Internal collision-induced magnetic reconnection & turbulence (ICMART) model
Fireball shock model

(Paczynski, Meszaros, Rees, Piran …)

Progenitor

Central Engine

GRB prompt emission

photosphere

internal shocks

external shocks
(reverse)
(forward)

Afterglow
Fireball Predictions: Internal shock vs. photosphere

Meszaros & Rees (00)

Daigne & Mochkovitch (02)

Pe’er et al. (06)
The case of a fireball: GRB 090902B
(Abdo et al. 2009; Ryde et al. 2010; Zhang et al. 2011; Pe’er et al. 2012)

A clear photosphere emission component identified

Not very common
The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)

Emission suppressed

At most $1/(1+\sigma)$ energy released

At most $1/(1+\sigma)$ energy released

$1/(1+\sigma_{end})$ energy released

---

central engine
$R \sim 10^7$ cm
$\sigma = \sigma_0 >> 1$

photosphere
$R \sim 10^{11} - 10^{12}$ cm
$\sigma \leq \sigma_0$

early collisions
$R \sim 10^{13} - 10^{14}$ cm
$\sigma \sim 1 - 100$

ICMART region
$R \sim 10^{15} - 10^{16}$ cm
$\sigma_{ini} \sim 1 - 100$
$\sigma_{end} \leq 1$

External shock
$R \sim 10^{17}$ cm
$\sigma \leq 1$

---

Zhang & Yan (2011)
ICMART simulations:

* High efficiency
* Relativistic mini-jets

Deng et al. (2015)
ICMART simulations
(Deng et al., 2015)

\[(\Gamma_2 m_2 + \Gamma_1 m_1)(1 + \sigma_{ini}) = \Gamma_m (m_1 + m_2 + U')(1 + \sigma_{end})\]
\[(\Gamma_2 \beta_2 m_2 + \Gamma_1 \beta_1 m_1)(1 + \sigma_{ini}) = \Gamma_m \beta_m (m_1 + m_2 + U')(1 + \sigma_{end})\]

\[\eta_{ICMART} = \frac{\Gamma_m U'}{(\Gamma_1 m_1 c^2 + \Gamma_2 m_2 c^2)(1 + \sigma_{ini})} = \frac{1}{1 + \sigma_{end}} - \frac{\Gamma_m (m_1 + m_2)}{1 + \sigma_{end}} \frac{1}{1 + \sigma_{end}}(if \ \sigma_{ini} \gg 1).\]

Zhang & Yan (2011)

### TABLE 4
\(\sigma_{b,f} - \sigma_{b,i}\) RELATION AND THE ANALYTICAL VS. NUMERICAL EFFICIENCIES.

<table>
<thead>
<tr>
<th>\sigma_{b,i}</th>
<th>\sigma_{b,f}</th>
<th>Efficiency (analytical)</th>
<th>Efficiency (numerical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.16</td>
<td>35.7%</td>
<td>33.3%</td>
</tr>
<tr>
<td>16</td>
<td>1.33</td>
<td>37.3%</td>
<td>34.4%</td>
</tr>
<tr>
<td>24</td>
<td>1.49</td>
<td>36.4%</td>
<td>34.7%</td>
</tr>
</tbody>
</table>

Deng et al. (2015)
Non-existence or weak photosphere component

GRB 080916C, Abdo et al. (2009)

GRB 110721A, Axelsson et al. (2009)
Basic Theoretical Framework

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Medium, as a relativistic shock propagates into the medium. Early on a reverse shock propagates into the jet itself and crosses the jet in a short duration of time. If the central engine is long-lived or if the ejecta has a Lorentz factor “stratification” (a wide distribution of $\Gamma$), the reverse shock can be long lived. Emission from these external shocks powers the long-lasting afterglow emission of GRBs.

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Hybrid model
Hybrid model (thermal + non-thermal)

Big Picture: GRB jet composition

- GRB jets have diverse compositions:
  - Photosphere dominated (GRB 090902B), rare
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, 110721A)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)

Most GRBs have significant magnetization
The high-energy component

Inverse Compton of some kind, internal emission

Pe’er et al. 2012

GeV afterglow emission (Racusin’s talk)
The “Band” function spectrum

\[ N(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( -\frac{E}{E_0} \right), & E < (\alpha - \beta)E_0, \\
A \left[ \frac{(\alpha - \beta)E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp(\beta - \alpha) \left( \frac{E}{100 \text{ keV}} \right)^\beta, & E \geq (\alpha - \beta)E_0 
\end{cases} \]

Josh Grindley (The 2009 Fermi Symposium, Nov. 2-5, at the David Band special session):
Challenge to theorists: Find the physical meaning of “Band” function in 10 years!
Why so difficult?

Neither synchrotron nor photosphere can explain the distribution of low-energy photon index

\[ \nu F_\nu \text{ (keV/cm}^2\text{s)} \]

\[ \text{Energy (keV)} \]

\[ \nu F_\nu = \text{obs} \]

\[ \nu F_\nu = \text{peak} \]

\[ \nu F_\nu = \text{time integrated} \]

\[ \alpha \]

\[ \sigma \]

\[ \text{Low-energy spectral index} \]

\[ \# \text{GRBS} \]

**Simplest synchrotron prediction**

**Simplest photosphere prediction**

_Nava et al. (2011)_
Synchrotron Model:
Fast Cooling Spectrum Can Be Harder!
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- B is decreasing with radius
- Electrons are not in steady state
- Electron spectrum deviates significantly from -2 below the injection energy

Alternative solution via turbulence: Talk of Siyao Xu next
Synchrotron in a decreasing magnetic field
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- The entire emission region is streaming out. The magnetic field in the emission region decreases with radius (time).
- Clear hard-to-soft evolution during the rising phase and throughout

(Lu et al. 2012)
Synchrotron Model: “Band” Function
(Uhm & Zhang, 2014, Nature Physics, 10, 351)

- In the BATSE or GBM band, the spectrum mimics a “Band” function with “correct” indices: $\alpha \sim -1$, $\beta \sim -2.2$

Requirement: Large emission radius where $B$ is low!
“Band” Function is made from synchrotron
(B.-B. Zhang et al., 2016)

• Work directly with the data of GRB 130606B

Band & synchrotron model fits
Energy Flow in GRBs

Smoking gun of Poynting flux dissipation: **bulk acceleration** in the emission region
Curvature effect


\[ F_{\nu_{\text{obs}}} \propto t_{\text{obs}}^{-\hat{\alpha}} \nu_{\text{obs}}^{-\hat{\beta}}, \quad \hat{\alpha} = 2 + \hat{\beta}, \]

Kumar & Panaitescu (2000)

Only applies for constant Lorentz factor
Smoking gun: evidence of bulk acceleration in X-ray flares

Spectral lags in an accelerating jet

Non-detection of neutrinos by Icecube

- Icecube so far has not detected any high-energy neutrino associated with GRBs!
Polarization data

- Four bright GRBs with polarization detections in gamma-rays: GRB 100826A: 27% ± 11% (Yonetoku et al. 2011)
- Early optical emission has “residual” ~10% polarization from reverse shock (Steele et al. 2009; Uehara et al. 2012)
- Prompt optical emission 8.3% ± 0.3% polarization (Troja et al. 2017)
Conclusions

• **Progenitor** (core collapse vs. NS-NS mergers, BH-NS mergers?)
• **Central engine** (black hole vs. magnetar: maybe both can make GRBs)
• **Jet composition** (fireball vs. Poynting flux & hybrid; most GRB jets may contain non-negligible Poynting flux)
• **Energy dissipation mechanism** (shock vs. magnetic reconnection)
• **Particle acceleration** ($1^{\text{st}}, 2^{\text{nd}}, 1.5^{\text{th}}$ order Fermi)
• **Radiation mechanisms** (synchrotron, quasi-thermal Comptonization, SSC, EC, hadronic ... )
Backup slides
Table 9.1 Grading chart for three representative GRB prompt emission models.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>photosphere</th>
<th>IS</th>
<th>ICMART</th>
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<tbody>
<tr>
<td><strong>Lightcurve properties:</strong></td>
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<tr>
<td>Slow variability</td>
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<td>Fast variability</td>
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<td>Superposition</td>
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<td>$E_p$ evolution: hard-to-soft</td>
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<tr>
<td>$E_p$ evolution: tracking</td>
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<td>Yes(?)</td>
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<td>Spectral lags</td>
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<td>Power density spectrum</td>
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<td><strong>Spectral properties:</strong></td>
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<tr>
<td>Origin of $E_p$</td>
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<td>Yes</td>
<td>Yes</td>
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<tr>
<td>$\alpha \sim -1$</td>
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<td>$\alpha &gt; -2/3$</td>
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<td>No</td>
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<td><strong>Other properties:</strong></td>
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<td>three-parameter correlations</td>
<td>No(?)</td>
<td>No(?)</td>
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</table>
Constrain NS EoS using short GRB data

\[
M_{\text{max}} = M_{\text{TOV}}(1 + \alpha P^\beta),
\]

\[
P_c = \left(\frac{M_s - M_{\text{TOV}}}{\alpha M_{\text{TOV}}}\right)^{1/\beta}.
\]

\[
\dot{E} = I\Omega\dot{\Omega} = -\frac{32GI^2e^2\Omega^6}{5c^5} - \frac{B_p^2R^6\Omega^4}{6c^3},
\]

\[
L_b = \frac{\eta B_p^2R^6\Omega_{\text{col}}^4}{6c^3},
\]

- Use sGRB data
- Use known NS-NS mass distribution
- Assume end of internal plateau is the collapse time of surpamassive NSs
Constraints on NS-NS merger products from known short GRBs

- For one EoS (GM1)
- Maximum mass: $\sim 2.37 \, M_\odot$
- Initial spin: $\sim 1 \, \text{ms}$
- BH:SMNS:SNS $\sim 4:3:3$
- Surface B field: $\sim 10^{15} \, \text{G}$
- Ellipticity: 0.004-0.007
- Energy output in the EM channel: $10^{49} \, \text{–} \, 10^{52} \, \text{erg}$
- Other energy channels:
  - GW emission
  - Fall into BH

Gao, Zhang & Lu, 2016, PRD, 93, 044065
More Equations of State

Internal X-ray plateau in short GRBs: Signature of supramassive fast-rotating quark stars?

Ang Li$^{1,2}$*, Bing Zhang$^{2,3,4}$, Naï-Bo Zhang$^{5}$, He Gao$^{6}$, Bin Qi$^{5}$, Tong Liu$^{1,2}$


<table>
<thead>
<tr>
<th>EoS</th>
<th>$P_k$ (ms)</th>
<th>$I_k$ (10$^{45}$ g cm$^2$)</th>
<th>$M_{TOV}$ ($M_\odot$)</th>
<th>$R_{eq}$ (km)</th>
<th>$\alpha$ ($P^{-\beta}$)</th>
<th>$\beta$</th>
<th>$A$ ($P^{-B}$)</th>
<th>$B$ (km)</th>
<th>$C$ (km)</th>
<th>$a$ (ms)</th>
<th>$q$ (P$^{-1}$)</th>
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Degeneracy with EM data only, with GW, can greatly narrow down