High-mass Relativistic Binaries

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Variable Galactic Gamma-Ray Sources V

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Outline

1. Introduction
2. Conclusions
3. The basics
4. Beyond the basics

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High-mass relativistic binaries

- HMRB: High-mass relativistic binaries; **among the most luminous galactic sources**
- massive star+compact object(BH/NS)+relativistic outflows(jets/winds)
- characterized using analogies with AGN or PWN
- Recently, models have gone **beyond analogy** (star, orbit, geometry, MHD, radiation reprocessing...).

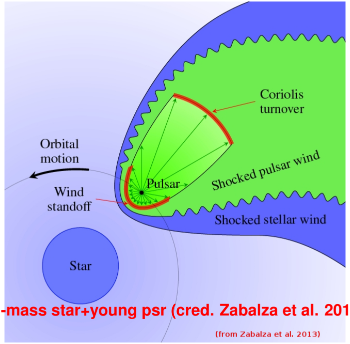
(e.g. B-R, Khangulyan, Aharonian, Barkov, Perucho + ...;

Bogovalov, + ...; Romero, + ...; Dubus, Lamberts, Cerutti + ...;

Sierpowska-Bartosik, Torres, + ...; Bednarek, + ...; Reitberger,

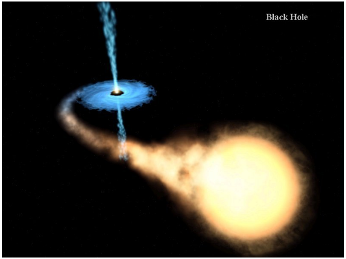
Reimer, + ...; Yoon, Heinz, + ...; Chernyakova, Neronov, + ...;

Takata, Kong, Cheng, + ...; etc.)



High-mass star+young psr (cred. Zabalza et al. 2013)

(from Zabalza et al. 2013)



High-mass microquasar (cred. ESA, NASA, F. Mirabel)

The most powerful HMRB

- The most powerful HMRB have compact objects of **unknown nature**.
- **LS 5039, 1FGL J1018.6−5856, LMC P3, and 4FGL J1405.1-6119**, are compact, hosting an early O star, and typically of moderate eccentricity.

  (e.g. Casares et al. 2005a, Hadash et al. 2012, Collmar & Zhang 2014, Chang et al. 2016; Fermi et al. 2012, HESS 2015, Monageng et al. 2017; Corbet et al. 2016, HESS 2018; Corbet et al. 2019).
- **LS I +61 303** is eccentric and compact, hosting a Be star.

  (e.g. Casares et al. 2005b, Hadasch et al. 2012, MAGIC 2016, Saha et al. 2016)
- All these sources produce radio, X-ray, and gamma-ray emission with complex phenomenology. Several of them show extended X-ray emission.

  (e.g. Paredes et al. 2007; Durant et al. 2011; Williams et al. 2015)

(Modeling: e.g. Leahy 2004; B-R & Paredes 2004; Romero et al. 2005; Paredes et al. 2006; B-R et al. 2006; Dermer & Böttcher 2006; Aharonian et al. 2006; Bednarek 2006; Dubus 2006; Khangulyan et al. 2008; Dubus et al. 2008; Sierpowska-Bartosik & Torres 2008; Takahashi et al. 2009; Cerutti et al. 2010; Zdziarski et al. 2010; Zabalza et al. 2011; Zabalza et al. 2013; Massi & Torricelli-Ciamponi 2014; del Palacio et al. 2015; Dubus et al. 2015)

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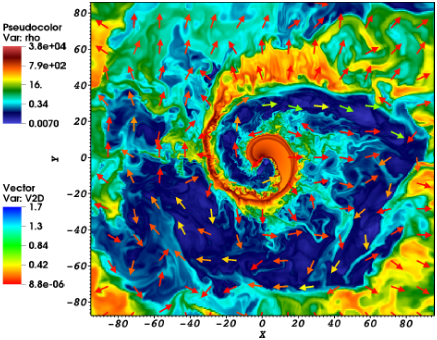
What is (not) known?

- Outflow initial properties and microphysics?
- The global emitting flow evolution is determined by
  - Supersonic winds/relativistic outflows
  - Orbital motion
  - Role of magnetic fields?
  - What about secondary emission?
- Energy dissipation on small, middle and large scales:
  - Multiple emitting sites
  - Acceleration processes?
  - Acceleration is efficient
  - Synchrotron and IC are dominant and compete with adiabatic losses



(B-R et al. 2015)

- Regarding non-thermal processes,
  - Acceleration is very fast
  - Gamma-ray emission is efficient
  - VHE γs: *system periphery*
- Termination regions?

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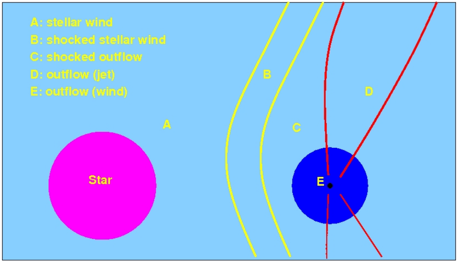
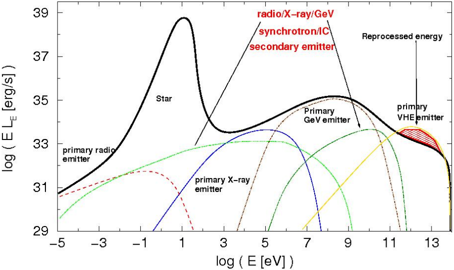
HMRB basics

Sketch/SED:





Continuous Doppler boosted emitter:

- Under flow RF anisotropy:
  $L_\gamma^{\rm MAX} \sim (4\pi/\Omega) L_\gamma^{\rm LAB}$
  $L_\gamma^{\rm MIN} \sim (\Omega/4\pi)^2 L_\gamma^{\rm LAB}$
- Under flow RF anisotropy:
  $L_\gamma^{\rm MAX} \sim L_\gamma^{\rm LAB}$
  $L_\gamma^{\rm MIN} \sim (\Omega/4\pi) L_\gamma^{\rm LAB}$
- Since $L_{\rm eng} \gtrsim L_{\rm NT} \gtrsim L_\gamma^{\rm LAB} \gtrsim L_\gamma^{\rm MIN}$
  Likely: $\rightarrow L_{\rm eng} \gg L_\gamma^{\rm MIN}$
- For $L_{\rm eng} \sim L_\gamma^{\rm LAB}$:
  Still huge energetics
  $U_{\rm NT} \sim U$ (one zone)
  $U_{\rm NT} < U$ (multi-zone)
  Equation of state and radiation feedback in emitting flow

Relevant aspects of the emission

- Electrons and positrons:
  $t_{\rm Br} \approx 10^6\,(\rho/m)_9^{-1}$ s
  $t_{\rm sy} = 1/a_{\rm s}\,B^2\,E \approx 390\,E_{\rm TeV}^{-1}\,B_0^{-2}$ s
  $t_{\rm IC} \approx 100\,E_{\rm TeV}^{0.7}\,T_{4.5}\,u_2^{-1}$ s (KN; monoenerg.); $t_{\rm IC} \approx 16\,E_{\rm 10GeV}^{-1}\,u_2^{-1}$ s (Th)

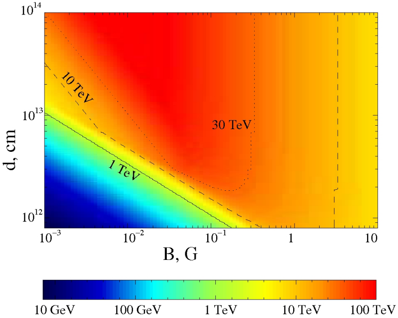
  Anistropic inverse Compton and synchrotron emission are the most relevant radiation processes. Proton/nuclei losses are small.

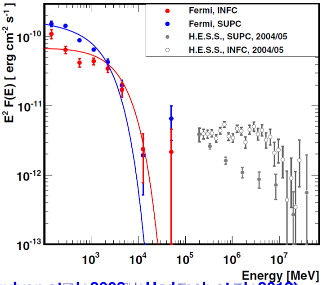
- Dynamical time and adiabatic losses: $t_{\rm dy} \sim l/v = 100\,l_{12}\,v_{10}^{-1}$ s
- Acceleration timescale: $t_{\rm acc} = \eta\,r_{\rm g}/c \approx 0.1\eta\,E_{\rm TeV}\,B_0^{-1}$ s; $\eta \geq 1$
- Diffusive escape time: $t_{\rm diff} = l^2/2\,D \approx 15000\,B_0\,l_{12}^2\,E_{\rm TeV}^{-1}\,\chi^{-1}$ s ($D = \lambda\,c/3 = \chi\,r_{\rm g}\,c/3$)
- Low-energy losses: $t_{\rm ion/c} \approx 3\times10^6\,E_{\rm GeV}\,(\rho/m)_9^{-1}$ s (overcome rel. Bremsstrahlung below 1 GeV)

Maximum energies

- Rate balance ($t_{\rm acc} = t_{\rm cool}$) yields:
  Synchr.: $E_{\rm max}^{\rm sy} \approx 60\,\eta^{-1/2}\,B_0^{-1/2}$TeV
  IC: $E_{\rm max}^{\rm KN} \approx 10^{10}\,(B_0\,T_{4.5}\,u_2^{-1}\,\eta^{-1})^{3.3}$TeV;
  $E_{\rm max}^{\rm Th} \approx 1.2\,B_0^{1/2}\,u_2^{-1/2}\,\eta^{-1/2}$TeV
- Dynamical time (escape, adiabatic cooling):
  $E_{\rm max}^{\rm dy} \approx 900\,R_{12}\,B_0\,v_{10}^{-1}\,\eta^{-1}$ TeV
  Diffusion:
  $E_{\rm max}^{\rm diff} \approx 370\,R_{12}\,B_0\,\eta^{-1/2}\,\chi^{-1/2}$ TeV
- HMRB have plenty of regions where acceleration can take place (Fermi I, II and shear; magnetic reconnection; converter mechanism...)

(see Rieger et al. 2007, B-R & Rieger 2012, and ref. therein)



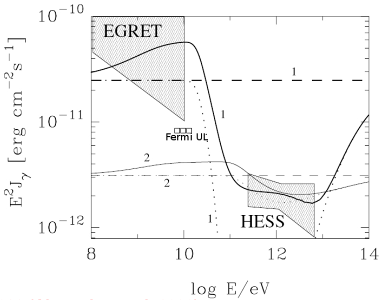


(↑ Khangulyan et al. 2008; ↓ Hadasch et al. 2012)

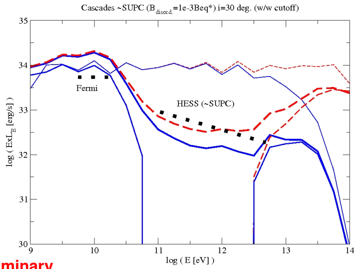
Radiation reprocessing

- **HMRB: $\tau_{\gamma\gamma} \approx 10\, L_{*38.5}\, l_{12.5}^{-1}$ (strongly anisotropic)**
- **IC-cascade efficient** if $\epsilon_\gamma >$ several $\epsilon_{\gamma\gamma\mathrm{th}}$, $\tau_{\gamma\gamma} >$ several, and $B \ll B_{\mathrm{eq}}^{\mathrm{ph}}$ ($e^{\pm}$ isotropization still expected)
- **Even if** $\tau_{\gamma\gamma} \lesssim 1$, synchrotron (X-rays) and IC ($\lesssim \epsilon_{\gamma\mathrm{th}}$) relevant
- Typically, **no clear features** of absorption or cascading

(Calculations: e.g. Bednarek 1997, 2006; Aharonian et al. 2006; Orellana et al. 2007; Sierpowska-Bartosik & Torres 2008; B-R et al. 2008; Cerutti et al. 2010; B-R & Khangulyan 2011)



LS 5039 (Aharonian et al. 2006)



Preliminary

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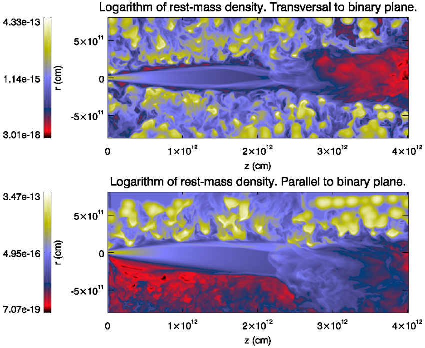
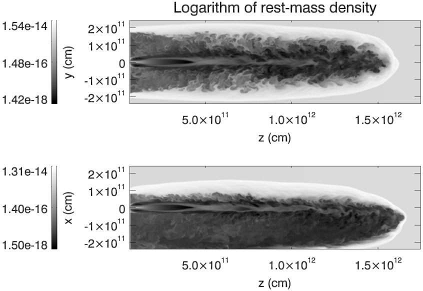
MQ: within the binary system and clumps

- **Jet strong, asymmetric recollimation shocks and fast instability growth are expected.**
- Weak jets can even be disrupted within the binary system.
- **Different energy dissipation regions** can emit non-thermal radiation.


Logarithm of rest-mass density. Transversal to binary plane.

Logarithm of rest-mass density. Parallel to binary plane.


Logarithm of rest-mass density

- **Presence of clumps strongly enhances the disruptive power of the wind.**

(clumpy winds in massive stars: e.g. Moffat et al. 2008)

(Perucho & B-R 2008, 2012; Perucho et al. 2010; and see also Yoon & Heinz 2015 and Yoon et al. 2016)

HMPB: within the binary system

- The pulsar wind **terminates** against the stellar wind, and then **reaccelerates**; strong **instabilities** already develop.

  (e.g. Bogovalov et al. 2008; B-R et al. 2012; Lamberts et al. 2013; etc.)

- In the classical *scenario*, the shocked pulsar wind emits at high energies.

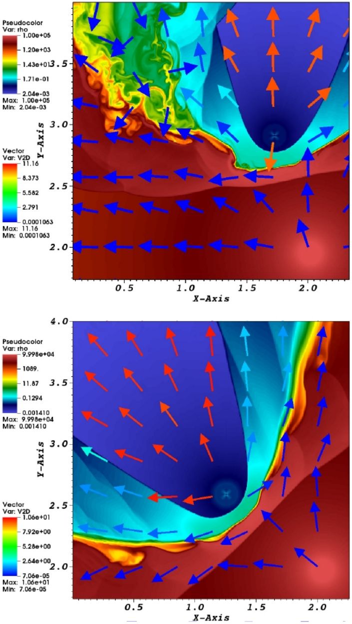
  (e.g. Maraschi & Treves 1981; Tavani et al. 1993; Dubus 2006; Khangulyan et al. 2007; etc.)

- The **unshocked pulsar wind** may be also a strong emitter.

  (e.g. Khangulyan et al. 2007; Petri & Dubus 2011; Derishev & Aharonian 2012)

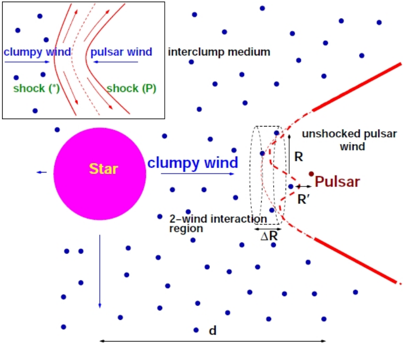
- The **Be disc** capture?

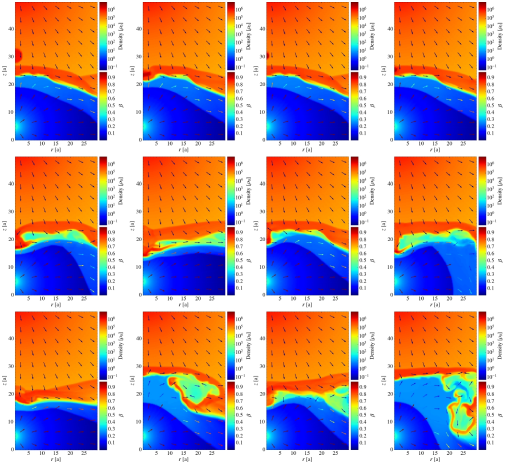
  (e.g. Yi & Cheng 2017)



(B-R et al. 2012)

HMPB: clumps



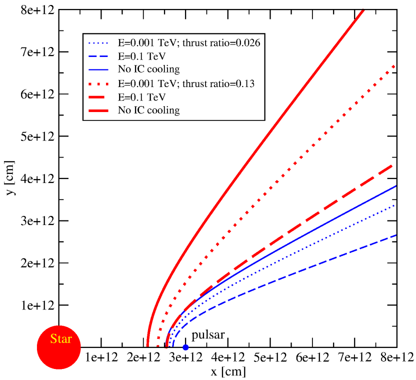


(Paredes-Fortuny, B-R, Perucho & Ribó 2015)

- **Clumps are ideal seeds for instability growth.**
- **Large clumps can strongly modify the overall interaction region.**

- Non-thermal phenomena should be strongly affected. **(B-R 2013; de la Cita et al. 2017; Kefala & B-R)**

Radiation dynamical feedback



- **Typically $\eta = L_{\rm p}/\dot{M}_{\rm w} v_{\rm w} c < 1$; $\dot{P}_{\rm w\perp} = \dot{P}_{\rm p\perp}$ including stellar photon IC.**

- **Fast IC emission brakes the pulsar wind, and changes its energy and momentum flux pattern.**

  (e.g. Khangulyan et al. 2007)

- If B is low in the unshocked pulsar wind, efficient IC cascades are expected.

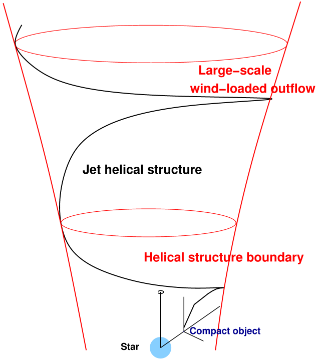
  (Sierpowska-Bartosik & Torres 2008)

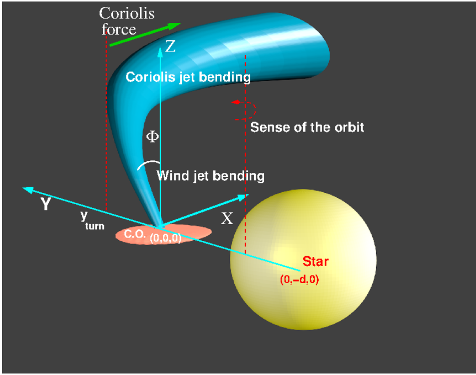
- A **high NT fraction in a relativistic emitting flow** under efficient cooling also changes the energy and momentum fluxes.

- Shocked pulsar winds, but also potentially MQ jets, should be affected by radiation feedback, due to both synchrotron and IC.

MQ: orbital motion (I)

- Microquasar jets cross the wind of the star while orbiting it.
- **For $\dot{P}_\mathrm{w}/4\pi\dot{P}_\mathrm{j} > 1$, the jets will be significantly affected by orbital motion.**





- The jet, surrounded and likely mass-loaded by shocked wind, develops an (unstable) spiral-like structure.

(B-R & Barkov 2016)

MQ: orbital motion (II)

- The stellar wind induces an **asymmetric recollimation shock** on the jet:

$$L_{\rm j} < \frac{\dot{P}_{\rm w} c^2 \gamma_{\rm j}(\gamma_{\rm j}-1)}{16 v_{\rm j}} \approx 7\times 10^{36}\,\frac{\dot{M}_{\rm w,-7}\, v_{\rm w,8.5}\,\gamma_{\rm j,0.3}(\gamma_{\rm j,0.3}-1)}{\beta_{\rm j}}\ {\rm erg\ s^{-1}} \tag{1}$$

- The jet is significantly **bent** by the wind ($\gtrsim \theta_{\rm j}$):

$$L_{\rm j} \lesssim \frac{(\gamma_{\rm j}-1)\dot{M}_{\rm w} v_{\rm w} c}{4\pi\gamma_{\rm j}\beta_{\rm j}} \approx 2\times 10^{36}\,\frac{\dot{M}_{\rm w,-7}\, v_{\rm w,8.5}(\gamma_{\rm j,0.3}-1)}{\gamma_{\rm j,0.3}\beta_{\rm j}}\ {\rm erg\ s^{-1}} \tag{2}$$

- The orbit-induced jet **helical** trajectory will be **non-ballistic** for:

$$L_{\rm j} \lesssim 6\times 10^{36}\,\frac{\theta_{\rm j,-1}\dot{M}_{\rm w,-7}\, v_{\rm w,8.5}^{1/3}(\gamma_{\rm j,0.3}-1)}{\gamma_{\rm j,0.3}\beta_{\rm j}^{1/3}}\ {\rm erg\ s^{-1}} \tag{3}$$

- The jet is expected to end as a **bipolar, broad, wind-loaded** flow with

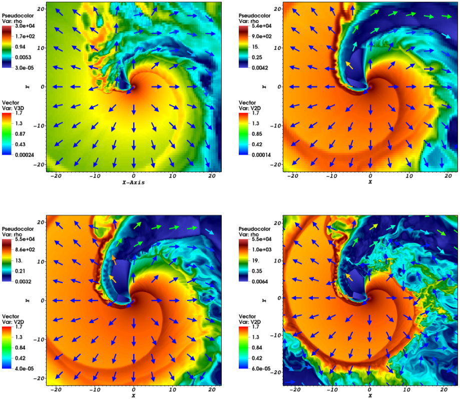
$$v_\infty \sim \left(\frac{2\theta_{\rm j}(\gamma_{\rm j}-1)v_{\rm w} c}{\pi\beta_{\rm j}\gamma_{\rm j}\chi_{\rm j}^3}\right)^{1/2} \approx 5\times 10^{8}\,\frac{\theta_{\rm j,-1}^{1/2}(\gamma_{\rm j,0.3}-1)^{1/2} v_{\rm w,8.5}^{1/2}}{\beta_{\rm j}^{1/2}\gamma_{\rm j,0.3}^{1/2}\,\chi_{\rm j}^{3/2}}\ {\rm cm\ s^{-1}} \tag{4}$$

(Barkov & B-R 2016)

HMPB: orbital motion

- The stellar wind ($\dot{M}_{\rm w}$) and orbit **confine** the pulsar wind ($L_{\rm p}$): **back reaction; dissipation**
- The orbit shapes a **spiral** flow; from the *Coriolis* **(back)shock** to **mixing and disruption**.
- Either from pressure balance or energy equipartion, the spiral arm propagates and expands with a **speed:** $v_r \lesssim \sqrt{v_{\rm w}/c}\, v_{\rm w} \ll c$.
- The mixed, partially isotropized flow becomes supersonic and **terminates on large scales**.

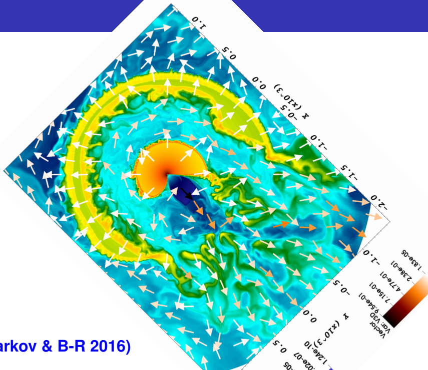
2D and 3D simulations with orbital motion yield **robust** results.



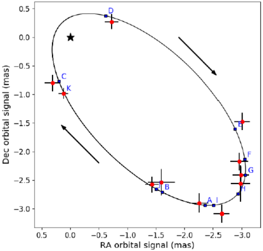
(B-R & Barkov 2011; B-R et al. 2012, 2015)

Large scales

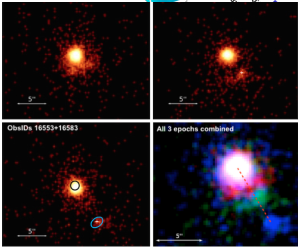
- **GENERAL:** A wind-loaded supersonic outflow **impacts the environment** potentially radiating **(B-R & Barkov 2011, 2016)**
- **HIGH *e* HMPB:** disrupted spiral matter produces shocks in the pulsar wind; decretion disc secondary **(Barkov & B-R 2016)**
- Fragments recurrently **move apastron-wards**, starting ∼ periastron, at ∼ 0.1 *c* **(Pavlov et al. 2015)**.



(Barkov & B-R 2016)



PSR B1259−63: Miller-Jones et al. 2018



PSR B1259−63: Pavlov et al. 2015