Orbitally-modulated X-ray and Gamma-ray Emission from Millisecond Pulsar Binaries

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NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

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Overview

Millisecond Pulsars (MSPs):

- Pulsars lose energy via: Magnetic dipole radiation

$$\dot{E} = \frac{\mu_0 \left|\ddot{p}_m\right|^2}{6\pi c^3}$$

  Spin-down luminosity

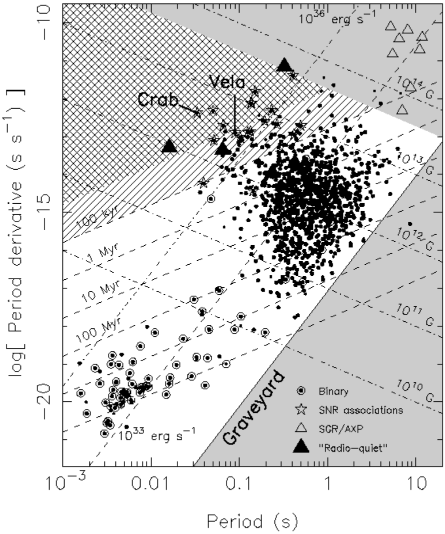
$$\dot{E}_{rot} = 4\pi I \dot{P} P^{-3}$$

- Old pulsars typically move into 'graveyard'

$$\tau = \frac{P}{(n-1)\dot{P}}$$

  for $n > 1$ and $\Omega_0 \gg \Omega$

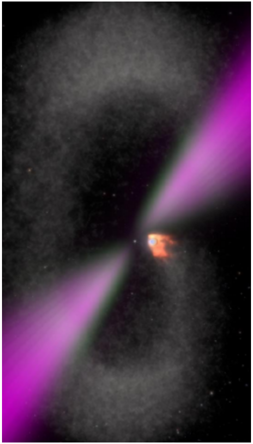
- Acquires a low mass companion and forms a low-mass X-ray binary (LMXBs)



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Introduction

- **What are spider binaries?**
  - MSP with tidally-locked low-mass star.
  - Thought to form from recycling scenario.
  - Once enough mass is transferred:
    - Accretion is stopped by pulsar radiation pressure.
    - Companion star becomes convective - mass loss dominated irradiation
  - Fermi-LAT has discovered nearly 100 MSPs - nearly 30 are RBs & BWs
- **Typical characteristics:**
  - $P_b < 24h$.
  - Intense pulsar wind heats companion and excites companion wind.
  - Flares may occur on companion: variable heating, magnetic variability.
  - Interaction of MSP and companion winds form an intra-binary shock.
  - BWs are physically smaller with lower-mass companions ($\sim 0.01 M_\odot$) than RBs ($\sim 0.1 M_\odot$).



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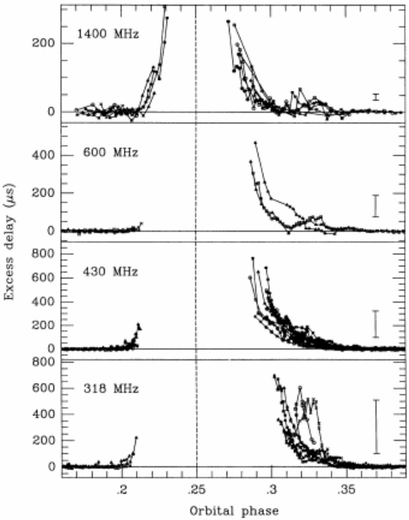
Radio properties

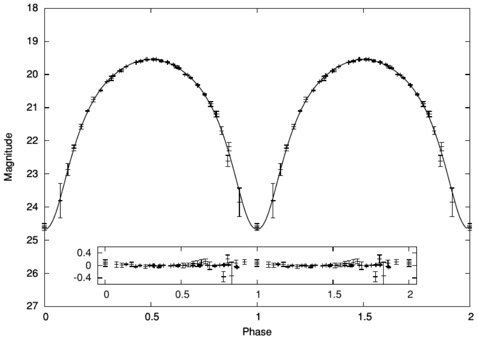
- Frequency-dependent radio eclipses.
- Shrouding of MSP radio emission.
- Phase gives shock orientation.
- Asymmetry of eclipse decreases with frequency: higher frequency probes denser regions closer to shock nose.



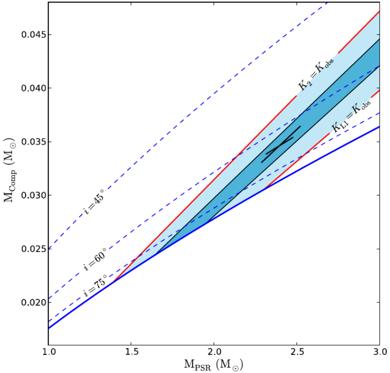
Ryba & Taylor (1991)

Optical properties

- Photometry plus model of anisotropic heating: constrain system inclination.
- Spectroscopic radial velocity studies: constrain mass ratio.
- Typical $T_{comp} \sim 10^4 K$.
- Radio + optical mass functions: constrain pulsar mass.



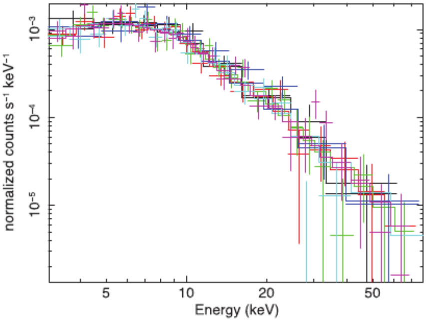
Reynolds et al. (2007)



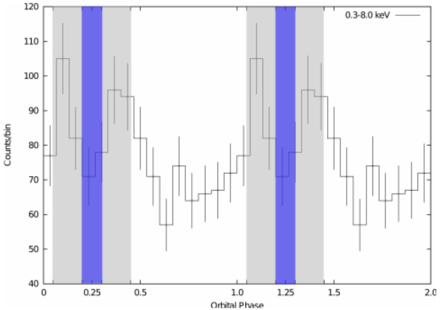
Van Kerkwijk et al. (2011)

X-ray properties

- Double-peaked emission: Doppler-boosted synchrotron emission from intra-binary shock.
- Hard power laws: hard underlying electron spectrum.
- Spectra extending up to 80 keV: constraints on $B_{sh} \sim 1G$.



Tendulkar et al. (2014)



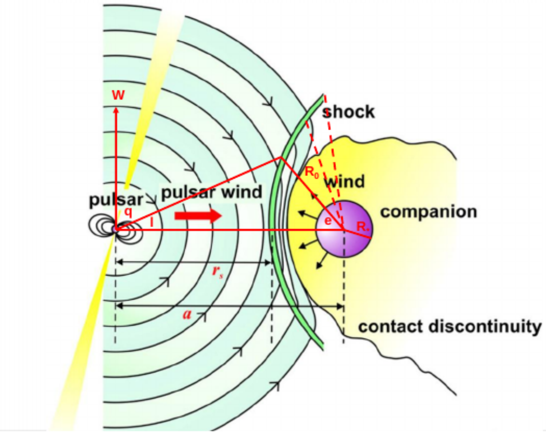
Huang et al. (2012)

Assumptions:

- Spherical polar cap shape for intra-binary shock.
- Azimuthal symmetry about line joining pulsar and companion ($\frac{d}{d\phi} = 0$).
- Steady-state ($\frac{d}{dt} = 0$).
- Isotropic black-body emission at temperature T from companion. Neglect SSC for now.
- Approximate particle transport using timescales.
- Isotropic steady-state particle spectrum in comoving frame.
- Bulk flow: linear profile for $\beta\Gamma(\theta)$

'Flipping' the code:

- New origin centred on the pulsar (RB). Now θ increases counterclockwise:
  - Lower IC (lower u_{ph}), Higher SR (larger B)
- $u_{ph} \sim [\Gamma(a - R_{star})]^{-2}$
  - Lower IC (Deboosting)
- Larger $d\Omega \sim \frac{cos(\theta_1) - cos(\theta_2)}{2}$
  - Increase Q_0
- Flip u_x to $-u_x$
  - Light curves change 0.5 in phase.

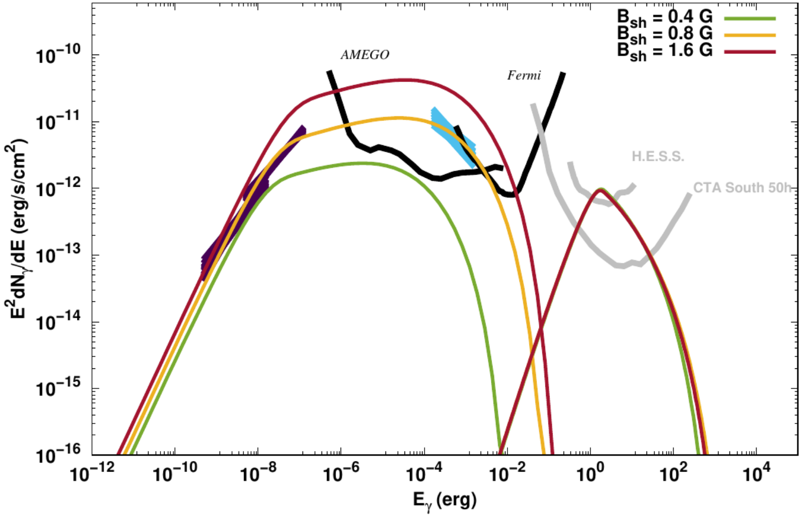


Venter et al. (2015); Harding & Gaisser (1990); Arons & Tavani (1993)

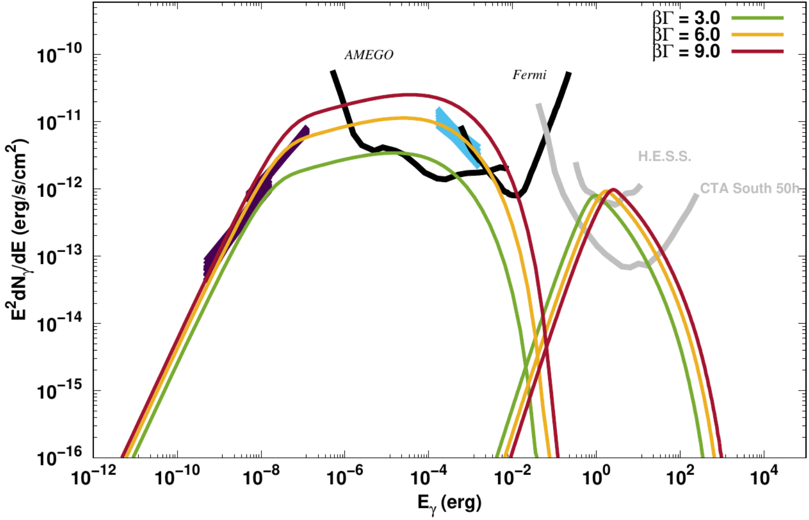
Parameters

		J1311-3430 Quiescent	J1311-3430 Flaring	J1723-2837
Parameter	Symbol	Values		
Pulsar mass	M_{psr} ($M_{\odot}$)	2.0	2.0	2.0
Orbital period	P_b (hr)	1.56	1.56	14.8
Inclination	i (degrees)	60	60	40
Mass ratio	q	180	180	3.5
Shock radius	R_0 (units of a)	0.5	0.4	0.3
B-Field at the shock	B_{shock} (G)	1.3	1.2	0.8
Companion temperature	$T_{companion}$ (K)	12000	45000	6000
Pair multiplicity	$M_{\pm}$	1000	5000	1000
Maximum particle conversion efficiency	$\eta_{p,max}$	0.9	1.0	1.5
Pulsar period	Period (ms)	2.56	2.56	1.86
Pulsar spin down	$\dot{E}$ (erg/s)	4.9e34	4.9e34	4.7e34
Moment of inertia of pulsar	I	2.0e45	3.0e45	1.0e45
Index for injected spectrum	Γ	1.8	1.6	2.6
Distance	d (kpc)	1.40	1.40	0.72
Bulk flow momentum	$\beta_{\Gamma,max}$	4.0	10	6.0

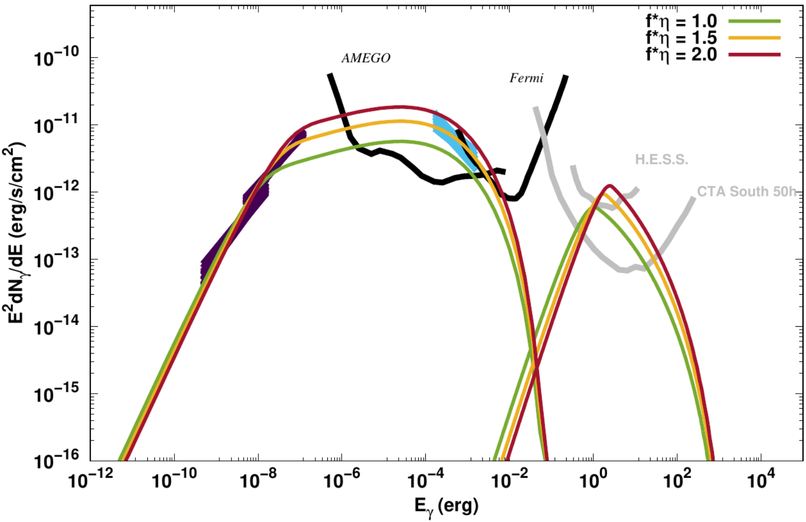
Effect of shock magnetic field



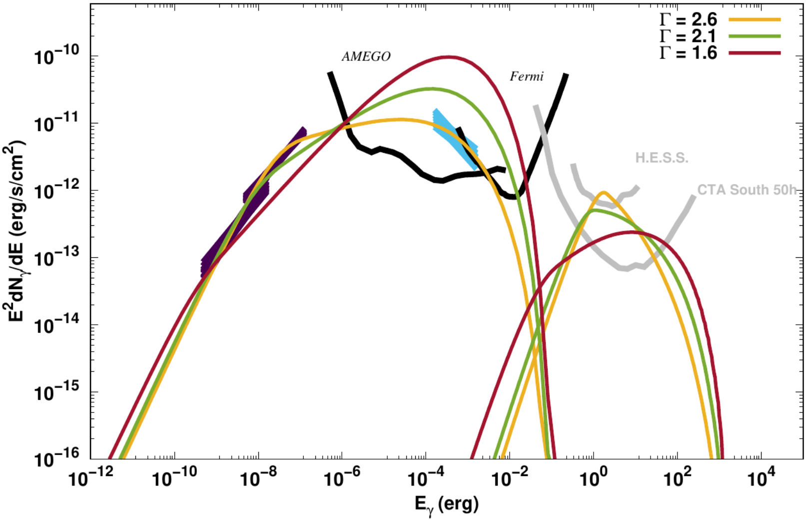
Effect of bulk flow momentum



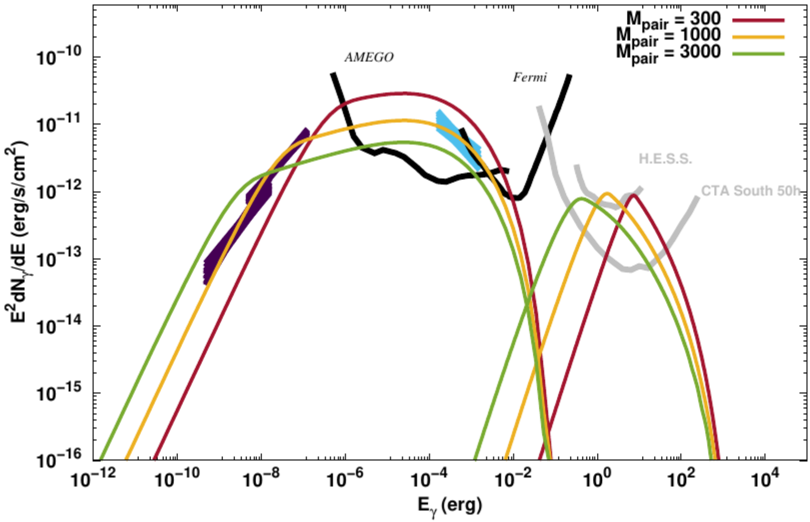
Effect of conversion efficiency



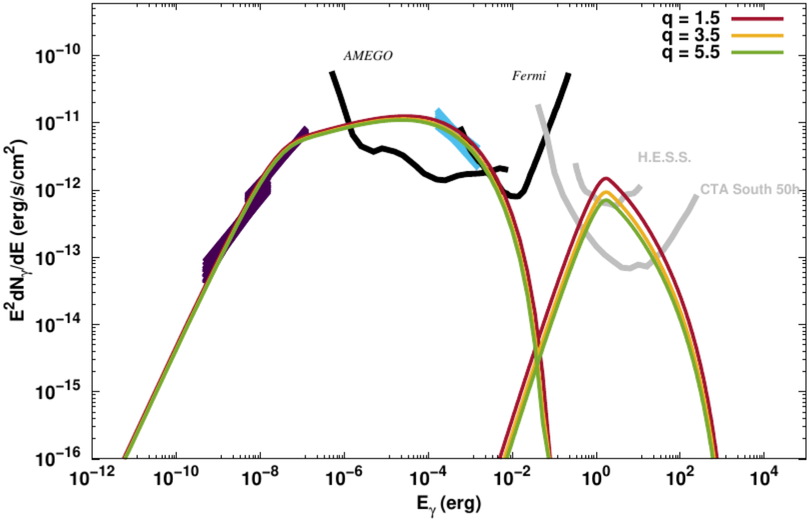
Effect of injection index



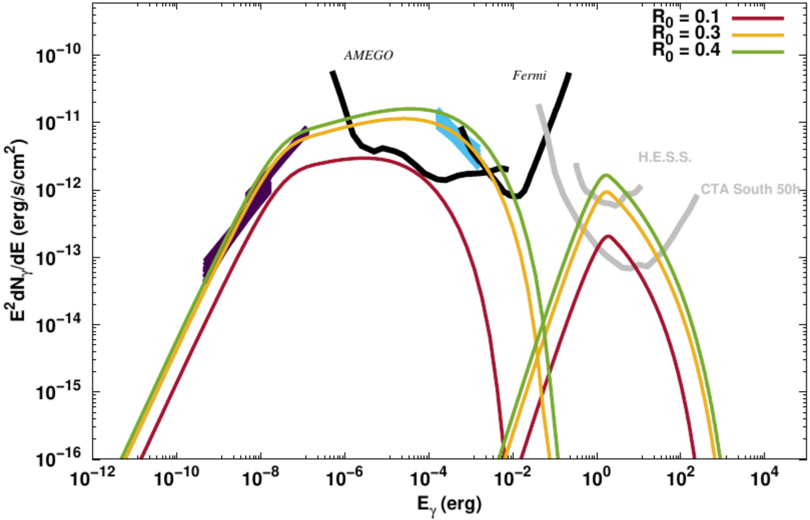
Effect of pair multiplicity



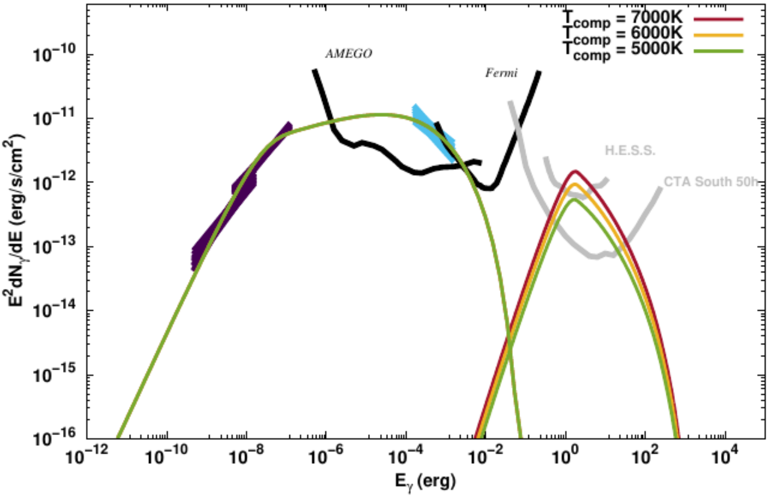
Effect of mass ratio



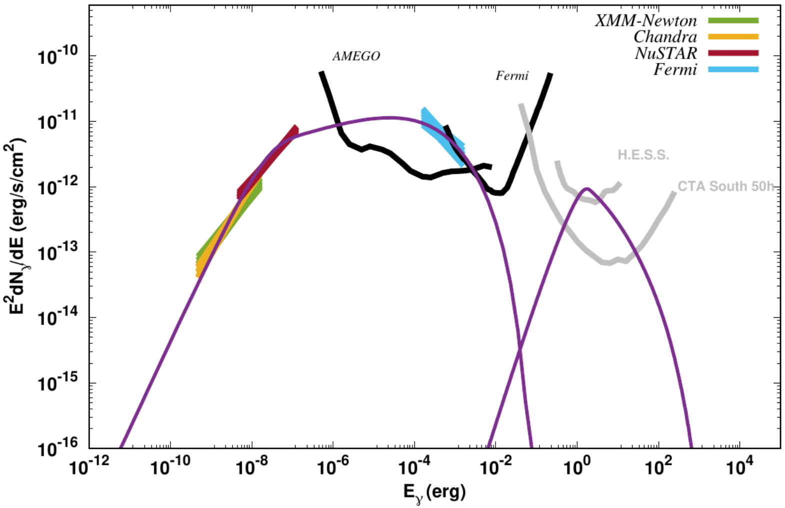
Effect of shock radius



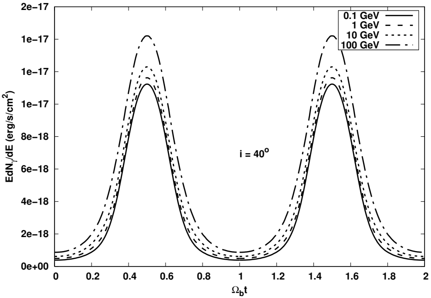
Effect of companion temperature



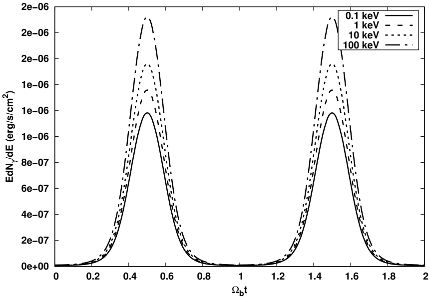
Spectral fit for J1723-2873 (RB)



Light curves for J1723-2873

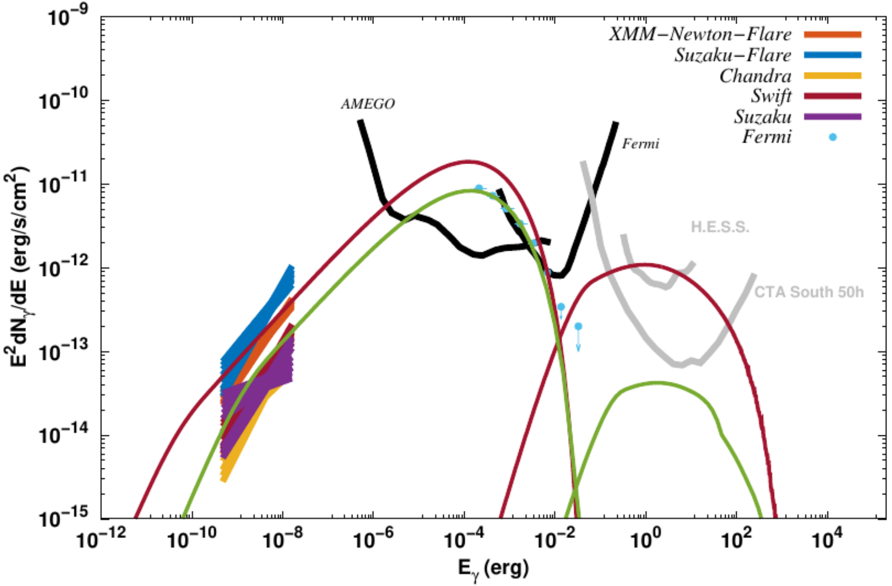


IC light curve

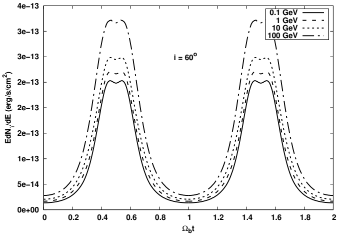


SR light curve

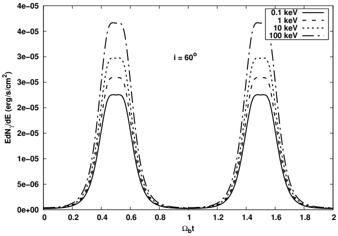
Spectral fit for J1311-3430 (BW)



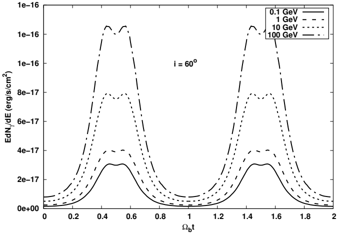
Light curves for J1311-3430



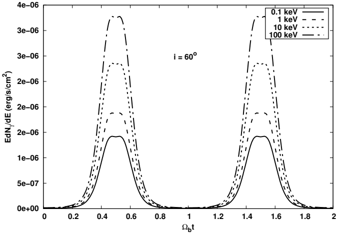
(a) Flaring state IC light curve



(b) Flaring state SR light curve



(c) Quiescent state IC light curve



(d) Quiescent state SR light curve

Conclusions:

- SR and IC from BWs and RBs: phase-resolved spectra and energy-dependent light curves.
- Promising H.E.S.S. targets for modulated SR/IC flux.
- Very promising for CTA era!

Future Work:

- Numerical code:
  - Improved shock geometry
  - Implement spatially-dependent acceleration
  - Refine transport model
  - SSC and Upstream IC components
- Exciting prospects:
  - H.E.S.S. observation time
  - Deeper Wider Faster (DWF) campaign observations

Thanks for your attention!

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Transport equation

$$\frac{\partial N_e}{\partial t} = -\vec{V} \cdot (\vec{\nabla} N_e) + \kappa(E_e)\nabla^2 N_e + \frac{\partial}{\partial E_e}(\dot{E}_{e,tot} N_e) - (\vec{\nabla} \cdot \vec{V}) N_e + Q$$

Injection spectrum

$$Q_{PSR}(E_e) = Q_0 E^{-\Gamma} exp(\frac{E_e}{E_{cut}})$$

where $E_{cut} = eR_0 B_{sh}$

Spectrum normalization

$$\int_{E_{min}}^{\infty} Q_{PSR} dE_e = (M_{\pm} + 1)\dot{N}_{GJ},$$

$$\int_{E_{min}}^{\infty} E_e Q_{PSR} dE_e = \eta_p \dot{E}_{rot},$$

$$\dot{N}_{GJ} = \frac{4\pi^2 B_{PSR} R_{PSR}^3}{2ceP^2}$$

SR loss rate

$$\dot{E}_{SR} = \frac{4\sigma_T c U_B \gamma_e^2}{3}$$

where $U_B = \frac{B_{sh}^2}{8\pi}$

IC loss rate

$$\dot{E}_{IC} = \frac{4\sigma_T c U \gamma_e^2}{3} \frac{\gamma_{KN}^2}{\gamma_{KN}^2 + \gamma_e^2},$$

where $U = \frac{2\sigma_{SB} T^4}{c}(\frac{R_*}{R_0})^2$

Boosting

$$\delta = \frac{1}{\Gamma(1 - \beta\vec{n} \cdot \vec{u})};\ \nu F_\nu^{obs} = \delta^3 \nu F_\nu^{em}$$