Gamma-Ray Binary Systems

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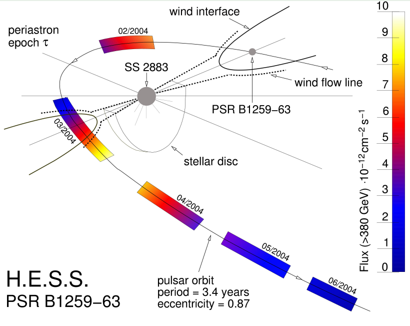
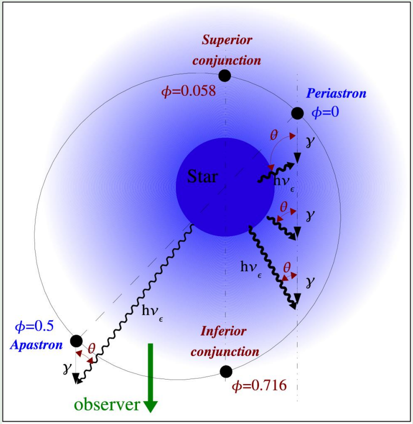
Outline

Outline

Sketches of PSR B1259 & LS 5039 from *HESS* discovery papers





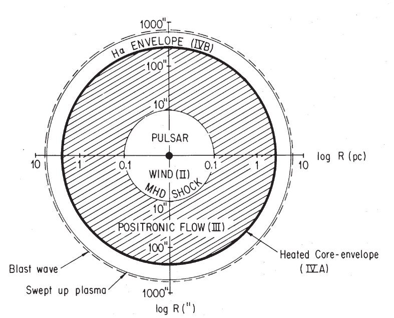
Gamma-Ray Binary Systems

Object	PSR B1259	LS 5039	LS I +61 303	Cyg X-1
Type	B+Pulsar	O+?	B+?	O+BH
$L_\star$,erg/s	$3 \cdot 10^{37}$	$7 \cdot 10^{38}$	10^{38}	$1.3 \cdot 10^{39}$
Orbit Size, cm	10^{13}–10^{14}	10^{12}–$3 \cdot 10^{12}$	$2 \cdot 10^{12}$–10^{13}	$3 \cdot 10^{12}$
Eccentricity	0.87	0.35	0.72	0
Inclination	35	10–75	30 ± 20	~ 30
HE Instrument	HESS	HESS EGRET	MAGIC VERITAS EGRET	MAGIC
TeV detection	$> 10\sigma$	$\sim 100\sigma$	$> 10\sigma$	4σ
TeV signal	variable	periodic	periodic	flare

Outline

Crab Pulsar

Kennel&Coroniti, 1984



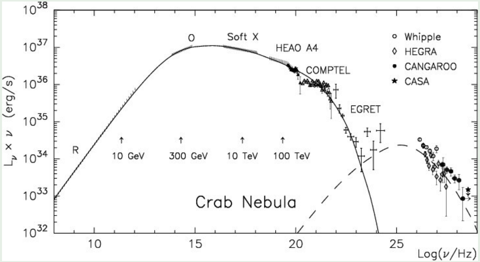
What is Crab?

- Pulsar ejects ultrarelativistic wind (Rees&Gunn, 1974)
- It interacts with SN remnant (Kennel&Coroniti, 1984)
- A non spherical structure (Bogovalov&Khangulyan, 2002)

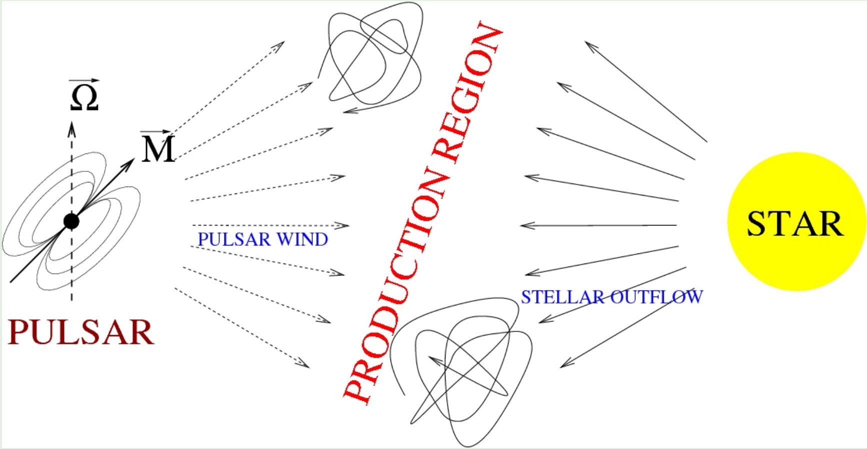
Crab Pulsar (II)

Crab Nebula

Aharonian&Atoyan, 1998



Physical scenario for Binary Pulsars



Binary Pulsar

Relativistic Pulsar/Non-relativistic Stellar Wind Colliding System

It means

- NOT like PSR B1913+16 (the “Nobel Prize” system, 1993)
  - $P \sim 8$ h; $a \sim R_\odot$
- NOT like PSR J0737-3039
  - Double Pulsar: two pulsar system
- NOT like IGR J17252-3616
  - Pulsar+Optical star system with accretion on the pulsar
- BUT PSR 1259 or PSR J0045
  - $P \sim 4$ yr; $a \sim 10^{13}$ cm

Outline

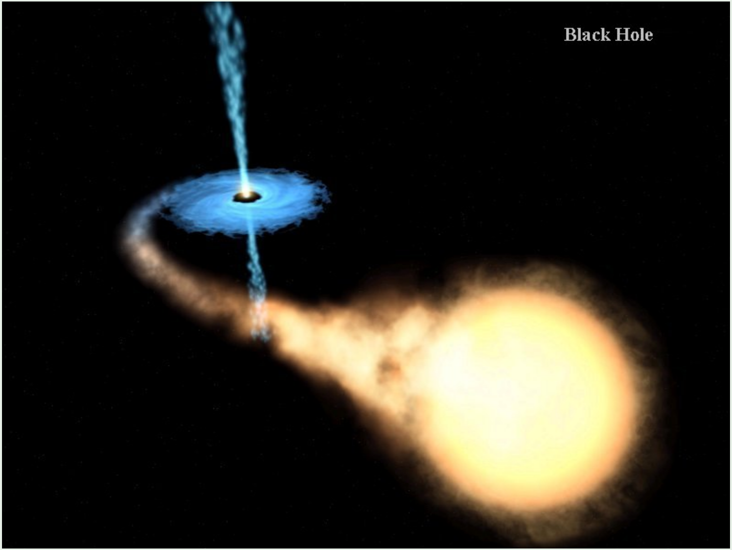
Microquasar

A microquasar is simply a Radio Emitting X-ray Binary displaying relativistic radio jets that can be imaged at a variety of angular scales using different interferometers
(M. Ribó, astro-ph/0402134)

It means

- X-ray Binary: Powered by accretion
- Radio Emitting: Non-thermal population of particles
- Radio Jets: Jets are sites of particle acceleration

Physical scenario for Microquasars



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TeV signal	variable	periodic	hints of periodicity	flare

What is the compact object?

Conclusive tests:

- Mass of the CO
- Pulsed emission
- Thermal emission of the accretion disk
- Non-thermal radiation (?)

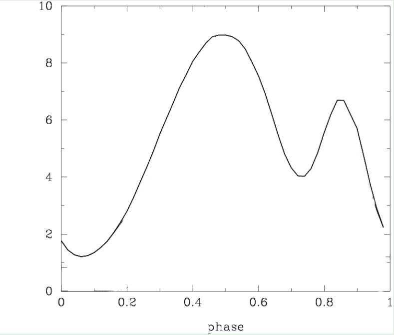
What is the compact object?

Are they conclusive?

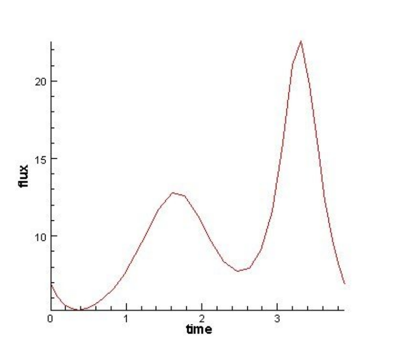
- Mass of the CO
  - Require precise spectrometric observations...
- Pulsed emission
  - May be absorbed in the dense stellar wind
- Thermal emission of the accretion disk
  - At which level?
- Non-thermal radiation (?)
  - Many impacting factors...

Non-thermal Emission (example)

"Microquasar"



"Binary Pulsar"



Outline

Radiation Efficiency

- Escape Time: $t_{\rm esc} = \min(t_{\rm diff}, t_{\rm ad})$

$$t_{\rm diff} = \frac{R^2}{2D} \sim 2\cdot 10^4\,\zeta^{-1} R_{12}^2 B_1 E_1^{-1}\ {\rm s}, \quad \zeta = \frac{D}{D_{\rm Bohm}}$$

$$t_{\rm ad} = \frac{R}{V_{\rm bulk}} \sim 10^2\, R_{12} V_{10}^{-1}\ {\rm s}$$

- Energy Transfer: $\mu = \frac{E_\gamma}{E_0}$
- Radiation Efficiency: $\kappa = \mu \min(1, t_{\rm esc}/t_{\rm int})$

Inverse Compton Scattering

- Cooling Time:

$$t_{\rm ic} = 40 \left(\frac{L}{10^{38}{\rm erg/s}}\right)^{-1} \left(\frac{R}{10^{12}{\rm cm}}\right)^{2} \left(\frac{T}{3\cdot 10^{4}{\rm K}}\right)^{1.7} E_{\rm TeV}^{0.7}\ {\rm s}$$

- Energy Transfer:

$$E_\gamma = \begin{cases} E_{\rm e}, & \epsilon E \gg m^2c^4 \\ \frac{\epsilon E_{\rm e}^2}{m^2c^4}, & \epsilon E \ll m^2c^4 \end{cases}$$

- Radiation Efficiency

$$\kappa \sim 1$$

Proton-proton interaction

- Cooling Time:

$$t_{\rm pp} = 10^6 \left(\frac{n_{\rm p}}{10^9 {\rm cm}^{-3}} \right)^{-1} {\rm s}$$

- Energy Transfer:

$$E_\gamma \sim 0.1\, E_{\rm p}$$

- Radiation Efficiency

$$\kappa = 10^{-3} \frac{t_{\rm esc}}{10^4 {\rm s}} \frac{n_{\rm p}}{10^9 {\rm cm}^{-3}}$$

Photo-meson production

- Cooling Time:

$$t_{p\gamma} = 3 \cdot 10^4 \left(\frac{L}{10^{38}\mathrm{erg/s}}\right)^{-1} \left(\frac{R}{10^{12}\mathrm{cm}}\right)^{2} \left(\frac{T}{3 \cdot 10^4\mathrm{K}}\right) \mathrm{s}$$

- Energy Transfer:

$$E_\gamma \sim 0.1\, E_\mathrm{p}$$

- Radiation Efficiency

$$\kappa = 0.03 \frac{t_\mathrm{esc}}{10^4\mathrm{s}} \frac{L}{10^{38}\mathrm{erg/s}} \left(\frac{R}{10^{12}\mathrm{cm}}\right)^{-2} \left(\frac{T}{3 \cdot 10^4\mathrm{K}}\right)^{-1}$$

Photo-disintegration

- Cooling Time:

$$t_{\rm pd} \sim 3 \cdot 10^3 \left(\frac{L}{10^{38}{\rm erg/s}}\right)^{-1} \left(\frac{T}{3 \cdot 10^4{\rm K}}\right) \left(\frac{R}{10^{12}{\rm cm}}\right)^2 \ {\rm s}$$

- Energy Transfer:

$$E_\gamma \sim 0.01\, E_{\rm N}$$

- Radiation Efficiency

$$\kappa = 0.03 \frac{t_{\rm esc}}{10^4{\rm s}} \frac{L}{10^{38}{\rm erg/s}} \left(\frac{R}{10^{12}{\rm cm}}\right)^{-2} \left(\frac{T}{3 \cdot 10^4{\rm K}}\right)^{-1}$$

The most favorable emission process in binary systems

Radiation Processes

Proc.	E_γ/E_0	κ
IC	1	1
pp	0.1	$10^{-3}\,\frac{t_{\rm esc}}{10^4{\rm s}}\,\frac{n_{\rm p}}{10^9{\rm cm}^{-3}}$
pγ	0.1	$0.03\,\frac{t_{\rm esc}}{10^4{\rm s}}\,\frac{L}{10^{38}{\rm erg/s}}\left(\frac{R}{10^{12}{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot10^4{\rm K}}\right)^{-1}$
Photo-des.	0.01	$0.03\,\frac{t_{\rm esc}}{10^4{\rm s}}\,\frac{L}{10^{38}{\rm erg/s}}\left(\frac{R}{10^{12}{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot10^4{\rm K}}\right)^{-1}$

IC as a primary gamma-ray Mechanism

- Optical Star Photon Field is perfect Target
  - All over the System
  - Fast cooling
- "Small" energy of parent Leptons $E_\gamma \sim E_\mathrm{e}$
  - Easier to accelerate
  - Easier to confine

Outline

Acceleration in Binary System

- Different acceleration mechanisms may take place in binary system.
  - Shock Acceleration (e.g. internal shocks)
  - Relativistic Shock Acceleration (e.g. in binary pulsars)
  - Shear Acceleration (e.g. in μQ jet)
  - Converter Mechanism (Derishev et al., Stern&Poutanen)
  - *etc*
- But electrons loss their energy very efficient
  - To compare the time scales

Acceleration vs Losses

Acceleration time

$t_{\rm acc} \approx 10\eta_{10} E_{\rm TeV} B_{0.1}^{-1}$

Hillas Criterion

$E < 3 \cdot 10 \left(\frac{R_{\rm acc}}{10^{12}}\right) B_{0.1}\ \rm TeV$

Klein-Nishina losses

$t_{\rm cool} \approx 2 \cdot 10^2 w_0^{-1} E_{\rm TeV}^{0.7}\ \rm s$ $\qquad E < 8 \cdot 10^3\ [B_{0.1}\eta_{10}^{-1} w_0^{-1}]^{3.3}\ \rm TeV$

Synchrotron losses

$t_{\rm cool} \approx 4 \cdot 10^4 B_{0.1}^{-2} E_{\rm TeV}^{-1}\ \rm s$ $\qquad E < 6 \cdot 10\ B_{0.1}^{-1/2}\ \eta_{10}^{-1/2}\ \rm TeV$

Electron maximum energy in LS 5039

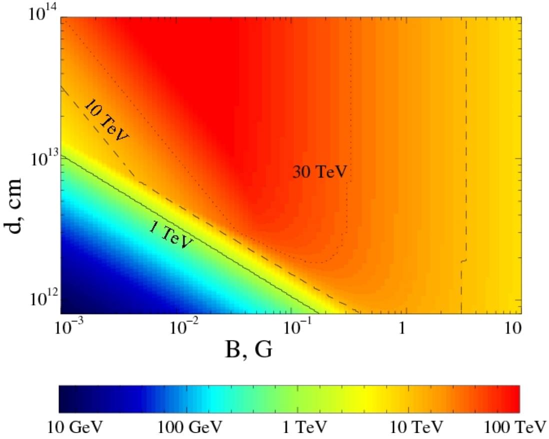
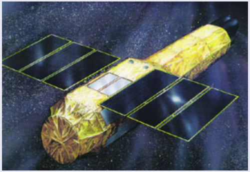


Figure: Maximum energy dependence on magnetic field and distance to the star (Khangulyan et al, 2008)

Outline

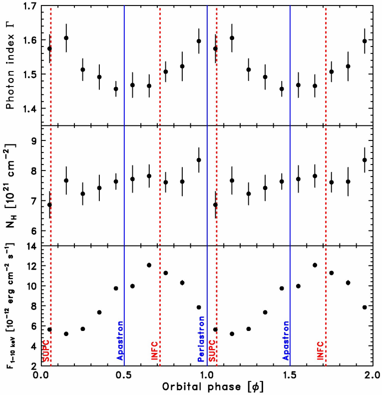
LS 5039 @ X-ray

Suzaku

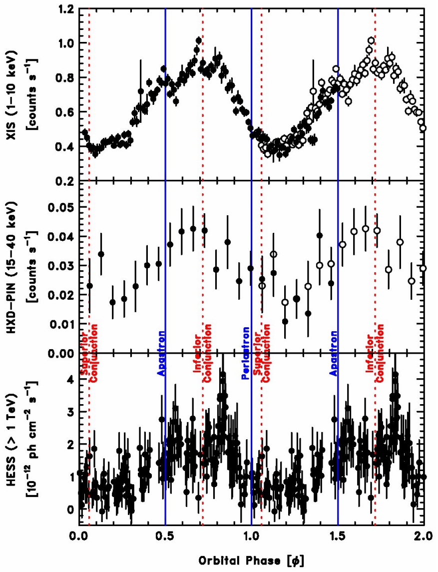


- Sensitivity
- 1.5 orbit
- Spectra
- Lightcurve

Observation (Takahashi et al., 2008)



X-ray and TeV emission from LS 5039



- Variable/Periodic
- Apparent similarities in lightcurves
- Hard distributions of parent particles

Takahashi et al., 2008

X-ray and TeV emission from LS 5039

TeV (Aharonian et al., 2006)

- Variable
- Periodic
- Strong variability in flux level
- Significant variability in photon index
- SUPC: lower fluxes and steeper spectra
- INFC: higher fluxes and harder spectra
- Very hard spectra at INFC

X-ray (Takahashi et al., 2008)

- Variable
- Seems to be periodic
- Significant variability in flux level
- Minor variability in photon index
- SUPC: lower fluxes and steeper spectra
- INFC: higher fluxes and harder spectra
- Hard spectra

Time-scales and Energy Bands

Suzaku

1keV–40keV

$\sim 10^{-11}\mathrm{erg/cm^2s}$

Fermi

100MeV–100GeV

?????

HESS

100GeV–100TeV

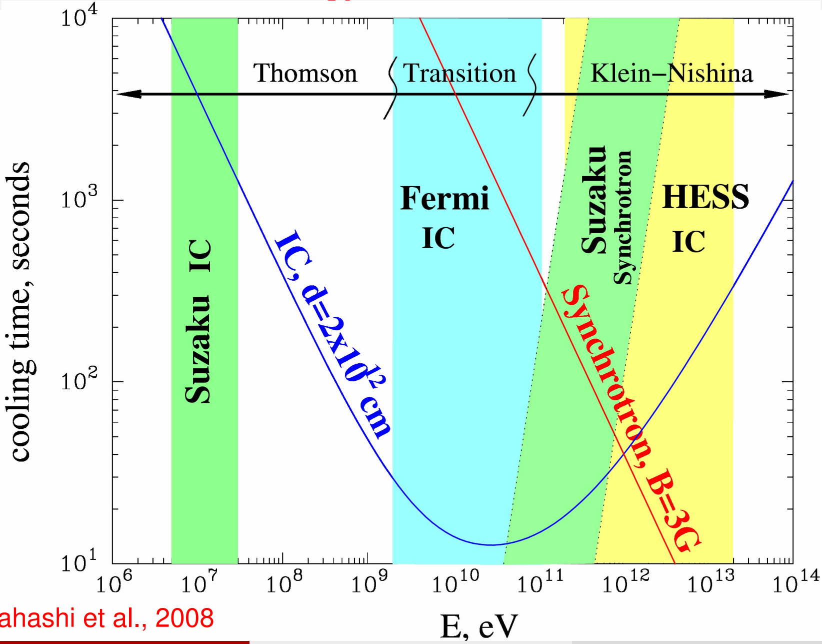
$\sim 5 \cdot 10^{-11}\mathrm{erg/cm^2s}$

Mechanism	Energy Band	Time-scale
Synchrotron	$\hbar\omega \sim 20 E_{\mathrm{TeV}}^2 B_{\mathrm{G}} \mathrm{keV}$	$t_{\mathrm{syn}} \sim 4 \cdot 10^2 E_{\mathrm{TeV}}^{-1} B_{\mathrm{G}}^{-2} \mathrm{s}$
Thomson	$\hbar\omega \sim 40 E_{\mathrm{GeV}}^2 \mathrm{MeV}$	$t_{\mathrm{Th}} \sim 10^3 D_{13}^2 E_{\mathrm{GeV}}^{-1} \mathrm{s}$
Klein-Nishina	$\hbar\omega \sim E_{\mathrm{TeV}} \mathrm{TeV}$	$t_{\mathrm{KN}} \sim 10^3 D_{13}^2 E_{\mathrm{TeV}}^{0.7} \mathrm{s}$

Could be useful to consider the parent particles, i.e. to make a transformation:

(Photon Energy, Fluxes) $\Longrightarrow$ (Electron Energy, Cooling Times)

Time-scales and Energy Bands



Takahashi et al., 2008

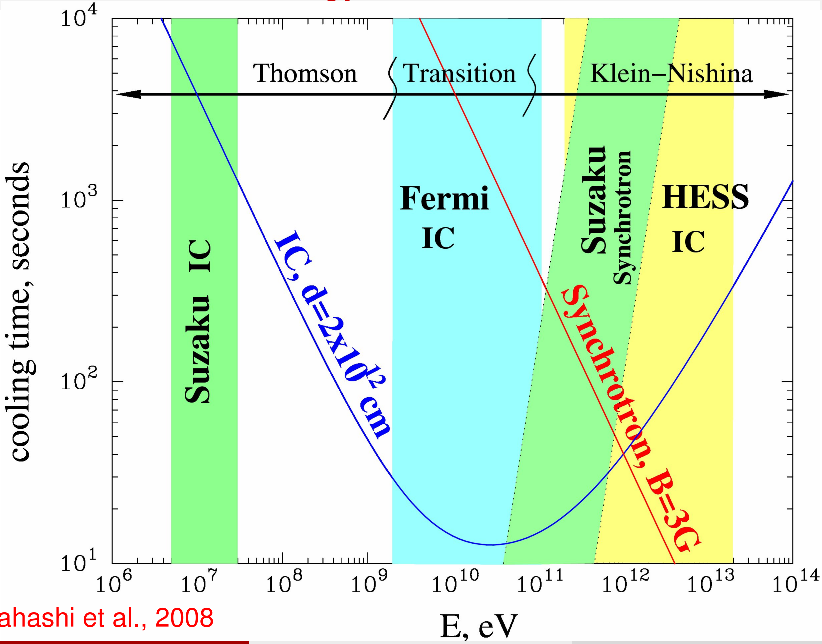
General Properties (spectral shape)

- Suzaku and HESS photons are likely produced by the electrons from overlapping energy bands
- A rather stable photon index ~ 1.5 measured by Suzaku suggests a power-law ($\sim \gamma^{-2}$) distribution of parent electrons
- In general γ^{-2} distribution of electrons leads (in the KN regime) to a rather steep VHE spectra with photon index ~ 3
  $\Rightarrow$ Recalls for anisotropic IC scattering (Aharonian&Atoyan, 1981; Khangulyan&Aharonian, 2005) with significant change of the interaction angle
- Relatively small distances between the optical star and the nonthermal emitter

General Properties (fluxes)

- From the spectral shape one can roughly determine the location of the production region
- This defines the efficiency of the IC production and the γ–γ attenuation
- Ratio of the X-ray and VHE energy fluxes allows to estimate the B-field strength ($\sim$ 3 G)

Time-scales and Energy Bands



Takahashi et al., 2008

General Properties (fluxes)

- From the spectral shape one can define the location of the production region
- This defines the efficiency of the IC production and the γ–γ attenuation
- Ratio of the X-ray and VHE energy fluxes allows to estimate the B-field strength ($\sim$ 3 G)
- Featureless hard HESS spectra recalls for a non-radiative dominant mechanism, e.g. adiabatic losses

Test Setup

The simplest one-zone model:

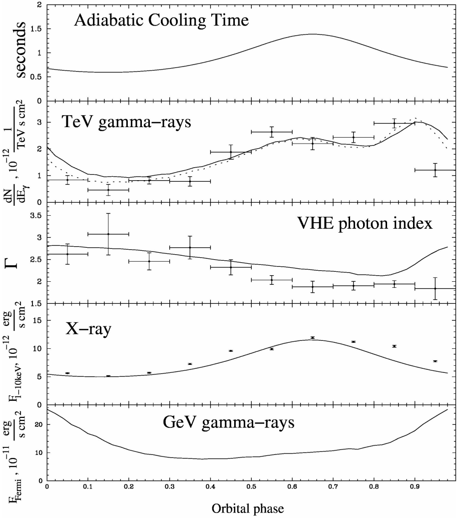
$$\frac{\partial\dot\gamma(\gamma)n}{\partial\gamma} = Q(\gamma)$$

where $\dot\gamma = \dot\gamma_{\rm IC} + \dot\gamma_{\rm syn} + \dot\gamma_{\rm ad}$

- Spectral shape defines IC losses (location of the emitter)
- Ratio of the fluxes defines synchrotron losses
- Spectral shape and X-ray light curve defines the level and orbital phase dependence of adiabatic losses
- The unconstrained parameters: the acceleration spectrum. The standard spectrum $\propto \gamma^{-2}$ was assumed.
- One has very few freedom!!!

Results

- Adiabatic cooling rate from X-ray data
- Good agreement with HESS fluxes
- Acceptable agreement with HESS spectral indexes
- Testable prediction for Fermi

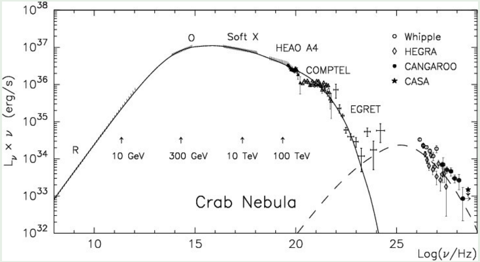


Outline

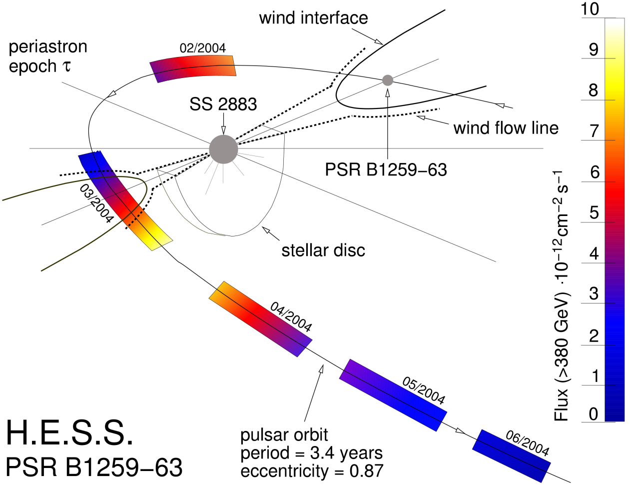
Crab Pulsar (II)

Crab Nebula

Aharonian&Atoyan, 1998

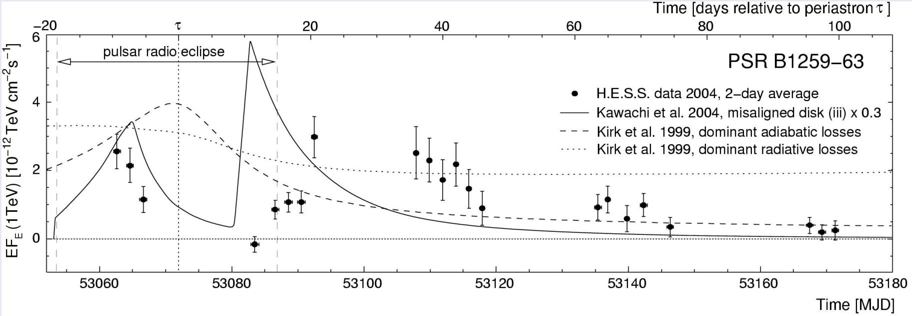


Observation of PSR B1259 with HESS



Observation of PSR B1259

HESS results are in contradiction with theoretical predictions



Possible Correlation between different energy bands

X-ray and radio emission show similar lightcurves!

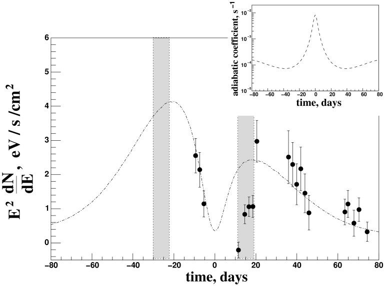
PSR B1259: Interpretation of Observation in Frameworks of a One-zone Model

Non-Radiative Loses

$t_{\rm ad} \ll t_{\rm syn}, t_{\rm IC}$ $\quad L_{\rm IC} = \frac{1/t_{\rm IC}}{1/t_{\rm ad}} L$ $\quad L_{\rm syn} = \frac{1/t_{\rm syn}}{1/t_{\rm ad}} L$

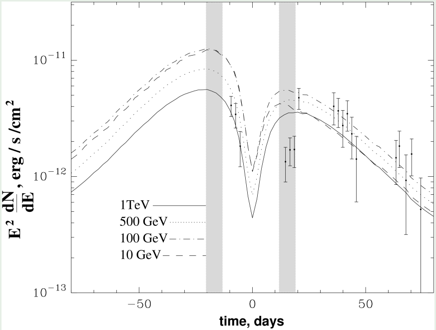
$t_{\rm syn}, t_{\rm IC} \propto D^{-2}$

This implies a very strong dependence of adiabatical losses $\Longrightarrow$

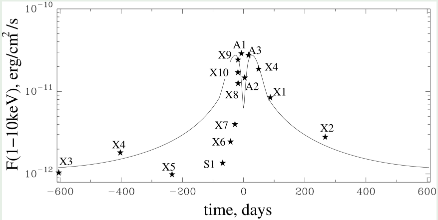


PSR B1259: Adiabatical Losses (Khangulyan et al, 2007)

Gamma-ray Lightcurve



X-ray Lightcurve



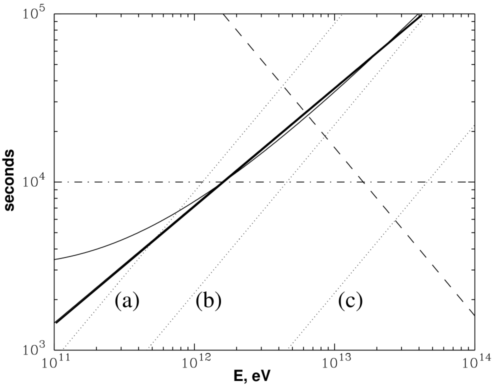
Discrepancy

Possible influence of a dense stellar disk?

PSR B1259: Interpretation of Observation in Frameworks of a One-zone Model

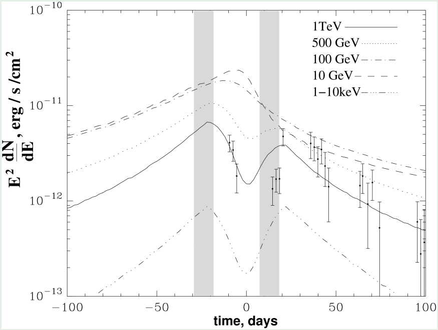
Sub-TeV cutoff

Competition between acceleration process and energy loss mechanisms leads to formation of an orbital phase dependence of maximum energy in the accelerated particle spectrum

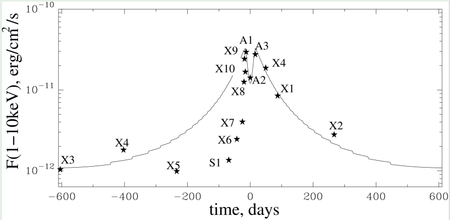


PSR B1259: Sub-TeV cutoff (Khangulyan et al, 2007)

Gamma-ray Lightcurve



X-ray Lightcurve



Discrepancy

Possible influence of a dense stellar disk?

PSR B1259: HD study

Motivation

- The leptonic one-zone models require additional assumptions:
  - Adiabatical losses⇒HD (MHD)
  - Acceleration efficiency may be linked to shock conditions⇒HD (MHD)
- Development of a "multi-zone model" require an adequate description of the system⇒HD (MHD)

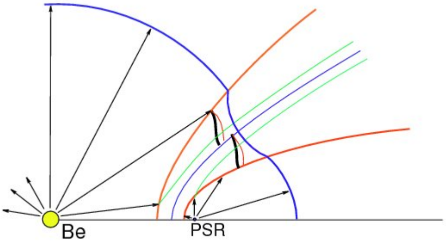
Hydrodynamics

- Hard to predict the result of two wind collision⇒HD (MHD) simulations are required

PSR B1259: HD model (Bogovalov et al, 2008)

Basic Assumptions

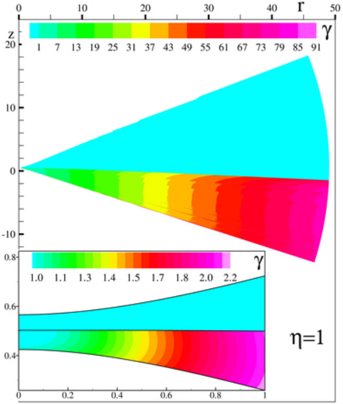
- HD
- Two radial winds
- Pulsar wind is ultrarelativistic
- Stellar wind is non-relativistic
- Steady sate
- Two dimensional



PSR B1259: HD results (Bogovalov et al, 2008)

Main Results

- High bulk Lorenz factors ($\Gamma \sim 100$)
- Unclosed structure of shock waves ($\eta > 10^{-2}$)
- Significant acceleration even if η is very small



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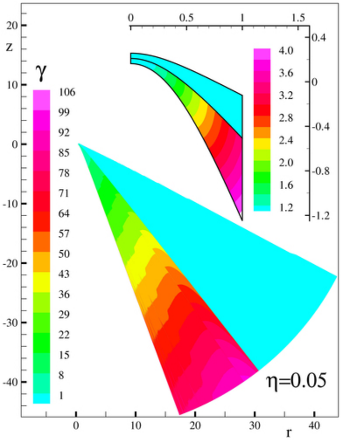

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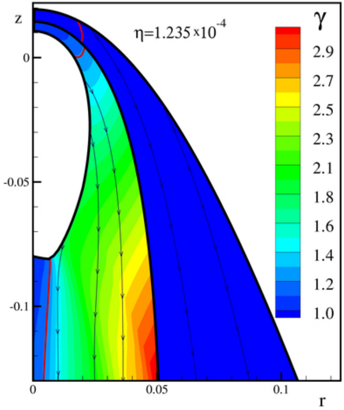
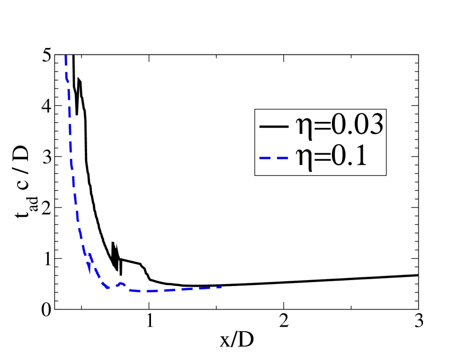


Implications of the HD calculations (still in progress...)

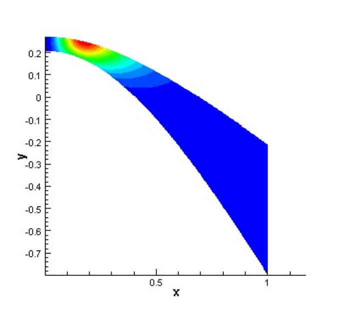
Adiabatical losses in binary pulsar



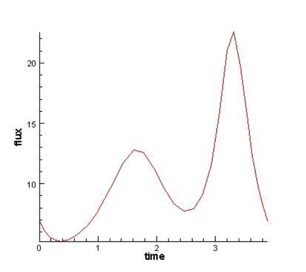
from Khangulyan et al, 2008

Implications of the MHD calculations (still in progress...)

Synchrotron emissivity



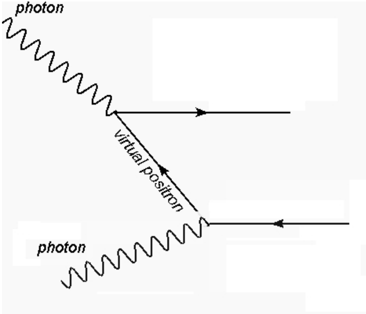
Impact of Doppler boosting on the light-curve



In preparation....

Outline

Gamma-Gamma Absorption

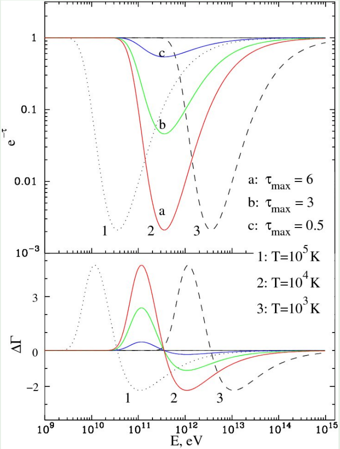


Gamma-Gamma Absorption in Binary Systems

Dense Radiation Field

- Optical Star Photons: $\epsilon \sim 2\, T_4$ eV, $w \sim 3 \cdot 10^2 L_{38} R_{12}^{-2} \mathrm{erg/cm^3}$,
- γ–γ Opacity
  $\tau = \sigma_{\gamma-\gamma} n_{\rm ph} R \sim$
  $E_\gamma \sim 0.4 T_4^{-1}$ TeV$\Longrightarrow \tau \sim 10 R_{12}$

Absorption Impact



Gamma-Gamma Absorption

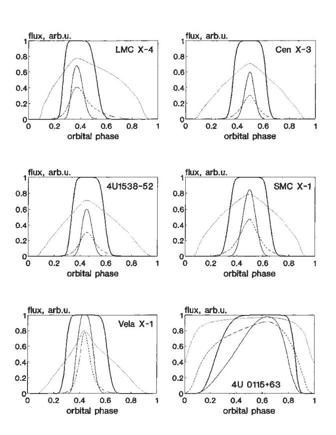
- Variability
- Softening/Hardening
- Secondaries
- Cascading

Gamma-Gamma Absorption in Binary Systems

"Evolution"

- Moskalenko&Karakula, 1994
  - Emitter located in the orbital plane
- Böttcher&Dermer, 2005
  - Emitter located in the jet
- Dubus, 2006
  - Emitter located in the orbital plane
  - Finite Size of the star

Moskalenko&Karakula, 1994



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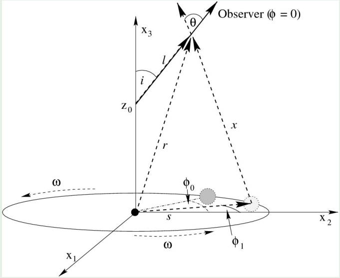

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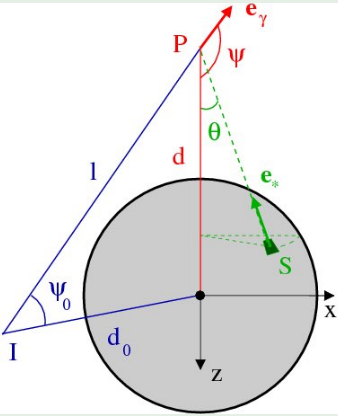
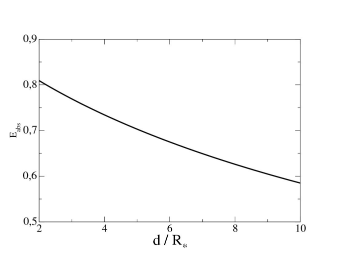


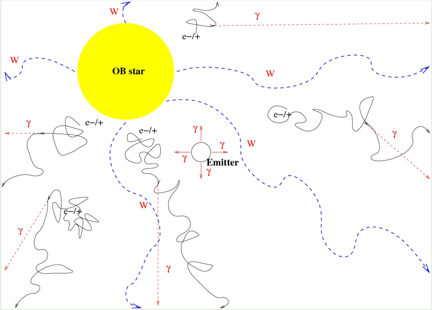
An Additional Emitting Component?

Fraction of Absorbed Energy



from Khangulyan et al, 2008

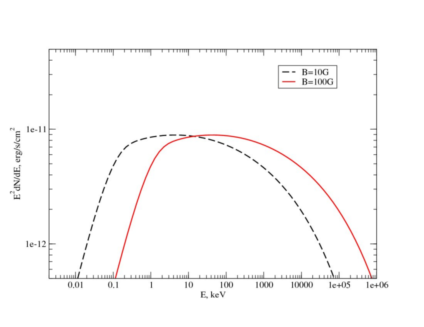
Absorption



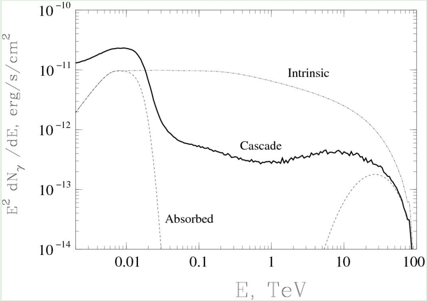
from Bosch-Ramon et al, 2008

Radiation of Secondary

Strong Magnetic Field



Weak Magnetic Field



Calculations for LS 5039 from Khangulyan et al, 2008

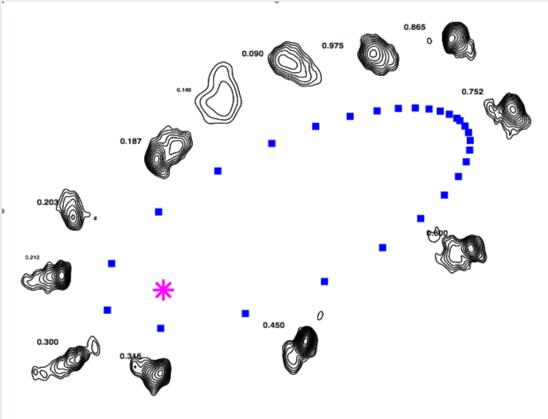
Cascading (Khangulyan et al, 2008)

- K-N regime $E_e \gg \frac{m^2c^4}{\epsilon_{ph}} = 30\left(\frac{\epsilon_{ph}}{10\mathrm{eV}}\right)^{-1}$ GeV
- $t_{IC} < t_{syn}$

$$E_e < 60\left(\frac{w_{pf}}{10w_{mf}}\right)^{0.6}\mathrm{GeV} = 60\left(\frac{B_{wind}R}{100\mathrm{G}R_{surf}}\right)^{-1.2}\mathrm{GeV}$$

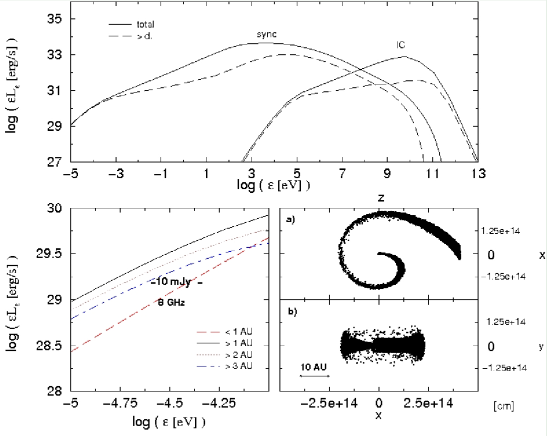
- B_{surf}= 200 G – 1 kG (Usov & Melrose (1992), Donati et al. (2002))
- For $B_{wind} \sim 10\left(\frac{R}{Rsurf}\right)^{-1}\mathrm{G} \longrightarrow$ NO CASCADING in TeV band
- For $B_{wind} \sim 100\left(\frac{R}{Rsurf}\right)^{-3}\mathrm{G} \longrightarrow$ NO CASCADING in TeV band

LS I +61 303 is a Be-Pulsar binary, not a Microquasar?



from Dhawan et al, 2006

LS I +61 303 is a TeV emitter?



from Bosch-Ramon et al, 2008

Summary

General

- Leptons are very attractive in the binary system context
- VHE emitter create a population of non-thermal particle in binary system
- HD/MHD simulations have very fundamental implications
- There are a LOT of open (interesting!) questions: acceleration, accretion, 3D cascading.....

Summary(I): Leptonic Model for PSR B1259

- One-zone modeling requires additional assumptions
- Scenario of a compactified nebula is unlikely
- Significant bulk acceleration
- Adiabatic losses are important
- Significant bulk acceleration even in the nearest zone $\Longrightarrow$ Radiative outcome is strongly anisotropic, and hard to estimate
- Correlation between different energy band is expected

Summary (II): Leptonic Model for LS 5039

- X-ray observations appeared to be crucial for one zone modeling
  - The parameter space is very restricted
  - Testable predictions in MeV, GeV and TeV energy bands
- Disfavours “standard” pulsar models (distant location of the production region)
- Disfavours microquasar models (higher energy budget)
- Being roughly consistent with one zone model, recalls for more detailed studies....