Where we failed with MAGIC

(a few personal surprises)

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Massive binaries → Cyg X-3 (Sco X-1, Her X-1 ?)

Łódź 14.02.2005

MAGIC observation project:

OBSERVATIONS OF THE HIGH MASS BINARIES

Principal investigator: Włodek Bednarek
(on behalf of the Lodz group)

Responsible for data analysis: Dorota Sobczyńska, Piotr Jacoń

Motivation

High Mass X-ray Binaries (HMXBs) containing a compact objects have been suspected for a long time as sites of high energy processes. In fact, a few HMXBs have been identified with the EGRET sources: LSI+61^o303 (2EG J0241+6119 - Thompson et al. 1995), Cyg X-3 (2EG J2033+4112 - Mori et al. 1997), Cen X-3 (GeV source - Vestrand et al. 1997), LS 5039 (3EG J1824-1514 - Paredes et al. 2000). Also the TeV γ-ray signal has been reported from Cen X-3 which contains a slow pulsar (Chadwick et al. 1998, 1999) and recently from the Be binary PSR B1259-63, containing an energetic pulsar (Schlenker et al. 2004). The γ-ray flux from this last source has been estimated on $\sim 5\%$ of the Crab flux at > 350 GeV.

Microquasar → Cyg X-3 (cont.)

Proposed objects

We propose to observe 2 HMXB visible from the northern hemisphere from which the γ-ray emission above 100 MeV have been reported and is expected to extend up to (or above) $\sim$ 100 GeV.

1. *(LS I+61°303/2CG 135+01/2EG J0241+6119)* seems to be similar to PSR 1259-63 but companion stars are much closer to each other. A compact object (probably a neutron star) is on an orbit around the Be type star. Both sources have similar X-ray luminosity. LS I+61°303 is relatively close, $\sim$ 2 kpc, and has the orbital period $\sim$ 26 days which allow investigation of the binary when the compact object is at different distances from the massive star. LS I+61°303 has been observed by the Whipple at energies > 350 GeV and > 500 GeV (Hall et al. 2003). Reported flux upper limit $\sim 9 \times 10^{-12}$ cm^{-2} s^{-1} is a factor of $\sim$ 3 below the extrapolation of the EGRET spectrum which extends up to $\sim$ 10 GeV. However such result is not surprising since a significant part of γ-rays produced inside this binary with energies greater than $\sim$ 100 GeV should be absorbed in the radiation field of the massive star (see e.g. calculations by Sierpowska & Bednarek 2003, 28th ICRC - Tsukuba). We would like to observe this source on a level of 5% of the Crab signal, i.e. comparable to the HESS observation of the binary PSR 1259-63/Be at energies close to $\sim$ 100 GeV..

2. *(Cyg X-3/ 2EG J2033+4112)* This very luminous source, $\sim 10^{38}$ erg/s in X-rays, is composed of a Wolf-Rayet star and a compact object on a very tight orbit with a period of 4.8 hrs. It shows frequent X-ray outbursts which power is several times larger than in the quiescent stage. Recently the upper limits on the TeV emission have been reported by both Cherenkov groups on the northern hemisphere (Aharonian et al. 2002, 2005; Lang et al. 2004). Both groups do not see the signal from Cyg X-3. However the enigmatic source at the distance of 0.6° from Cyg X-3 have been reported. The HEGRA group puts the upper limit on the flux from Cyg X-3 at a level of 1.7×10^{-13} ph cm^{-2} s^{-1} at energies above $\sim$ 0.7 TeV. In fact, so low upper limit is not very surprising since the γ-rays with energies produced within Cyg X-3 binary system should be absorbed by the thermal radiation of the luminous WR star (e.g. Sierpowska & Bednarek 2005). So then, this does not yet mean that high energy processes does not play important role in this object. We would like to observe Cyg X-3 at as low as possible energies in order to prove or disprove the importance of high energy processes in this famous object.

Microquasar → Cyg X-3 (cont.)

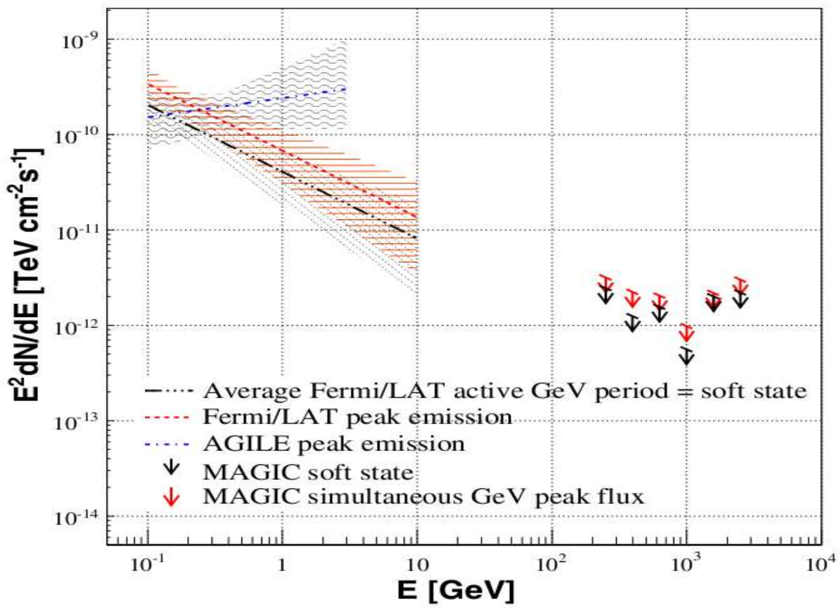

Figure 4. Cygnus X-3 SED in the high-energy and VHE bands. The lines indicate the power-law spectra derived from *Fermi*/LAT and *AGILE* integral fluxes and photon indices, where the corresponding errors were taken into account and are shown in shadowed areas. The arrows display the 95% CL MAGIC differential flux ULs, and their slope indicates the assumed power-law spectrum with a photon index of 2.6. The black indicators show the SED during the period of enhanced GeV activity coinciding with the SS, whereas the colorful ones show it during the high-energy peak emission (MJD 55031–55034).

- Does GeV spectrum continues to TeV ?
- Absorption of TeV γ-rays on stellar photons ?
- Can present telescopes answer this question ?

Novae → V339 Del (and other)

MAGIC
APPLICATION FOR OBSERVING TIME
Cycle 9

Proposal

1a. Title of proposal:	Search for TeV emission from novae.
1b. Physics Working Group:	Galactic Sources PWG

2. Abstract:

In the last few years Fermi-LAT has unexpectedly discovered GeV γ-ray emission from a few novae, in particular from a nova in a symbiotic system V407 Cygni. We investigated radiation processes due to electrons and hadrons accelerated during the explosion of a symbiotic nova. In that scenario GeV γ-ray emission is produced by the electrons with energies of a few tens of GeV in the inverse Compton scattering of stellar radiation. On the other hand, the hadrons are expected to reach larger energies, due to the lack of radiation losses during acceleration process, producing TeV γ-rays. We would like to continue and expand the search of TeV emission from novae with the MAGIC telescopes which we started in cycle 8.

3a. Principal Investigator Data (PID): (**NB:** PID has full responsibility for the content of this proposal!)

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3c. Backup Responsible if PID leaves MAGIC (BR): (**NB:** should have a permanent position)

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R. Lopez (data analysis), IFAE
J. Rodriguez Garcia (data analysis), MPI
E. Carmona, CIEMAT
S. Shore (physics discussion), INFN Pisa

5. If this is a PhD thesis project, please give name of student, supervisor and expected time of completion:

6. Proposal type: ToO proposal [X] multi-frequency campaign [ ] monitoring [ ] multi-year program [ ]

time critical, dates:

number of hours requested: in total up to 60 hours (40 dark + 20 moon)

Novae (cont.)

A&A 582, A67 (2015)

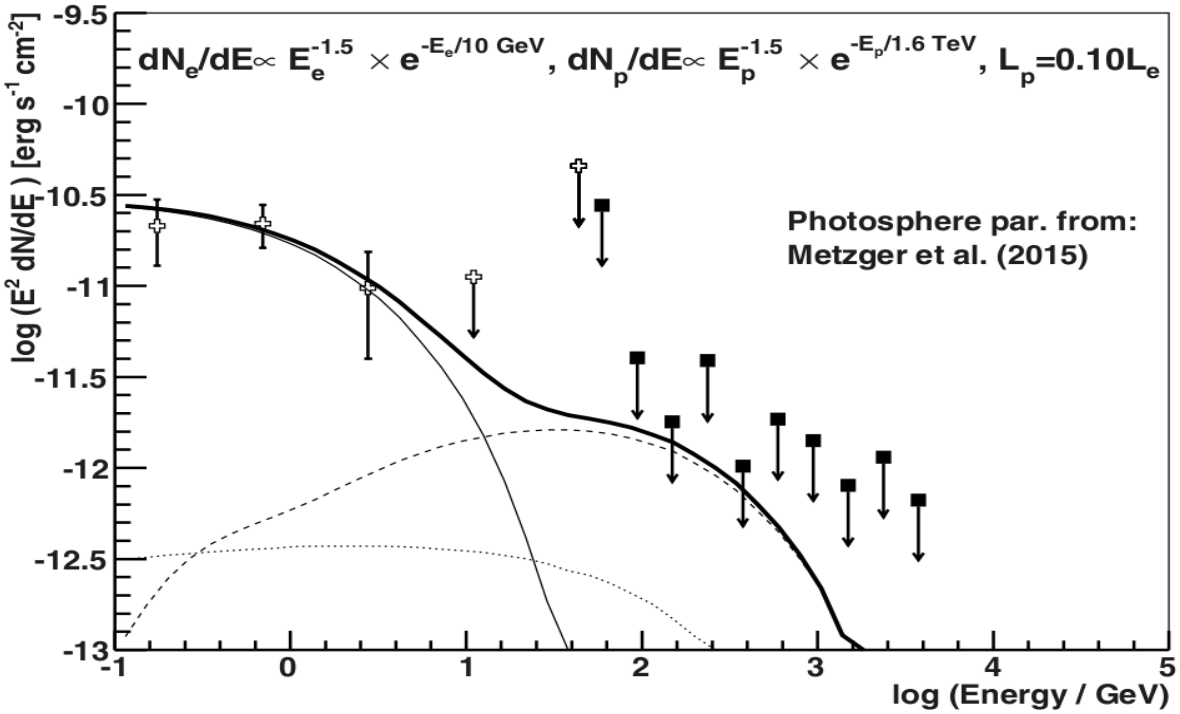

Fig. 2. Differential upper limits on the flux from V339 Del as measured by MAGIC (filled squares) and the flux measured by *Fermi*-LAT (empty crosses) in the same time period, 2013 August 25 to September 4. The thin solid line shows the IC scattering of thermal photons in the nova's photosphere. The dashed line shows the γ-rays coming from the decay of π^0 from hadronic interactions of the relativistic protons with the nova ejecta. The dotted line shows the contribution of γ-rays coming from IC of e^+e^- originating from $\pi^+\pi^-$ decays. Thick solid lines show the total predicted spectrum. The total energy of electrons is 6×10^{41} erg and the assumed proton to electron luminosity ratio is $L_p/L_e = 0.1$. Electrons and protons are injected with a power law with a spectral index of 1.5 and the cut-offs reported in the figures. Photosphere parameters (see Table 1) obtained from Metzger et al. (2015).

- **Only electrons accelerated ?**
- **Where are relativistic protons ?**
- $L_\mathrm{p}/L_\mathrm{e} < 0.1$ **!**

Milisecond Pulsar Binaries → Black Widow B1957+20

M A G I C Proposal

APPLICATION FOR OBSERVING TIME

Cycle 8

1a. Title of proposal: Searches for gamma-ray emission from the black-widow millisecond pulsar B1957+20 itself and its surrounding nebula

1b. Physics Working Group: Galactic Sources PWG + Pulsars PWG

2. Abstract:

The aim of the proposal is the discovery of sub-TeV γ-ray emission from the famous millisecond pulsar B1957+20 within the black-widow binary system and from the nebula surrounding this system. Recently, pulsed emission from B1957+20 has been discovered by Fermi-LAT. It is expected in some models that millisecond pulsars should show the sub-TeV tail in the pulsed spectrum extending to a few tens of GeV as recently discovered in the case of the Crab pulsar. Moreover, a synchrotron nebula has been discovered around the system indicating on the efficient injection of leptons by the pulsar or their acceleration at the shock between the pulsar and stellar winds. The discovery of sub-TeV gamma-ray emission from the millisecond pulsar binary systems of the black-widow type will have important concequences for the studies of acceleration processes of particles by pulsars and their binary systems.

3. Principal Investigator: (**NB:** The P.I. has full responsibility for the content of this proposal!)

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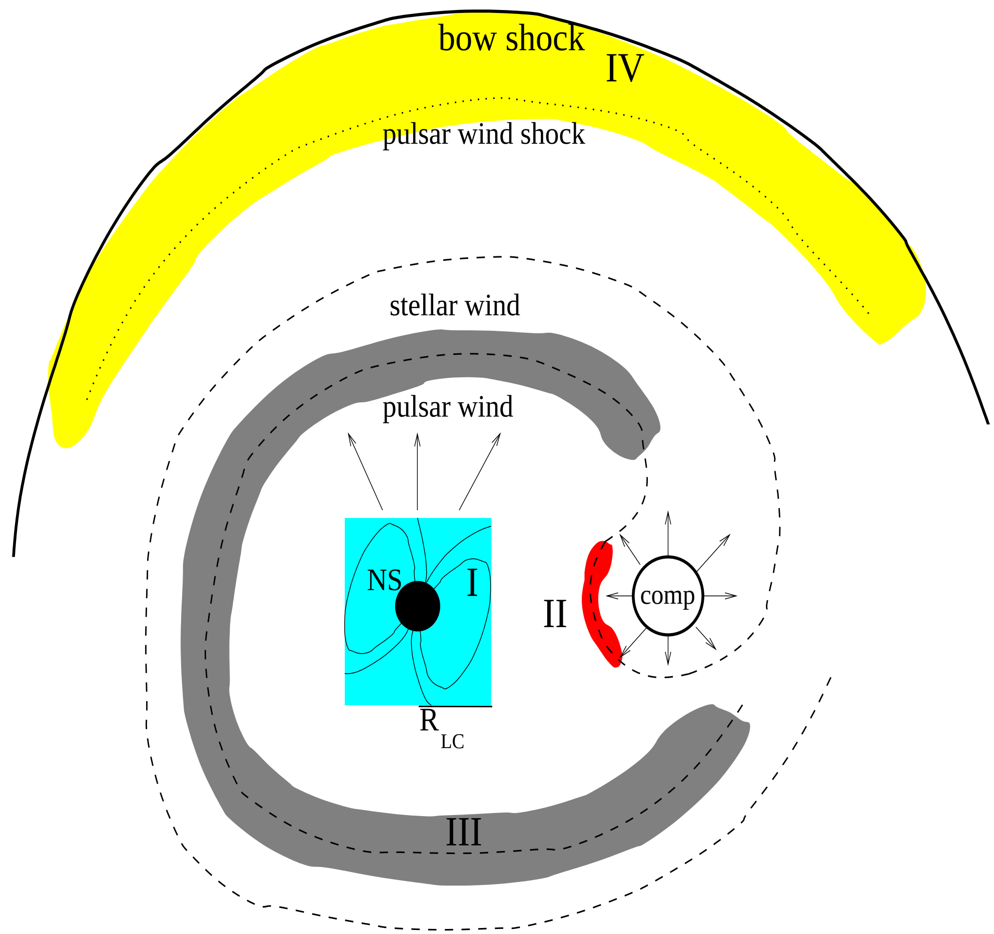

Black Widow B1957+20 (cont.)

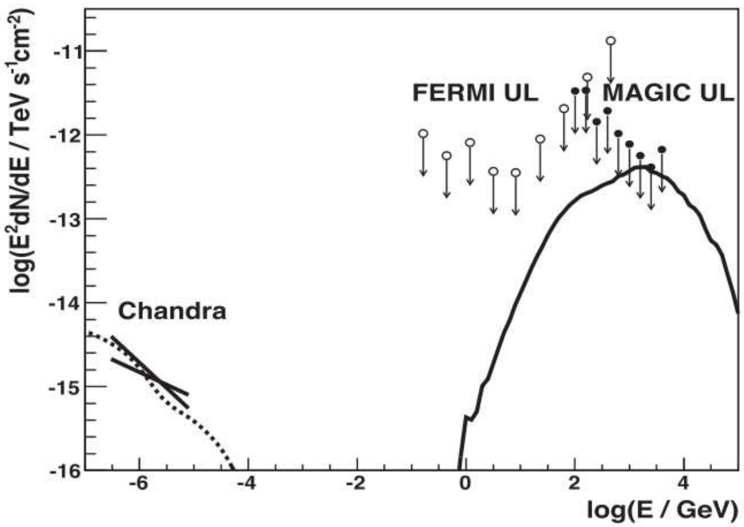

Figure 8. Comparison of the upper limits on the γ-ray emission from the nebula around the black widow binary pulsar B1957+20 obtained with MAGIC (10 arcmin radius extension assumed, filled points), *Fermi*-LAT (point-like, open points) and the X-ray tail emission detected by *Chandra* (Huang et al. 2012, thick bow-tie) with the predictions of the bow shock nebula model (region I) by Bednarek & Sitarek (2013b) (solid and dotted lines). Assumed model parameters: leptons are injected from the pulsar wind region using a power-law spectrum with an index of 2.5 between 3 and 90 TeV, the magnetization parameter of the pulsar wind $\sigma = 0.01$, the shock in the wind is located at a distance of 10^{16} cm from the pulsar and the minimum magnetic field strength within the nebula is $0.5\,\mu$G.

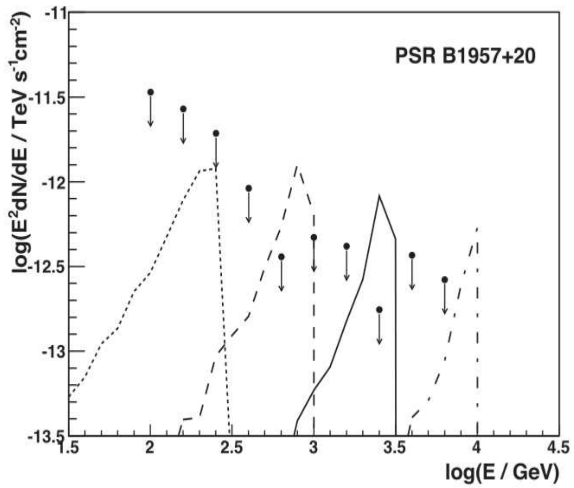

Figure 9. The comparison of the upper limits on the point-like TeV γ-ray emission from the inner part of nebula around the black widow binary pulsar B1957+20 with the predictions of the mixed wind nebula model (region II). The leptons in the model are accelerated with the mono-energetic spectrum with energies equal to 300 GeV (dotted curve), 1 TeV (dashed), 3 TeV (solid) and 10 TeV (dot–dashed). It is assumed that the factor, describing the level of γ-ray emission, is equal to $\Delta_{mix}\varepsilon = 0.1$ (see Section 4.2 for details).

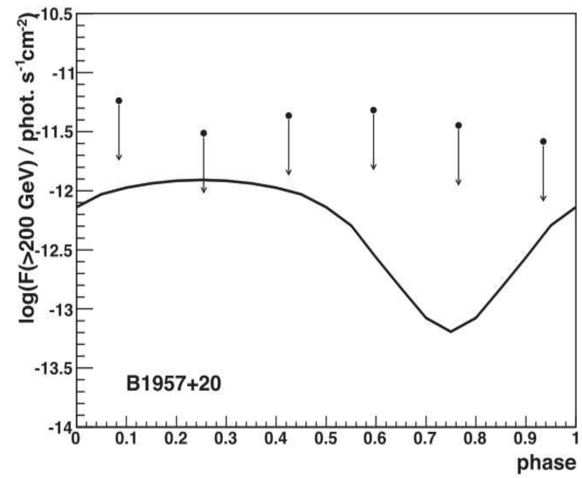

Figure 10. The comparison of the γ-ray light curve, folded with the orbital period of the system, at energies above 200 GeV, expected from the MSP binary system B1957+20 in terms of the IC model (region III) discussed by Bednarek (2014), with the upper limits on the γ-ray flux from this binary system at specific range of phases. The predicted γ-ray fluxes are obtained from the normalization of the synchrotron spectra, produced by the same population of electrons, to the observed modulated X-ray emission from this binary (see Huang et al. 2012).

- **66.5 hrs $\rightarrow$ only $\sim 2.2\sigma$ excess (10 arcmin)?**
- **Leptons not accelerated to TeV by MSPs ?**
- **No target for their interaction or not confined ?**

Globular Clusters → M13, M15

MAGIC observation of Globular Clusters in Cycle 3
Physics Working Group on Galactic Sources

1 Scientific Justification

Globular clusters (GC) contain typically $\sim 10^5 - 10^6$ late type stars inside a very small volume of the order of a few parsecs. GC are distributed spherically around our Galaxy at characteristic distances of the order of ~ 10 kpc. They also contain many millisecond pulsars and compact binary systems. More than 100 millisecond pulsars have been already detected up to now in 24 globular clusters. However, much more are expected in specific clusters. The estimates of the milisecond pulsars in a typical cluster, based on the evolution of stars, argue that a large fraction of hidden milisecond pulsars should exist. Their true number per globular cluster should be close to one hundred (Tavani 1993). It is suggested that some globular clusters may contain medium size black holes and can be surrounded by halos of dark matter particles due to the required strong gravitational potential.

It is expected that compact objects in GC can efficiently generate energy which may become a source for acceleration of particles. For example some X-ray sources (probably low mass compact binary systems) and millisecond pulsars are expected to inject energetic particles which propagate in the radiation field produced by extremely dense stellar cluster. These particles (electrons) should produce γ-rays in the MAGIC energy range as a result of inverse Compton process.

The upper limit on the GeV emission from GC have been put by the EGRET telescope on a level of $(1-2)\times 10^{-7}$ ph. cm^{-2} s^{-1} above 100 MeV (Michelson et al. 1994, Manandhar et al. 1996). There are also some limits on the TeV emission (> 500 GeV) reported by the Whipple collaboration on a level which does not constrain strongly the possible existence of energetic particles in these objects.

1.1 Gamma-ray fluxes from globular clusters

Details of the calculations of the expected γ-ray fluxes from some globular clusters are recently published in Bednarek & Sitarek (2007). We show in Fig. 1 and 2, the results of calculations compared with sensitivities of the MAGIC and other telescopes. In Table 1, we report the constraints on the injection rates (η) of leptons by milisecond pulsars present in these globular clusters. It is clear that with the MAGIC telescope, the predicted γ-ray fluxes should be detected. In case of non-detection the upper limits on η should significantly constrain the present models for the injection of leptons by milisecond pulsars.

In conclusion, M15 and M13 should be detected either by the GLAST (in the GeV energies) or Cherenkov telescopes (in the TeV energies) depending on the shape of the spectrum of injected leptons provided that: (1) leptons are accelerated up to ∼1 TeV; (2) specific globular clusters contain at least several MSPs; and (3) the power conversion efficiency from the pulsar winds to relativistic leptons is comparable to that one observed in the case of the Crab Nebula ($\eta \sim 10\%$). It is expected, that in the case of acceleration of leptons in the inner pulsar magnetosphere's, η is also of similar order, i.e. $\sim 3\%$ (Harding, Usov & Muslinov 2002).

1.2 Proposed objects

We propose two globular clusters (M15 and M13) as targets for the Cycle 3. They are selected in order to allow the lowest possible zenith angle observations with the MAGIC telescope (M15: Dec. +12.10.01., R. 21 29 58.3 and M13: +36.27.37, R. 16 41 41.5). The small zenith angle observations are specially required since leptons injected from the pulsar magnetosphere are expected to produce γ-rays with energies not much larger than ~ 100 GeV (e.g. Harding et al. 2005).

I. M15 (NGC 7078): at a distance of 9.4 kpc, belonging to the class of the core collapse globular clusters, has

CONSTRAINING PROCESSES AROUND MILLISECOND PULSARS WITH MAGIC DEEP OBSERVATIONS OF GLOBULAR CLUSTERS

(Proposal for the MAGIC Key Observation Programme)

Names of proposers

PI: Włodek Bednarek

PID PI: Julian Sitarek (Uni. Lodz)

PIT PI: Włodek Bednarek

Co-PIs: Francesco Longo, Rachele Desiante (analysis of Fermi data),
Pratik Majumdar (analysis of MAGIC data), Takauki Saito (analysis and theory advise),
...

Observation time: 150 hrs, wobble with 0.4 deg offset, maximum integration time 2 years

Abstract:

Recent discoveries of GeV γ-ray emission from several globular clusters (GCs), with the spectra very similar to those observed from the millisecond pulsars (MSPs), strongly support the expectations that these huge concentrations of old low mass stars should contain large population of millisecond pulsars. In fact, about 150 MSPs have been discovered within globular clusters in radio observations. Theoretical predictions of the stellar encounter rates in GCs and estimates, based on the comparison of the γ-ray fluxes from GCs and isolated MSPs, allow to conclude that specific GCs may contain up to a few hundred MSPs (see Fig. 1). MSPs are able to accelerate leptons to TeV energies. Leptons find well defined background for the Inverse Compton scattering provided by the thermal radiation from low mass stars. Therefore, GCs are very interesting targets for TeV γ-ray astronomy.

However, up to now only one TeV γ-ray source has been found in the direction of globular cluster Ter 5 by the HESS array. The relation of this source to Ter 5 is not at present completely certain due to the off-set of the TeV source from the GC center by the distance corresponding to the half mass radius of GC (see Fig. 3). Other collaborations invested only limited amount of time (typically several hours) on these very interesting candidate TeV sources.

Clear detection of the TeV γ-ray emission from GCs will provide very important tool for investigating in detail the processes occurring within the inner pulsar magnetospheres, their wind regions and termination shock regions. From the observations of Pulsar Wind Nebulae (PWNe) around classical pulsars we already know that acceleration of leptons occur there to over TeV energies very efficiently. Similar processes are expected to occur in the vicinity of MSPs. However, in contrast to PWNe, MSPs in GCs interact with very well defined background radiation field which allow detailed study of the acceleration processes within and around pulsars since the number of uncertainties are reduced. The level of TeV emission from GCs should depend on the number of MSPs and efficiency of energy conversion from pulsars to relativistic leptons. The first parameter can be constrained by e.g. Fermi obs. but the second one by Cherenkov obs.

In this Key Observation Programme we request for deep observation of one GC on the northern hemisphere. We analysed (F. Longo + R. Desiante) 6 years of Fermi data available for 4 massive GCs (M15 - 8 known radio MSP, M13 - 5, M5 - 5, and M3 - 4). The analysis indicates that M15 is within the direction of the Fermi source (see Table 1). The observed flux allows us to estimate the number of MSPs in this cluster. The observation time should be of the order of 150 hrs in order to allow to constrain the efficiency of lepton acceleration in the vicinity of MSPs on the level of a few 10^{-3}, allowing to test the models for acceleration of leptons in the pulsar vicinity.

The detection of TeV γ-ray emission from GC will be the first explicit indication of the acceleration of leptons in the vicinity of MSPs, supporting the theoretical and observational conclusions on the similarity of acceleration processes in the classical and millisecond pulsars. Such observations will provide constraints on the models of pulsar inner magnetospheres (injection rate of leptons), the pulsar wind and collision regions and also put new light on the

Globular Clusters → M13 (cont.)

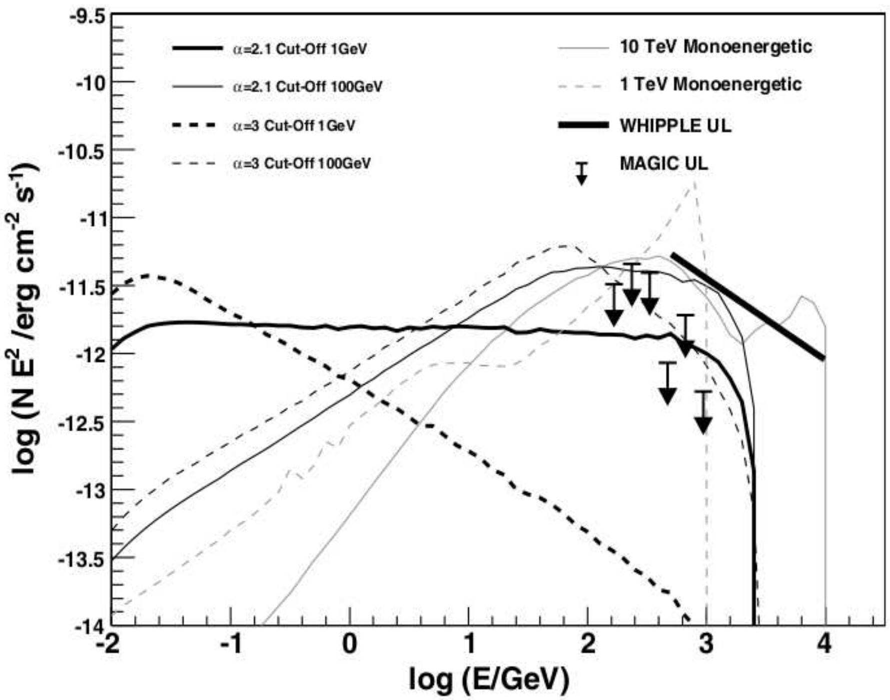

Figure 2. MAGIC γ-ray flux upper limits for M13 compared with spectra expected for the range of parameters of the model shown in Figures 9 and 10 of Bednarek & Sitarek (2007). The specific γ-ray spectra are calculated for lepton upper energy cutoff at 3 TeV and lower energy cutoff at 1 GeV (black thick) and 100 GeV (black thin), and power-law spectral indices of 2.1 (solid) and 3 (dashed). The γ-ray spectra produced by monoenergetic leptons of 10 TeV and 1 TeV are shown by a gray solid curve and a dashed one, respectively. All calculations are computed assuming the conservative value of 1 for the free parameter of the model $N_{\mathrm{MSP}} \cdot \eta$. The Whipple differential upper limit shown here has been derived from the integral quoted in Hall et al. (2003) assuming a spectral index of 2.6.

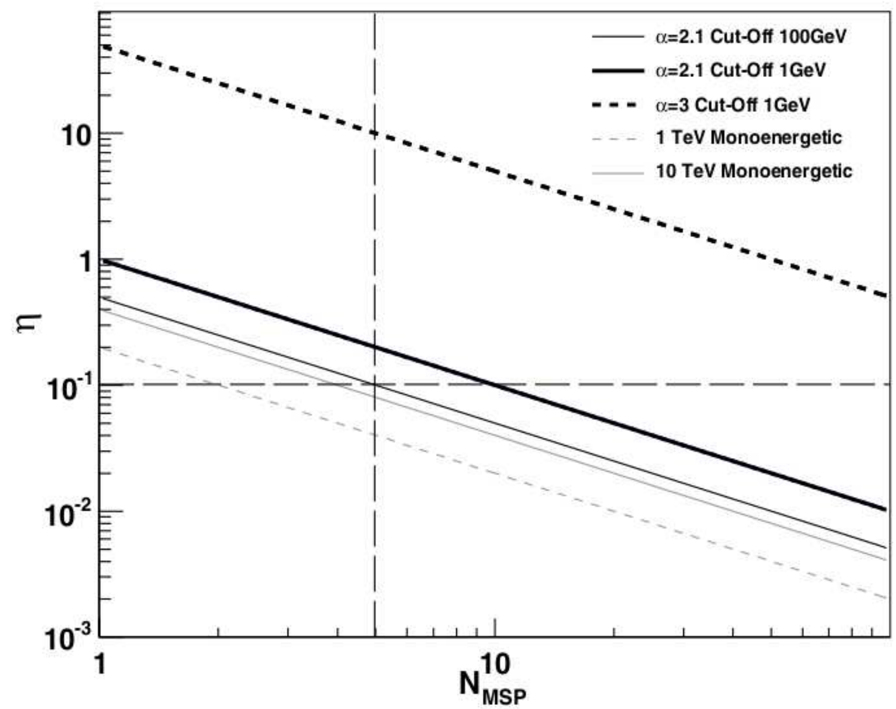

Figure 3. Exclusion contours in the N_{MSP}, η plane for the different models considered in the text. The model with parameters $\alpha = 3$ and cutoff at 100 GeV overlaps the $\alpha = 2.1$ with cutoff at 1 GeV one. The horizontal and vertical long-dashed black lines show the reference values of $\eta = 0.1$ and $N_{\mathrm{MSP}} = 5$ respectively.

Globular Clusters → M15 (preliminary)

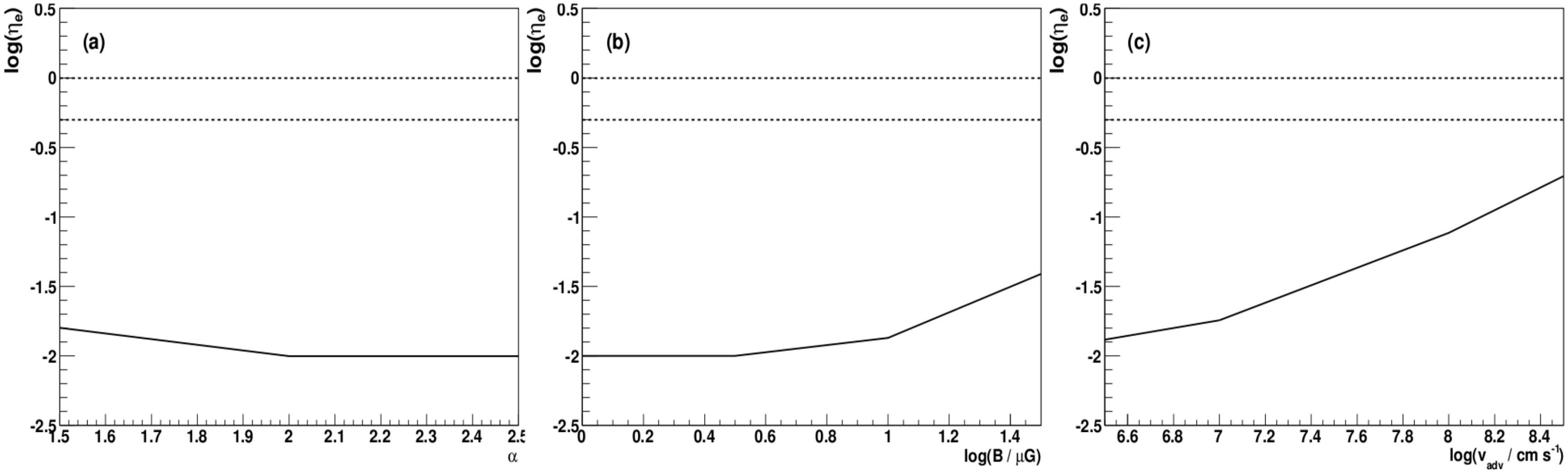

Figure 7. Constraints on the coefficient, η_e, of the conversion of the energy loss rate of MSPs to the $e^{\pm}$ pairs in GC M15 in the case of injection of leptons with the power law spectrum from the pulsar wind collision regions. The limits on η_e are obtained for the specific propagation and injection models corresponding to the figures (a), (b), and (c) as shown in Fig. 6. The dotted line mark the level of the energy conversion efficiency from the pulsars to leptons equal to 100%.

- **If no advection of leptons:**

$$\Downarrow$$

Energy in TeV $e^{\pm}$ pairs $\sim 1\%$ of L_{MSP} → Below theoretical predictions

- **$e^{\pm}$ pairs effectively advected from globular cluster !**