

Searches for periodic neutrino emission from binary systems with 22 and 40 strings of IceCube

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ABSTRACT

In this paper we present the results of searches for periodic neutrino emission from a catalog of binary systems. Such modulation, observed in the photon flux, would be caused by the geometry of these systems. In the analysis, the period is fixed by these photon observations, while the phase and duration of the neutrino emission are treated as free parameters to be fit with the data. If the emission occurs during $\sim 20\%$ or less of the total period, this analysis achieves better sensitivity than a time-integrated analysis. We use the IceCube data taken from May 31, 2007 to April 5, 2008 with its 22-string configuration, and from April 5, 2008 to May 20, 2009 with its 40-string configuration. No evidence for neutrino emission is found, with the strongest excess occurring for Cygnus X-3 at 2.1σ significance after accounting for trials. Neutrino flux upper limits for both periodic and time-integrated emission are provided.

1. Introduction

Recently, the observation of Very High Energy (VHE) γ -ray emission from several high mass X-ray binaries has established a new subclass of VHE or “ γ -ray-loud” binaries. While much of the evidence from multi-wavelength observations favors leptonic emission, it is likely that a hadronic component is also accelerated in the jets of these binary systems. These binary systems are powerful

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accelerators with jets capable of accelerating cosmic rays and can have a role as PeVatron accelerators of galactic cosmic rays. The observation of neutrino emission would be clear evidence for the presence of a hadronic component in the outflow of these sources. Four such binary systems, PSR B1259-63, LS 5039, HESS J0632+057, and LS I +61° 303, have been identified as persistent TeV γ -ray emitters (Aharonian et al. 2005a,b, 2007; Albert et al. 2006), while Cygnus X-1 is a possible candidate. The binary pulsar system PSR B1259-63 was also recently discovered to have periodic emission in GeV photons (Abdo et al. 2011). PSR B1259-63 is formed by a B2Ve star orbited by a young 48 ms pulsar (Tavani & Arons 1997) both exhibiting a strong wind. As observed in (Aharonian et al. 2005a), its VHE emission could come from Inverse Compton scattering on shock-accelerated leptons from the interaction zone between the pulsar and wind from the star though a hadronic interpretation cannot be excluded. On the other hand, the driving factor of the VHE emission in Cygnus X-1, most probably a black hole orbiting a super-giant O9.7 star (Ziółkowski 2005), could be the interaction of the black hole with the strong stellar wind of the star. However, there has been no other evidence for steady VHE emission of Cygnus X-1, though a VHE flare of about 1 h was observed (Albert et al. 2007). HESS J0632+057 was recently seen to have a periodic modulation in X-rays by Swift, with heightened TeV emission coincident with the X-ray maximum (Bongiorno et al. 2011).

LS I +61° 303 remains a mystery even after four decades of observations over a wide range of wavelengths, from radio (Gregory 2002), soft and hard X-ray (Torres et al. 2010; Li et al. 2011; Zhang et al. 2010; Sidoli et al. 2006; Harrison et al. 2000), GeV (Abdo et al. 2009a) and TeV photons (Albert et al. 2009; Acciari et al. 2009). The best measurement of its period, $P_1 = 26.4960 \pm 0.0028$ d, comes from radio data (Gregory (2002) and references therein) with the orbital zero phase taken by convention at JD 2443366.775 (Gregory & Taylor 1978), but the same modulation has also been detected in other wavelengths, notably in the GeV/TeV band emission (Abdo et al. 2009a; Albert et al. 2009). Together with LS 5039, discovered in the TeV γ band (Aharonian et al. 2005a), LS I +61 303 lacks a strong evidence supporting the black hole or neutron star nature of the compact object. This prevents clear classification of them as microquasars or pulsar systems (Paredes (2011); Paredes et al. (2000); and references therein). A discussion of the different theoretical models for these systems is presented in Bosch-Ramon & Khangulyan (2009). As with all of the binary systems above, the detection of multi-TeV neutrinos would complement the VHE photon observations and unequivocally prove the existence of hadronic acceleration.

The analysis in this paper has been performed using a likelihood method in which the underlying hypothesis is that the neutrino emission is periodically modulated due to the geometry of the X-ray binary systems. Neutrinos would be produced by a beam of hadrons accelerated by the compact object and interacting with the matter of the massive star and its atmosphere. The periodic modulation would be connected to the orbital motion of the system. This modulation is observed in photons from radio to X-ray, and in the VHE band. The analysis is designed to incorporate only minimal assumptions regarding the neutrino emission. The period is fixed to that observed in an electromagnetic band, while the phase and duration of neutrino emission are free parameters and not constrained to match the photon emission. This is to account for the fact that photons can be absorbed when the accelerator is behind the large star of the binary system while

neutrino production can be enhanced if enough matter is crossed. The neutrino energy spectrum is fit with a simple power law with the index also a free parameter.

The paper is organized as follows. In Sec. 2 we describe the IceCube observatory and the data taken with two detector configurations (Achterberg et al. 2006). The analysis method is described in Sec. 3, and the expected sensitivity and discovery potential are shown. To avoid bias, the search has been performed in a blind fashion by defining cuts before looking at the true times (equivalently, the right ascension values) of the final event sample. In Sec. 4 we present the results of the search performed on a catalog of seven galactic binary stars in the Northern sky. The selected objects are considered as microquasars in Distefano et al. (2002), where their expected emission of neutrinos is calculated. While that paper is not specifically about the periodic emission from these sources, nonetheless the objects considered there are promising neutrino emitters for which radio observations allow identification of jet parameters such as the Lorentz factor and the luminosity of the jet. All of the sources considered are located in the Northern Hemisphere, where IceCube is most sensitive (Abbasi et al. 2011).

2. The IceCube data

Construction of the IceCube Neutrino Observatory started with a first string installed in the austral summer of 2005/2006 (Achterberg et al. 2006) and was completed in December 2010. It is composed of an array of 86 strings with a total of 5160 Digital Optical Modules (DOMs) instrumented between a depth of 1,450 and 2,450 m. The deep ice detector is complemented at the surface by the extensive air shower array IceTop. Each DOM consists of a 25 cm diameter Hamamatsu photomultiplier (Abbasi et al. 2010) and electronics to digitize the PMT output voltage (Abbasi et al. 2009b), all in a spherical, pressure-resistant glass housing. IceCube observes the Cherenkov photons emitted by relativistic charged particles produced in high-energy neutrino interactions. The PMT signals are digitized and the charge and arrival time of photons measured. The data taking and performances of the detector during the two seasons analyzed here are described in Abbasi et al. (2009a) and Abbasi et al. (2011). The main background comes from down-going muons due to cosmic ray interactions in the atmosphere above the detector: in the 40-string configuration these trigger the detector at a rate of about 950 Hz and in the 22-string configuration at about 350 Hz. During the austral summer the atmosphere above the South Pole gets warmer and thinner and the probability of pions generated in cosmic ray air showers to decay rather than interact increases (Tilav et al. 2009), causing the trigger rate to vary by about $\pm 10\%$. A series of event selections and higher-level event reconstructions are applied to remove these downward-going events, while retaining upward-going tracks from muons induced by neutrinos which crossed the Earth. At the final level of analysis, this remaining background of upward-going atmospheric neutrinos comes from many different directions on the other side of the Earth. Temperature effects average over a wide terrestrial region and the seasonal modulation is only a few percent. This variation has a period of one year, much longer than any period considered in this search.

The searches presented here used two data samples. The data taken with the 22-string con-

figuration have a livetime of 275.7 days, 89% of the operation period from May 31, 2007 to April 5, 2008, or Modified Julian Date (MJD) 54251-54561. The sample is described in Abbasi et al. (2009a), and consists of 5114 events, which are mostly neutrino induced upward-going muons with declinations from -5° to $+85^\circ$. The deadtime is mainly due to test and calibration runs during and after the construction season. The livetime of the 40-string data used in analysis is 375.7 d which is 92% of the nominal operation period from April 5, 2008 to May 20, 2009 (MJD 54561-54971). The handling and processing of the data to obtain the final neutrino candidate event sample are fully described in Abbasi et al. (2011). The final 40-string sample contains 36,900 atmospheric neutrino and muon events distributed over the whole sky, of which 14,121 events are upward-going (the rest are downward-going events from the Southern Sky, used for neutrino source searches strictly above PeV energies). The median angular resolution for the final sample for energies greater than 10 TeV is $< 1^\circ$. The energy of each event is estimated using the density of photons along the muon track due to stochastic energy losses of pair production, bremsstrahlung and photonuclear interactions which dominate over ionization losses for muons above 1 TeV. The energy resolution is about 0.3 in \log_{10} of the muon energy in the detector between 10 TeV and 10^5 TeV. The estimated muon energy is a lower bound on the primary neutrino energy, since for interactions that occur outside the detector the muon loses energy over an unknown distance before reaching the detector. (Energy distributions used internally within the analysis therefore refer to the observable muon energies.) The muon neutrino flux upper limits at 90% CL for time-integrated searches (depending on declination) are between $E^2 dN/dE \sim 3 - 20 \times 10^{-12} \text{ TeV cm}^{-2} \text{ s}^{-1}$ in the northern sky where the sources considered in this paper are located.

The 22 and 40-string data samples used in this paper were also used to look for bursting neutrino sources in Abbasi et al. (2012) where the stability of the data taking is discussed in detail. Azimuthal geometry effects of the 22 and 40-string IceCube detectors (due to the fact that they are more elongated in one direction than in others) and the rotation of the Earth interfere constructively for source periods that match to multiples of a half sidereal day, which is not the case for any of the source periods tested.

The limits in this paper were produced assuming a flux of only muon neutrinos and antineutrinos at the Earth with simulated energies from 10^8 to 10^{19} eV. For standard neutrino oscillations over astronomical distances (Athar et al. 2000), equal fluxes of all neutrino flavors at the Earth are expected from a source producing neutrinos via pion decay with a ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. For the assumption of equal fluxes of muon and tau neutrinos at the Earth, the resulting upper limits on the sum of both fluxes are about 1.7 times higher than if only muon neutrinos are considered (Abbasi et al. 2011). This sets better limits than the expected factor of two due to oscillations if no tau neutrinos were detectable. This is due to the tau decay channel into muons with a branching ratio of 17.7%. In addition to this, tau leptons with energy greater than several PeV that may travel far enough to be reconstructed as tracks in IceCube before decaying. For an E^{-2} neutrino spectrum, the contribution due to the detectable tau neutrino flux for sources at the horizon is 10% and rising to 15% for sources in the Northern hemisphere.

The main systematic uncertainties on the flux upper limits come from photon propagation in

ice, absolute DOM efficiency, and uncertainties in the Earth’s density profile and muon energy loss. For an E^{-2} spectrum, the estimated total uncertainty is about 16% (Abbasi et al. 2011). They are included in the upper limits calculations following the method of Conrad et al. (2003) with the modification described in Hill (2003).

3. Method

The likelihood method used in this analysis was described in full detail and demonstrated in Braun et al. (2008, 2010), and applied to the 40-string data in Abbasi et al. (2012). In the likelihood ratio method, the data are modeled as a combination of signal and background populations. The probability density functions (PDFs) for signal and background consist of three terms: a space term, an energy term and a time term. The first two are implemented in the same way as in Abbasi et al. (2011). For signal, the space term characterizes the clustering of event directions around the hypothesized source location (effectively, the point spread function for the reconstructed muon, since the interaction angle between the incoming neutrino and outgoing muon is subdominant at the energies of these data samples). For background, the space term is simply estimated by time-scrambling of the real data. The energy term for background is similarly a PDF built from the energy estimates of events in the real data (selected from a declination band similar to the declination of the source being searched for). For signal, distinct energy PDFs are constructed for simulated events arising from a range of neutrino source spectra from E^{-1} to E^{-4} . The chief purpose of the energy term in this search is not to determine the spectrum of the source (if one were detected). Rather, it is to enhance the detectability of a source if its spectrum is relatively hard (e.g. E^{-2}) by leveraging the difference in the energy distribution of the signal events compared to nearby background events, which are primarily atmospheric neutrinos with a soft ($\sim E^{-3.7}$) spectrum.

The third term in the PDF incorporates timing information. For signal, a periodic emission with Gaussian time profile is assumed. The period is fixed to that determined by photon observations, while the phase and duration of the neutrino emission are left as free parameters. A Gaussian shape is used for the profile to provide a smooth function with the fewest assumptions about the exact time profile of the neutrino emission. The time PDF for the i th event can thus be expressed as:

$$S_i^{\text{time}} = \frac{1}{\sqrt{2\pi}\sigma_T} e^{-\frac{|\varphi_i - \varphi_0|^2}{2\sigma_T^2}}, \quad (1)$$

where σ_T is the width of the Gaussian, φ_i is the phase of the event and φ_0 is the phase of the peak of the neutrino emission. The fit parameters are σ_T and φ_0 . For background, the time term is a flat function, because in the absence of detector biases the background events are randomly distributed in time.

For each candidate source, the likelihood ratio analysis finds best-fit values for four parameters: the number of signal events, the spectral index of the signal, the peak phase of the signal and its duration. An initial estimate of the significance is made by assuming the likelihood ratio follows a χ^2 distribution and converting to a (pre-trial) p-value. To ensure a robust estimate of the final

significance, however, this assumption is not used, and a correction for the number of trials is also included. For the final significance, the analysis is performed on time-scrambled data and the same catalog of sources. The final post-trial p-value is given by the fraction of analyses which yield a smaller (pre-trial) p-value for any of the sources in the catalog.

We calculate the sensitivity and median upper limit at 90% confidence level using the method in Feldman & Cousins (1998). The discovery potential is the flux required to achieve a p-value less than 2.87×10^{-7} (5σ of the upper tail of a one-sided Gaussian) in 50% of trials. It should be noted that the threshold significance to claim a discovery in IceCube is set to 5σ . Fig. 1 shows the sensitivity and the discovery potential for the analysis, together with the corresponding values from the time-integrated search (Abbasi et al. 2009a).

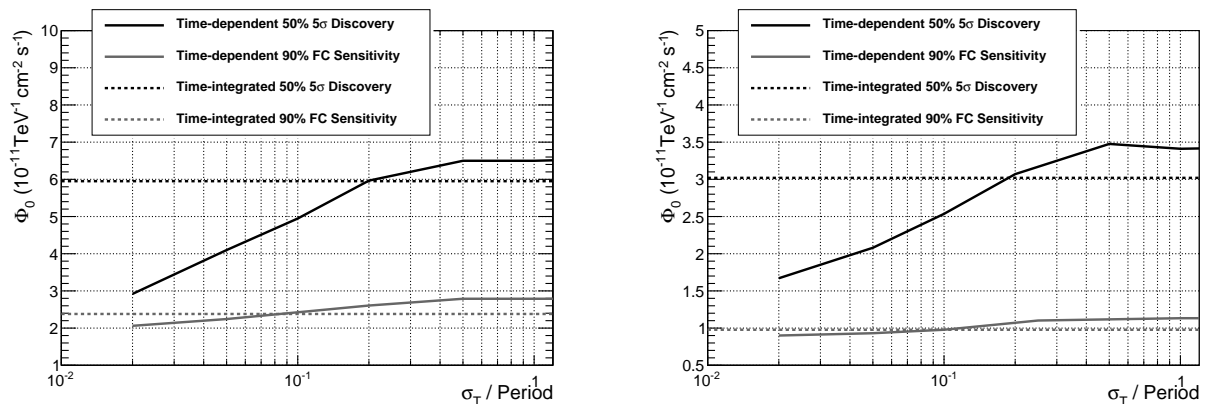


Fig. 1.— Discovery potentials (5σ in 50% trials, solid and dashed upper lines in the plot) and the average sensitivity at 90% CL calculated with the prescription in (Feldman & Cousins 1998) (solid and dashed lower lines) for the periodic search applied to the 22-string data (left) and to the 40-string data (right). The y-axis shows the flux normalization Φ_0 for a E^{-2} simple power law spectrum emission from LS I +61° 303, i.e. $d\Phi/dE = \Phi_0 (E/\text{TeV})^{-2}$. The x-axis shows the width σ_T of the Gaussian emission normalized to its period $P = 26.4960$ d. Shown are the results for the time-integrated searches (Abbasi et al. 2009a, 2011) (dashed line) and for the periodic time-dependent search (solid line). The time-dependent search sensitivity and discovery potential are expressed as the equivalent flux normalization of a steady source averaged over the period.

Compared to the time-integrated analysis, searching for periodicity in neutrino emission results in a better discovery potential if the duration of the emission σ_T is less than about 20% of the total period (see Fig. 1). As the time-dependent search adds two additional degrees of freedom to the analysis, the discovery potential is on the other hand roughly 10-15% better using the time-integrated search if neutrinos are actually emitted at a steady rate or over a large fraction of the period. For both the 22-string and 40-string analyses, if the emission has a σ_T of 1/50, the method requires about half as many events for discovery as the time-integrated search.

4. Results

The seven predefined sources, listed in Table 1, were used for the initial search with the 22-string data from 2007-2008. The most significant outcome in this sample was for the source SS 433, with a pre-trial estimated p-value of 6%. In identical analyses of time-scrambled data, we find at least one of the seven tested sources to be more significant in 35% of the analyses.

The analysis was subsequently performed on the 40-string data from 2008-2009, which provided twice the sensitivity of the previous sample (see Fig. 1). The most significant outcome in this sample was for Cygnus X-3. The pre-trial estimated p-value of this source is 0.0019. To account for trials and for the fact that the likelihood ratio is not perfectly χ^2 distributed, the analysis is performed again on time-scrambled data. An equivalent or more significant outcome from any of the sources is found in 1.8% of scrambled samples (expressed in Gaussian standard deviations, a 2.1σ excess), so the result is compatible with random fluctuations of the background. The best-fit peak emission is found to be at phase $\hat{\varphi}_0 = 0.82$, and $\hat{\sigma}_T = 0.02$. The best-fit number of source events is $\hat{n}_s = 4.28$ and spectral index is $\hat{\gamma}_s = 3.75$. The full results of the analysis on each source (with time-dependent and time-integrated flux upper limits) are given in Table 1.

Table 2 compares the 40-string time-integrated limits to the model predictions in Distefano et al. (2002) for each source. The model predicts the neutrino flux based on the radiative luminosity associated to the jet from radio observations in quiescent states and during flares the durations of which are specified in Tab. 4 in that paper. The figure shows limits for both the persistent and time-dependent cases for a time window similar to the observed flare but not coincident to it (since IceCube was not active at the time of radio observations noted in the paper). For the persistent case of SS 433 the model predicts more than 100 events during the 40-string data taking period, a flux level which is excluded by previous searches by the AMANDA detector (Achterberg et al. 2007). Distefano et al. (2002) noted that for the specific case of SS 433, the model may be biased because the source is surrounded by the diffuse nebula W50, which can affect the estimate of the radio emission used in the model for this source. For Cygnus X-3, the IceCube limits are near the prediction with the 40-string data.

The main parameters on which the neutrino flux depends in this model are: the fraction of jet kinetic energy converted to internal energy of electrons and magnetic field, η_e ; the fraction of the jet luminosity carried by accelerated protons, η_p ; and the fraction of proton energy in pions f_π , which strongly depends on the maximum energy to which protons can be accelerated. We show as an example for the case of a 3-day burst of Cygnus X-3 how the parameters are constrained by our result. We assume equipartition between the magnetic fields and the electrons and the proton component ($\eta_p = \eta_e$) for setting a constraint on $f_\pi < 0.11$. If equipartition does not apply, we assume $f_\pi = f_{\pi,peak}$ as given in Table 2 in Distefano et al. (2002) (for Cygnus X-3 $f_{\pi,peak} = 0.12$) and constrain η_p to be less than 92% of η_e . In deriving these limits we have assumed that the Lorentz factor of the jet is well known from radio measurements, but in many cases there is a large uncertainty on this parameter. Hence, our limits for the parameters of this model may have different implications that we cannot disentangle: protons may not be dominant in the jet, they may lose

Source	Period (days)	p-value (pretrial)	T_0 (MJD)	$\hat{\varphi}_o$ (phase)	$\hat{\sigma}_T$ (period ⁻¹)	Reference	Time-Dependent UL (TeV ⁻¹ cm ⁻² s ⁻¹)	Time-Integrated UL (TeV ⁻¹ cm ⁻² s ⁻¹)
Cygnus X-3	0.199679	0.0019	54896.693	0.819	0.02	(Abdo et al. 2009b)	$3.01 \cdot 10^{-11}$	$6.64 \cdot 10^{-12}$
Cygnus X-1	5.5929	0.080	41874.707	0.031	0.02	(Brocksopp et al. 1998)	$4.08 \cdot 10^{-12}$	$7.41 \cdot 10^{-12}$
LS I + 61° 303	26.498	0.23	43366.775	0.916	0.02	(Acciari et al. 2008)	$1.82 \cdot 10^{-11}$	$9.78 \cdot 10^{-12}$
GRS 1915+105	30.8	0.43	53945.7	0.502	0.045	(Neil et al. 2007)	$2.57 \cdot 10^{-12}$	$3.23 \cdot 10^{-12}$
SS 433	13.0821	0.35	50023.62	0.779	0.02	(Hilwig & Gies 2008)	$3.15 \cdot 10^{-12}$	$3.03 \cdot 10^{-12}$
XTE J1118+480	0.169934	0.28	52287.9929	0.985	0.13	(McClintock et al. 2003)	$7.29 \cdot 10^{-12}$	$8.18 \cdot 10^{-12}$
GRO J0422+32	0.21214	0.037	50274.4156	0.831	0.02	(Webb et al. 2000)	$1.46 \cdot 10^{-11}$	$6.89 \cdot 10^{-12}$

Table 1: Results of the analysis with the IceCube 40-string data sample from 2008-2009. T_0 is the time of zero phase for the binary systems tested. $\hat{\sigma}_T$ is the standard deviation of the best-fit Gaussian, as a fraction of the period of the binary system. The value for σ_T is constrained to be larger than 0.02, to prevent the method from isolating a single event. We also include the reference used for the orbital information. The last columns give the 90% CL upper limits on the normalization of the flux for an E^{-2} neutrino spectrum, for the time-dependent and time-integrated hypotheses. The upper limits also incorporate a 16% systematic uncertainty.

Source	Emission duration	Time-Integrated 90% UL (events)	Model Prediction (events)	Time-Dependent Sensitivity (events)
Cygnus X3	3 days	5.1	3.0	2.9
Cygnus X1	Persistent	3.3	1.9	—
LS I +61 303	Periodic, 26% duty cycle	5.9	1.3	5.0
GRS 1915+105	6 days	4.3	0.5	2.8
SS 433	Persistent	3.3	220	—
GRO J0422+32	1 days	5.1	0.068	2.9
	20 days		1.6	2.7

Table 2: The time-integrated upper limit (UL) at 90% CL on the number of events is compared to the expected number of events for model predictions according to Distefano et al. (2002) for specific sources for the 40-string configuration. The neutrino energy range used to calculate the total number of events is $10^{11} - 5 \times 10^{14}$ eV, comparable to what was assumed in the model. For non-persistent but flaring sources, the parameters of the model were estimated for flares observed before IceCube construction. Hence the time-dependent sensitivities are calculated averaging over a duration equal to the model flare during 40-string data taking. LS I +61° 303 is modeled as a periodically flaring source in a high state during 26% of the orbit.

smaller energies into pion decay than the values considered in Distefano et al. (2002), or the Lorentz factor is lower than the value indicated in Table 1 in that paper.

5. Conclusions

The exploration of the GeV and TeV photon sky with the instruments on board the Fermi spacecraft and the ground-based Cherenkov telescopes has heralded the golden age of γ -ray astronomy. The connection to neutrino astronomy is clear: high energy processes which cause the observed VHE emission can be responsible for the observed high energy cosmic rays. This implies hadronic acceleration mechanisms in astrophysical sources which can result in an observable neutrino flux with giant neutrino telescopes like IceCube.

The available photon observations have made it possible to enhance the sensitivity of searches for neutrino fluxes by incorporating assumptions derived from the γ -ray data. One crucial development has been the formulation of time-dependent neutrino flux searches, postulating a connection between the time modulation of the high energy emission and the possible neutrino flux. This assumption has increased the sensitivity of these searches in comparison to their time-averaged counterparts.

This paper presented a search for neutrinos from objects with periodic photon/broadband emission. Seven X-ray binaries in the Northern Hemisphere were selected as candidate sources in analyses of IceCube 22-string and 40-string data. The most significant source in the catalog is Cygnus X-3 with a 1.8% probability after trials (2.1σ excess). Comparing the time-integrated limits for each source to model predictions from Distefano et al. (2002), we show that our limits can constrain the fraction of jet luminosity which is converted into pions and the ratio of jet energy into relativistic leptons versus relativistic hadrons, under some assumptions. For instance, for Cygnus X-3 and equipartition between electrons and protons, the fraction of proton energy in pions is limited to about 11%. All of the results in this paper are compatible with a fluctuation of the background.

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REFERENCES

- Abbasi, R., et al. 2009a, *ApJ*, 701, L47
- . 2009b, *Nucl. Inst. & Meth. in Phys. Res.*, A601, 294
- . 2010, *Nucl. Inst. & Meth. in Phys. Res.*, A618, 139
- . 2011, *ApJ*, 732, 18
- . 2012, *ApJ*, 744, 1
- Abdo, A. A., et al. 2009a, *ApJ*, 701, L123
- . 2009b, *Science*, 326, 1512
- . 2011, *ApJ*, 736, L11
- Acciari, V., et al. 2009, 700, 1034
- Acciari, V. A., et al. 2008, *ApJ*, 679, 1427
- Achterberg, A., et al. 2006, *Astropart. Phys.*, 26, 155
- . 2007, *Phys.Rev.*, D75, 102001
- Aharonian, F., et al. 2005a, *A&A*, 442, 1
- . 2005b, *Science*, 309, 746
- . 2007, *A&A*, 469, L1
- Albert, J., Aliu, E., Anderhub, H., et al. 2006, *Science*, 312, 1771
- Albert, J., et al. 2007, *ApJ*, 665, L51
- . 2009, *ApJ*, 693, 303
- Athar, H., Jezabek, M., & Yasuda, O. 2000, *Phys. Rev. D*, 62, 103007

- Bongiorno, S. D., Falcone, A. D., Stroh, M., Holder, J., Skilton, J. L., Hinton, J. A., Gehrels, N., & Grube, J. 2011, *ApJ*, 737, L11
- Bosch-Ramon, V., & Khangulyan, D. 2009, *Int.J.Mod.Phys.*, D18, 347, * Brief entry *
- Braun, J., et al. 2008, *Astropart. Phys.*, 29, 299
- . 2010, *Astropart. Phys.*, 33, 175
- Brocksopp, C., Tarasov, A. E., Lyuty, V. M., & Roche, P. 1998, *A&A*, 343, 861
- Conrad, J., Botner, O., Hallgren, A., & Perez de los Heros, C. 2003, *Phys.Rev.*, D67, 012002
- Distefano, C., Guetta, D., Waxman, E., & Levinson, A. 2002, *ApJ*, 575, 378
- Feldman, G. J., & Cousins, R. D. 1998, *Phys. Rev. D*, 57, 3873
- Gregory, P. C. 2002, *ApJ*, 575, 427
- Gregory, P. C., & Taylor, A. R. 1978, *Nature*, 272, 704
- Harrison, F. A., Ray, P. S., Leahy, D. A., Waltman, E. B., & Pooley, G. G. 2000, *ApJ*, 528, 454
- Hill, G. C. 2003, *Phys.Rev.*, D67, 118101
- Hillwig, T. C., & Gies, D. R. 2008, *ApJ*, 679, 1427
- Li, J., et al. 2011, *ApJ*, 733, 89
- McClintock, J. E., et al. 2003, *ApJ*, 593, 435
- Neil, E. T., Baily, C. D., & Cobb, B. E. 2007, *ApJ*, 657, 409
- Paredes, J. M. 2011, *Nuovo Cimento C*, 034, 167
- Paredes, J. M., Martí, J., Ribó, M., & Massi, M. 2000, *Science*, 288, 2340
- Sidoli, L., Pellizzoni, A., Vercellone, S., Moroni, M., Mereghetti, S., & Tavani, M. 2006, *A&A*, 459, 901
- Tavani, M., & Arons, J. 1997, *ApJ*, 477, 439
- Tilav, S., et al. 2009, in *Proc. of the 31st Int. Cosmic Ray Conf, Lodz, Poland, Atmospheric Variations as observed by IceCube*, arXiv:1001.0776
- Torres, D. F., et al. 2010, *ApJ*, 719, L104
- Webb, N. A., Naylor, T., Ioannou, Z., Charles, P. A., & Shahbaz, T. 2000, *MNRAS*, 317, 528
- Zhang, S., Torres, D. F., Li, J., Chen, Y. P., Rea, N., & Wang, J. M. 2010, *MNRAS*, 408, 642

Ziółkowski, J. 2005, MNRAS, 358, 851