Are GeV and TeV spectra connected?  
the case of Galactic $\gamma$-ray sources

P. Tam  
Institute of Astronomy and Department of Physics,  
National Tsing Hua University, Hsinchu, Taiwan

S. Wagner  
Landessternwarte, Universität Heidelberg, Königstuhl, Heidelberg, Germany

To understand Galactic objects that emit GeV-TeV emission, a spatial correlation study between the Fermi bright source catalog \cite{1} and TeV source population was carried out in \cite{2}, finding that a significant number of very high-energy (VHE; $E > 100$ GeV) sources are also emitting at GeV energies. We extended our previous study utilizing the first Fermi catalog (1FGL) sources \cite{3}. A cross-correlation comparison of the 1FGL sources was carried out with the VHE $\gamma$-ray sources in the literature as of May 2011. While it is found that a significant number of VHE $\gamma$-ray sources were also detected in the GeV band, the GeV-TeV spectra of some of these spatially coincident sources cannot be described by a single spectral component. While some of these cases are $\gamma$-ray pulsars accompanied by VHE $\gamma$-ray emitting nebulae, we present cases where the 100 MeV to multi-TeV spectra of coincident 1FGL/VHE source pairs do not seem to be well fit by a single spectral component.

I. INTRODUCTION

During the last decade, many different kinds of astrophysical objects in our Galaxy were discovered at photon energies above 100 MeV: pulsars (PSRs), pulsar wind nebulae (PWNe), supernova remnants (SNRs), high-mass X-ray binaries (HMXBs), and one H II region. They were all made by utilizing the high-energy (HE; 30 MeV–100 GeV) and very high-energy (VHE; 100 GeV–100 TeV) $\gamma$-ray experiments including current generation of imaging atmospheric Cherenkov telescopes (IACTs) H.E.S.S., MAGIC, and VERITAS, and the Large Area Telescope (LAT) aboard the Fermi satellite. More than 100 sources are now known at VHE $\gamma$-ray energies and 1451 sources are listed in the first Fermi LAT catalog, comparing with $\sim$10 VHE $\gamma$-ray sources and $\sim$300 HE $\gamma$-ray sources around the turn of the century. Given the large number of sources, we follow previous studies \cite{2} \cite{4} and compare the HE and VHE source positions, as an important step to identify a group of sources emitting both in the HE and VHE bands.

II. SPATIAL COINCIDENCE STUDY

We cross-correlated the 1FGL source centroid positions with VHE $\gamma$-ray source centroid positions. Only sources that are not associated with an extragalactic source were considered. Using the same manner as described in \cite{2}, the VHE source extent and 95% uncertainty in the 1FGL source centroids are taken into account. All first Fermi/LAT catalog sources are assumed to be point sources as in \cite{3}. Those sources with an ending ‘c’ should be regarded with caution given the imperfect knowledge of the diffuse $\gamma$-ray background \cite{3}. In total we identified 31 1FGL sources that are spatially coincident with one VHE source. In addition, the VHE source in the Westerlund 1 region, which are $\sim$0.6$^\circ$ extended, is found to be spatially coincident with three 1FGL sources. HESS J1809$-$193 is coincident with two 1FGL sources. The list of these 1FGL-VHE source pairs are presented in Table I.

Based on pulsar timing information and dedicated efforts described in the corresponding literature, as well as spatial coincidences, the 1FGL sources in the list of coincidences include several classes: 2 HMXBs (LS I$+61^\circ$ 303 and LS 5039), 8 PSRs, 4 SNRs (IC 443, W28, W49B, W51C), 2 PSR/PWN (Crab and Vela), 6 SNR/PWN candidates, one H II region, and 13 unassociated sources.

III. GEV-TEV SPECTRA

The GeV spectral points are taken from the 1FGL catalog where point source analysis was used, while the VHE spectra shown are the best-fit power law taken from the respective literature.

We identify several cases of which the 0.1–100 GeV spectra and the VHE spectra cannot be described by a single spectral components, as shown in Figs 1–5. The flux in the five energy bands in \cite{3} are plotted together with the best-fit power law in the VHE range. In several other cases, the GeV emission come from a $\gamma$-ray pulsar, i.e., those 1FGL source identified as a pulsar, that shows cutoff at several GeV and VHE emission mostly likely come from the associated VHE $\gamma$-ray emitting PWN. We only present cases where the 1FGL source is not identified as a pulsar.
IV. CASES OF SPECTRAL ‘MIS-MATCH’

We found five VHE sources that are spatially coincident with a 1FGL source but the GeV–TeV spectra are incompatible with a single spectral component: HESS J0852−463, HESS J1614−518, HESS J1702−420, HESS J1809−193, and HESS J1848−018. The cases presented here might represent a group of GeV/TeV sources where the spectral mis-matches indicate different radiations working at different energies or that radiation comes from different parts of a γ-ray source. Further studies of these spectral mis-match GeV/TeV spatially coincident cases are encouraged.

V. CONCLUSION

In this study, it is found that a significant number of VHE sources are spatially coincident with a counterpart in the first Fermi/LAT catalog, establishing a population of sources that emit both in the HE and VHE energy bands. This confirms our previous assessment using the Fermi bright source list[2]. However, the GeV-TeV spectra of some of these spatially coincident sources cannot be described by a single spectral component. While some of these cases are γ-ray pulsars accompanied by VHE γ-ray emitting nebulae, we highlight five cases where the 100 MeV to multi-TeV spectra of coincident 1FGL/VHE source pairs do not seem to be well fit by a single spectral component.

Notes added in proof: The second Fermi catalog has been released after the conference. We note that one of the coincidence pairs, 1FGL J1702.4−4147c, does not have a 2FGL counterpart.

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TABLE I: 1FGL sources with spatially coincident VHE counterpart as of May 2011. The class denoted ‘SNR/PWN’ means SNR/PWN candidates, according to [3].

| 1FGL source | association | class | $\gamma$-ray source | association | \(l\) | \(b\) | extension | ref |
|-------------|-------------|-------|---------------------|-------------|------|------|-----------|-----|
| J0240.5+6113 | LS I+61 303 | HMXB | VER J0240+612 | LS I+61 303 | 1.08 | pt src | [9] |
| J0534.5+2200 | Crab | PSR/PWN | HESS J0534+220 | Crab nebula | 5.78 | pt src | [6] |
| J0617.2+2333 | IC 443 | SNR | VER J0616.9+2330 | IC 443 | 0.16 | [4, 5] |
| J0835.3−4510 | Vela | PSR/PWN | HESS J0835−455 | Vela X | 0.43 | [9] |
| J0854.0−4632 | SNR/PWN | HESS J0852−463 | RX J0852.0−4622 | 1.0 | [10] |
| J1023.0−5746 | PSR J1023−5746 | HESS J1023−575 | PSR J1023−5746/Wd 2 | 0.18 | [11] |
| J1418.7−6057 | PSR J1418−6058 | PSR | J1418−6059 | G343.3+0.1 (Rabbit) | 0.06 | [12] |
| J1420.1−6048 | PSR J1420−6048 | PSR | J1420−607 | PSR J1420−6048 | 0.07 | [12] |
| J1501.6−4204 | SNR/PWN | HESS J1502−421 | SN 1006 SW | 0.13 | [13] |
| J1503.4−5805c | Unid | SNR/PWN | HESS J1503−582 | PVW J19.8+0.3? | 0.24 | [16] |
| J1617.4−5138c | Unid | PSR | HESS J1614−518 | 0.58 | [2] |
| J1640.8−4634c | SNR/PWN | HESS J1640−465 | G338.3−0.0 | 0.05 | [15] |
| J1648.4−4690c | PSR J1648.4−4611 | PSR | 339.47−0.79 | Jesterlund I region | 0.9 | [16] |
| J1649.3−4501c | Unid | SNR/PWN | 340.44−0.38 | same as above | [16] |
| J1651.5−4602c | Unid | SNR/PWN | 339.91−1.12 | same as above | [16] |
| J1702.4−4147c | Unid | PSR | HESS J1702−420 | PSR J1702−4128 | 0.22 | [17] |
| J1707.9−4110c | Unid | SNR/PWN | 345.66−0.44 | 0.08 | [17] |
| J1709.7−4429c | PSR B1706−44 | PSR | HESS J1708−443 | PSR B1706−44/G343.1−2.3 | 0.29 | [18] |
| J1711.7−3944c | SNR/PWN | PSR J1713−397 | RX J1713.7−3946 | 0.25 | [19] |
| J1718.2−3825 | PSR J1718−3825 | PSR | 348.83−0.49 | 0.015 | [20] |
| J1745.6−2800c | SNR/PWN | HESS J1745−290 | Sgr A°/G359.95−0.04 | 0.04 | [21] |
| J1800.5−2359c | W28−A2 | H II region | HESS J1800−240B | W28−A2 | 0.17 | [22, 23] |
| J1801.3−2322c | W28 | SNR | HESS J1801−233 | W28 | 0.17 | [22, 23] |
| J1805.2−2137c | SNR/PWN | HESS J1804−216 | W30/PSR J1803−2137? | 0.20 | [22, 23] |
| J1808.5−1554c | Unid | SNR/PWN | HESS J1809−193 | PSR J1809−1917? | 0.03 | [23] |
| J1810.9−1905c | Unid | SNR/PWN | 10.43−0.03 | same as above | [20] |
| J1826.2−1450c | LS 5039 | HMXB | HESS J1826−148 | LS 5039 | 0.28 | [24] |
| J1837.5−0659c | Unid | SNR/PWN | 25.13−0.12 | HESS J1837−069 | 0.12 | 7.2°x3' | [15] |
| J1844.3−0309c | Unid | SNR/PWN | 29.32−0.13 | ~29.08±0.16 | 0.25 | [25] |
| J1848.1−0145c | Unid | SNR/PWN | 30.99−0.08 | HESS J1843−033 | ~29.08±0.16 | [25] |
| J1907.9+0602c | PSR J1907+0602 | PSR | HESS J1908+063 | MGRO J1908+06 | 0.39 | [27] |
| J1910.9+0906c | SNR | W 49B | HESS J1912+101 | PSR J1913+101 | 0.27 | [30] |
| J1913.7+1007c | Unid | SNR/PWN | 44.48−0.28 | PSR J1923+141 | 0.15 | [31, 32] |
| J1922.9+1411c | W 51C | SNR | 49.14−0.6 | w51 | 0.15 | [31, 32] |
| J2020.1+0404c | Unid | SNR/PWN | 78.37−2.53 | VER J2019+047 | 0.11 | [33] |
| J2032.2+4127c | PSR J2032.2+4127 | PSR | 80.22±1.03 | TeV J2032+4130 | 0.10 | [34] |

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FIG. 1: The 100 MeV to several tens TeV spectra of four spatially coincident but spectrally ‘mis-match’ 1FGL/VHE source pairs

FIG. 2: The 100 MeV to several tens TeV spectra of 1FGL J1848.1-0145c and HESS J1848-018. 1FGL J1848.1-0145c has a 0FGL counterpart whose best-fit power law is also shown.