1. Unpulsed magnetospheric emission, and PWN searches

In this section, we will search for emission in the phase range between the peaks of the pulsar's light curve. This potential DC emission could originate in the pulsar winds, from inside a pulsar's magnetosphere, or the emission could be physically unrealted to the pulsar.

GeV emission in the off-peak regions around LAT-detected pulsars has been studied in several previous publications. In particular, the spatially-extended Vela X pulsar wind nebula has been detected by the LAT in the off-peak region of the Vela pulsar (Ackermann et al. 2011) and the Crab nebula has been detected by the LAT (Abdo et al. 2010b). Surprisingly, this GeV emission from the Crab nebula was found to be variable in time (Abdo et al. 2011).

Most prominently, a dedicated analysis was performed using LAT data of the off-peak emission of 54 LAT-detected pulsars using 16 months of survey observations (Ackermann et al. 2011). The search discovered ten pulsars with significant off-peak emission. Along with Vela X and the Crab nebula, the search discovered a source coincident with the TeV source HESS J1023-575 in the off-peak window of PSR J1023-5746. In addtion, five of the other regions showed a significantly cutoff pulsar-like spectrum and are suspected to be of magnetospheric origin.

We expand upon this previous work by searching in the off-peak region of all 117 pulsars in this catalog. In addition to the larger list of pulsars, we use an expanded observation time, a larger energy range, and an improved analysis method.

1.1. Off-peak Phase Selection

To study the off-peak emission of LAT-detected pulsars, we first developed a systematic method to define the off-peak region of a pulsar. The primary constraint for this method was for it to be systematic, model independent, and computationally efficient.

The method we developed proceeds by deconstructing the pulsar's phaseogram into simple Bayesian Blocks using the algorithm described in Jackson et al. (2005). To produce Bayesian Blocks on a periodic phaseogram, we applied the blocks three sets of the data from a phase of -1 to 2 and selected the blocks from a phase of 0 to 1.

TO improve the off-peak region definition, we first optimized the pulsar phaseogram by varying the minimum energy and radius of the included photons to optimize the H-test. We then selected the lowest block to be the off-peak region, but removed 10% of the emission from either side of the block to avoid potential contamination.

There is one free parameter in the Baysian Block algorithm called $\mathrm{ncp_{prior}}$ which modifies the probability that the algorithm will divide a block into smaller intervals. For our situation, we found that setting $\mathrm{ncp_{prior}} = 8$ protected against the Bayesian Block decomposition containing unphysically small blocks. For a few very marginally-detected pulsars, the algorithm failed decomposed the phaseogram into multiple blocks and in these situations we decreased $\mathrm{ncp_{prior}}$ until the algorithm succeeded.

In some situations, there can be two well defined off-peak regions between two pulsed peaks. The method we used to select a second phase range was to take the second lowest Bayesian block but only when the emission in this block is consistent with the emission in the lowest block (at the 99% confidence level) and when the second block contained at least half as much phase as the first block.

Figure Figure 1 shows the energy-and-radius optimized light curve and the off-peak selection for a representative sample of pulsars. The off-peak definition for all pulsars is contained in the auxiliary material.

1.2. Off-peak Analysis Method

We developed a procedure for characterizing emission found in off-peak phase region for all pulsars in this catalog. This procedure used both the spectral and spatial characteristics of any observed emission to determine its physical origin.

PWNe are often expected to be spatially resolvable at GeV energies. For example, Vela X and HESS J1825-137 are PWN that have been spatially resolved by the LAT (Ackermann et al. 2011; Grondin et al. 2011). On the other hand, not all PWN are expected to be significantly spatially resolved due to the finite instrument resolution of the LAT. For example, the Crab nebula cannot be resolved by that LAT LAT but is distinguished from the Crab pulsar in the off-peak region by its hard spectrum for E$\gtrsim$1 GeV. (Abdo et al. 2010b).

On the other hand, pulsars can have DC emission in the off-peak region due to the geometry of the pulsar magnetospheres. A previous analysis by the LAT collaboration found five off-peak regions to have significant emission which is point-like in nature and characterized by a pulsar-like cutoff spectrum (Ackermann et al. 2011). We can therefore use either spatial extension or a hard spectrum to distinguish PWN emission and point-like emission with a cutoff spectrum to distinguish magnetospheric emission.

To perform this analysis, we used the likelihood fitting package `pointlike` to study the spatial character of emission in the off-peak regions and `gtlike` in binned model to study

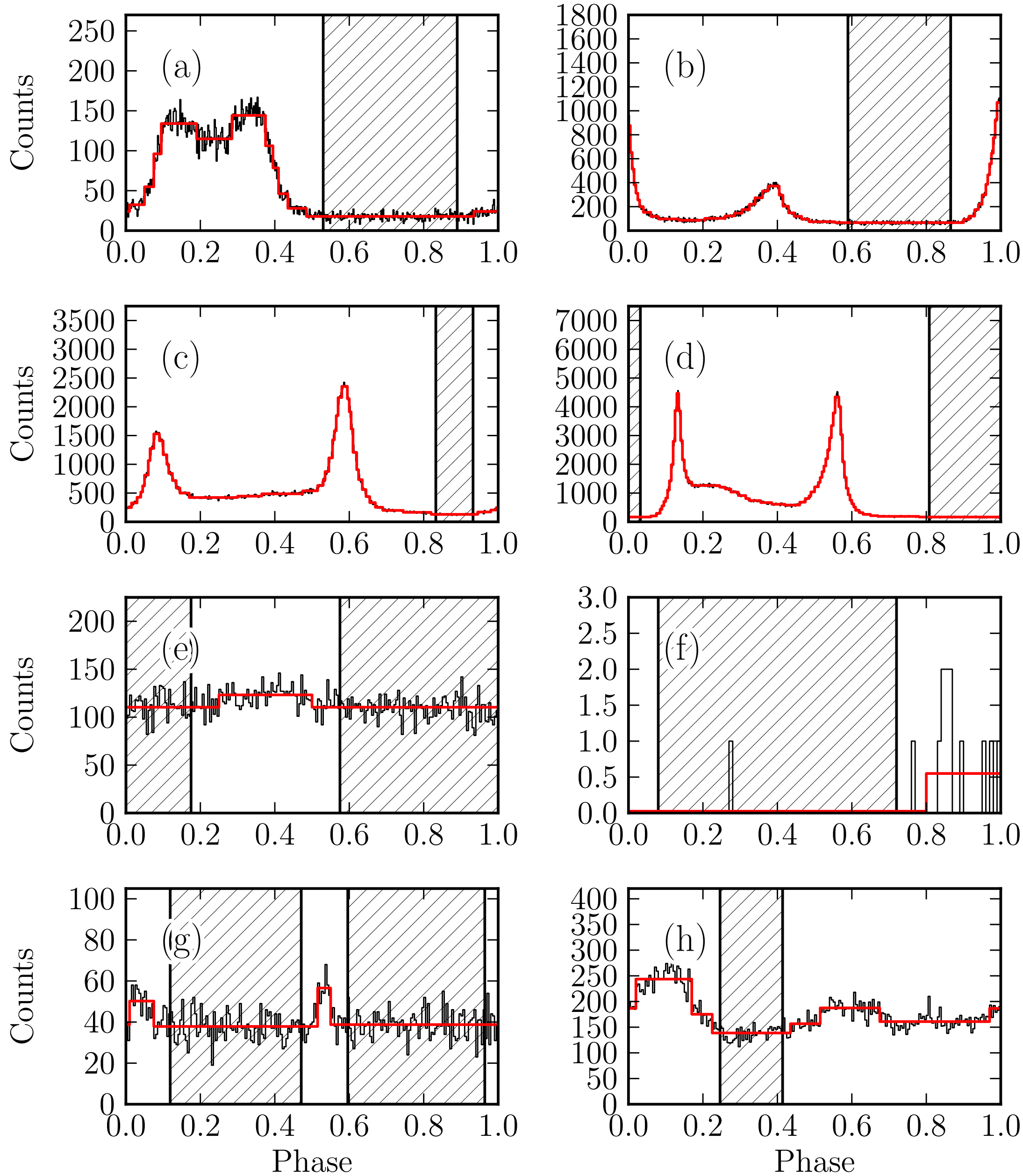

Fig. 1.— The phaseogram and off-peak selection for (a) PSRJ0007+7303, (b) PSRJ0534+2200, (c) PSRJ0633+1746, (d) PSRJ0835-4510, (e) PSRJ1702-4128, (f) PSRJ1747-4036, (g) PSRJ1801-2451, and (h) PSRJ2021+4026. The black histogram represents the energy-and-radius optimized phaseogram. The gray lines (colored red in the electronic version) represent the Bayesian block decomposition of the pulsar light curves. The hatched areas represent the off-peak regions selected by this method.

the spectral character of the emission. These tools provide complementary features and this method is very similar to the approach used in the second LAT catalog (Nolan et al. 2012) and a follow up search for spatially extended sources (Lande et al. 2012).

For this analysis, we build a model of the sky consistent with the second LAT catalog. We included as background sources all nearby sources from the second catalog and we also used the same background models (Nolan et al. 2012). For out analysis, we used an energy range from 100 MeV to 316 GeV ($10^{5.5}$ MeV). For this analysis, we removed all photons from the on-peak emission and scaled the exposure so as to fit the all-phase flux assuming the emission was constant with phase.

First, we assumed any potential emission in the off-peak region to have a point-like spatial model and (unless otherwise noted) a power-law spectral model. We used `pointlike` to fit the position of the off-peak region following the procedure described in Nolan et al. (2012). We used the best fit positions obtained by `pointlike` and performed a spectral analysis using `gtlike`.

With the best-fit position, we used `gtlike` to test the significance of the detection of the source. We define the likelihood-ratio test for the detection of the source as

$$\mathrm{TS} = 2\log(\mathcal{L}_{\mathrm{pt}}/\mathcal{L}_{\mathrm{bg}}) \tag{1}$$

where $\mathcal{L}_{\mathrm{pt}}$ is the Poisson likelihood for a model including the source and $\mathcal{L}_{\mathrm{bg}}$ the likelihood for a model not including the source. We set the threshold for detection of significant emission at TS > 25, corresponding to a significance just over 4σ (Abdo et al. 2010a).

For the significantly-detected source, we tested to see if the spectrum of the source is significantly cutoff following the prescription in Ackermann et al. (2011). We fit the source in `gtlike` with both a power-law and exponentially-cutoff spectral model and define the likelihood-ratio test for a cutoff spectrum as

$$\mathrm{TS}_{\mathrm{cutoff}} = 2\log(\mathcal{L}_{\mathrm{cutoff}}/\mathcal{L}_{\mathrm{pt}}) \tag{2}$$

where $\mathcal{L}_{\mathrm{cutoff}}$ is the Poisson likelihood for a model including the cutoff spectrum. We set the threshold for detecting a significant cutoff at $\mathrm{TS}_{\mathrm{cutoff}} > 16$, corresponding to a 4σ detection (Ackermann et al. 2011) .

We used `pointlike` to simultaneously fit the position and the extension of the assumed radially-symmetric Gaussian source, following the description in (Lande et al. 2012). After the extension fit, we refit the spectrum of the spatially extended source using `gtlike` We tested the significance of the spatial extension and computed the likelihood-ratio test for the significance of the extension:

$$\mathrm{TS}_{\mathrm{ext}} = 2\log(\mathcal{L}_{\mathrm{ext}}/\mathcal{L}_{\mathrm{pt}}). \tag{3}$$

Here, $\mathcal{L}_{\rm ext}$ is the Poisson likelihood assuming the source is spatially extended. We set the threshold for detecting the significance of a spatially extended source at $\mathrm{TS}_{\rm ext} > 16$, corresponding to a 4σ detection (Lande et al. 2012).

For sources that are not significantly detected, we compute flux upper limits assuming a point-like spatial model and a fixed spectral index of 2.0. We also compute pulsed upper limit assuming a canonical pulsar spectrum with an index of -1.7 and a cutoff energy of 3 GeV.

To better assess the spectral charter of any emission in the off-peak region, we performed a spectral analysis in three independent energy bins (100 MeV to 1 GeV, 1 GeV to 10 GeV, and 10 GeV to 316 GeV). In each bin, we independently fit the flux and the spectral index of the source. We also computed flux upper limit assuming a fixed spectral index of 2 when the source was not significantly detected in the energy range.

Following the discovery of time-variable emission from the Crab nebula by the LAT, it is interesting to search for other variable PWN (Abdo et al. 2011). Therefore, we tested all off-peak regions for variability. We divided the 3-year time range into 36 month-long intervals and fit the flux of the source independently in each time range. We computed the significance of variability with a likelihood-ratio test by computing $\mathrm{TS}_{\rm var}$ following the procedure of 2FGL (Nolan et al. 2012). Since we divided our time range into 36 months-long bins, the null distribution for $\mathrm{TS}_{\rm var}$ follows a χ^2 distribution with 35 degrees of freedom. We set the detection criteria for significant variability at $\mathrm{TS}_{\rm var} > 91.7$, corresponding to a 4σ significance detection threshold.

In many situations, this algorithm failed or was biased due to failing to model nearby sources. We expect to be more sensitive to nearby sources than the second LAT catalog both because of our expanded data set (3 years of observations instead of 2) and also because, for very bright pulsars, we are more sensitive to nearby sources in the off-peak.

Unfortuantly, in many situations, this algorithm failed due to systematics associated with the modeling nearby sources. The large and energy depdended point-spread function of the LAT causes the analysis of any one source to be sensitively affected by the modeling of nearby sources. Therefore, we had to, in many situations, iteratively improve the model of a region by including new sources. This procedure involved generating maps of residual test statistic assuming the presence of a new source (of a fixed spectral index of 2) and looking for regions with $\mathrm{TS} \geq 25$. For these positions, we would include a new source into our model, fit the position and spectrum of this source, and iterate until there was no remaining $\mathrm{TS} \geq 25$ emission.

Even so, there are still some linering regions which have significant emission but which remain particular difficult to model and understand the origion of the emission for. These issues are most likely due to systematics associated with the model of the galactic diffuse emission in the region and issues associated with modeling nearby sources. We will flag these problematic regions in our analysis.

Describe special case of Crab spectrum

1.3. Results

After analyzing the off-peak emission using the pipeline described in § 1.2, we consider any emission in the off-peak region to be magnetospheric in nature if the emsision is not significantly-extended and has a significantly-cutoff spectrum. We consider the emission to originate in the pulsar wind if it is spatially extended or had a hard spectral index. If the source is point-like and had a soft spectrum, or if it is spatially extended but the extension is biased by modeling of the background, we are unable to determine the origin of the emission.

A summay of the reuslts of the pipepline can be found in Table 1. It includes off off-peak phase ranges selected using the method described in § 1.1. This table includes TS, $\mathrm{TS}_{\mathrm{ext}}$, and $\mathrm{TS}_{\mathrm{cutoff}}$ for the significantly detected pulsars (with TS > 25). This table also includes the best fit flux and spectral index for these pulsars assuming the best hypothesis (either point-like, spatially-extended, or expontentially cutoff). For the sources that are significantly cutoff, the spectral index refers to the index from the fit of a cutoff spectral model and the final column includes the cutoff energy derived from the fit.

Figure 2 shows the cutoff test…

Consistent with (Abdo et al. 2011), we found the Crab nebula to be highly variable with $\mathrm{TS}_{\mathrm{var}}$ =XXXX. Besides that, we found no significantly variable off-peak emission. The results of the variability test are contained in the auxiliary information.

The results of the spectral analysis in smaller energy bands described in section § **??** are included in the auxiliary information. In addition, upper limits computed assuming a powerlaw spectral model and a canonical pulsar spectrum are included in the auxiliary information.

Results:

- List of all XXX detections
- For each pulsar, is it a

Table 1. Off-Peak Spatial and Spectral Results

PSR	Phase	TS_{point}	TS_{ext}	TS_{cutoff}	$F_{0.1-316}$ (10^{-9} erg cm^{-2} s^{-1})	Γ	E_{cutoff} (MeV)
J0007+7303	0.53 - 0.89	71.2	10.8	0.0	47.22 ± 8.60	2.61 ± 0.14	···
J0034−0534	0.21 - 0.68	42.8	0.0	4.9	16.82 ± 4.58	2.44 ± 0.16	···
J0101−6422	0.22 - 0.61	25.2	0.0	18.2	45.76 ± 6.41	-5.00 ± 0.00	100.02 ± 1.46
J0102+4839	0.81 - 0.57	69.6	0.0	5.3	26.34 ± 4.89	2.42 ± 0.10	···
J0106+4855	0.67 - 0.03, 0.18 - 0.54	25.5	0.0	0.2	29.14 ± 7.04	2.80 ± 0.17	···
J0218+4232	0.82 - 0.21	50.1	0.0	6.6	55.94 ± 11.20	2.72 ± 0.13	···
J0340+4130	0.13 - 0.64	26.8	0.1	16.5	2.45 ± 1.48	0.93 ± 2.51	645.30 ± 580.54
J0534+2200	0.59 - 0.87	5253.1	0.0	0.0	764.73 ± 18.42	···	···
J0633+1746	0.83 - 0.93	3649.0	2.3	237.3	719.12 ± 27.80	-1.42 ± 0.09	998.24 ± 116.74
J0734−1559	0.28 - 0.84	28.4	10.7	33.4	31.63 ± 6.36	1.77 ± 0.40	100.10 ± 3.01
J0835−4510	0.81 - 0.03	506.0	241.9	0.0	431.14 ± 22.25	2.11 ± 0.03	···
J0908−4913	0.66 - 0.04, 0.17 - 0.54	35.5	9.3	74.1	40.13 ± 37.59	-1.20 ± 0.71	999.01 ± 0.71
J1023−5746	0.67 - 0.03	84.8	57.7	14.1	230.75 ± 6722.99	2.04 ± 0.72	···
J1044−5737	0.55 - 0.97	27.9	187.0	0.0	243.05 ± 2.30	1.95 ± 0.00	···
J1105−6107	0.73 - 0.46	28.9	36.6	78.6	161.16 ± 6644.93	2.14 ± 0.72	···
J1112−6103	0.31 - 0.04	122.2	93.4	12.4	232.99 ± 26.43	2.12 ± 0.04	···
J1119−6127	0.59 - 0.18	40.7	18.3	0.0	54.59 ± 3399.22	2.16 ± 0.70	···
J1124−5916	0.69 - 0.05	86.2	0.0	24.2	26.39 ± 19.44	-0.79 ± 0.72	1000.00 ± 0.71
J1410−6132	0.55 - 0.24	42.4	91.6	12.5	81.41 ± 2783.70	1.79 ± 0.72	···
J1513−5908	0.53 - 0.15	100.6	2.1	0.0	15.83 ± 984.68	1.74 ± 0.72	···
J1620−4927	0.54 - 0.98	27.9	0.5	39.9	72.80 ± 22.94	-0.86 ± 0.25	1000.00 ± 173.04
J1744−1134	0.14 - 0.74	61.4	0.0	15.0	33.38 ± 15.81	2.25 ± 0.09	···
J1746−3239	0.41 - 0.99	53.8	7.2	42.0	61.29 ± 54.13	-1.18 ± 0.71	999.95 ± 0.71
J1747−2958	0.66 - 0.1	53.6	0.0	102.6	146.08 ± 125.15	-1.17 ± 0.71	991.64 ± 0.70
J1809−2332	0.53 - 0.91	31.5	13.0	15.2	85.80 ± 49.10	2.45 ± 0.11	···
J1813−1246	0.77 - 0.01	57.8	0.0	12.0	147.87 ± 33.22	2.46 ± 0.05	···
J1836+5925	0.76 - 0.92	10450.2	0.0	364.6	497.25 ± 10.72	-1.49 ± 0.02	2024.58 ± 59.89
J2021+4026	0.25 - 0.41	1712.8	37.4	228.3	1248.80 ± 20643.72	2.23 ± 0.72	···
J2043+1711	0.79 - 0.06, 0.18 - 0.55	151.6	0.0	11.9	23.36 ± 9.33	2.18 ± 0.08	···
J2055+2539	0.37 - 0.87	117.0	0.0	30.4	30.05 ± 31.95	-1.45 ± 0.70	999.99 ± 0.71
J2124−3358	0.09 - 0.69	177.7	0.0	27.0	10.88 ± 3.78	-0.61 ± 0.64	1000.01 ± 437.18
J2302+4442	0.75 - 0.23	113.7	0.0	8.4	34.35 ± 5.34	2.36 ± 0.09	···

Note. —

Put table comments

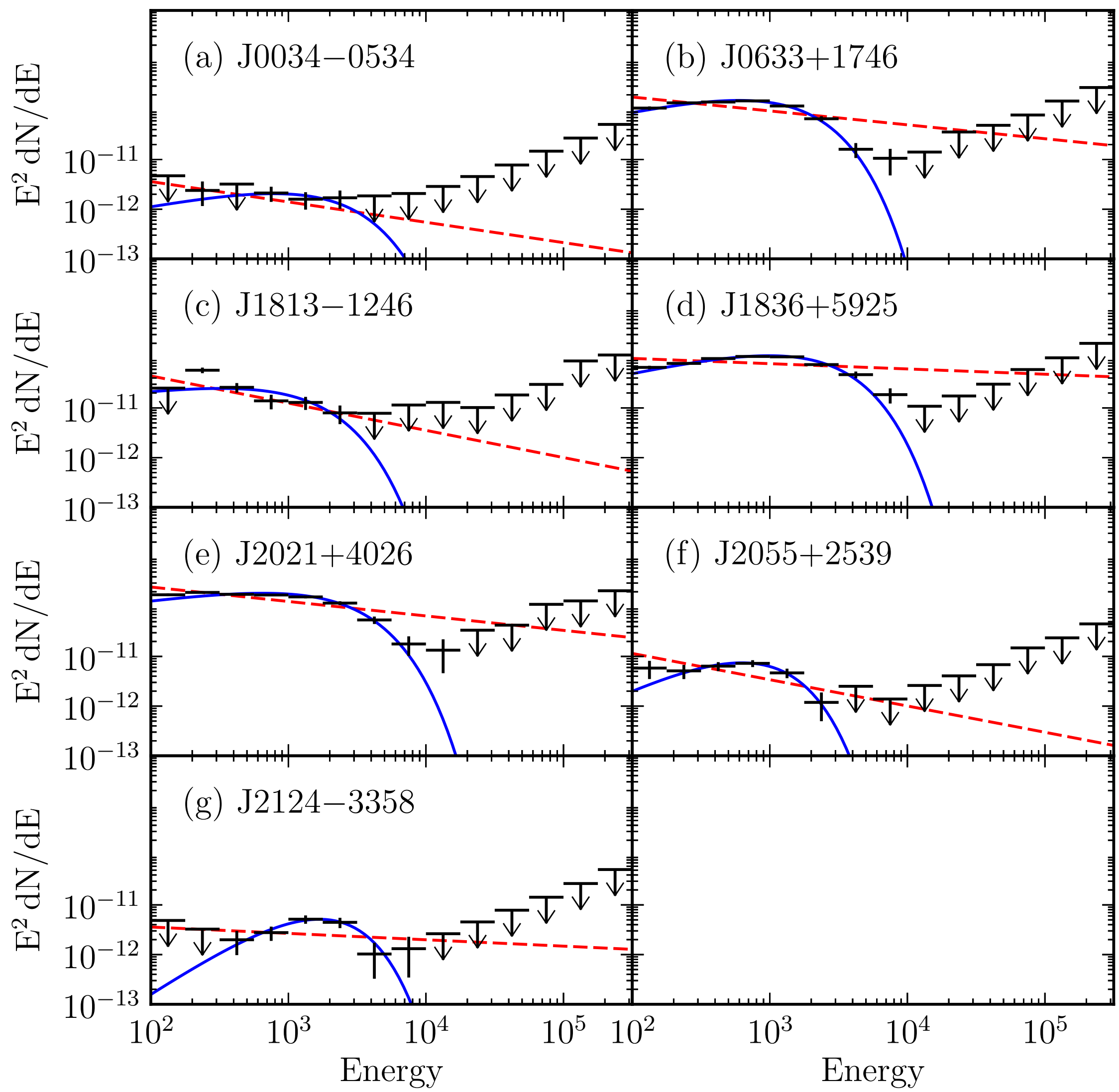

Fig. 2.— Cutoff test for some pulsars…

  - Magnetospheric emission
  - PWN emission
  - Region where the fit shows trouble for some reason.

In our analysis, we detected the the Vela X PWN (associated with PSRJ0835−4510), the Crab Nebula (associated with PSRJ0534+2200), and MSH 15−52 (associated with PSRJ1513-5908).

What to say about PSRJ1023-5746

Sources we detect as clearly magnetospheric

Special cases/problem cases:

- PSRJ0101-6422: Very weird spectrum
- PSRJ1112-6103: Very close to MSH 11 62 (arXiv:1202.3371v1). Nearby source is 2FGL J1112.1-6040. Significant extension.
- When fitting PSRJ1119-6127, description of adding nearby point source to represent emission residual from o represent residual from PSRJ1112-6103 looking spatially extended.
- PSRJ1418-6058 and PSRJ1420-6048, very difficult to analyze because both very near eachother.
- Something about the complciated Gamma Cygni PSR: PSRJ2021+4026
- PSRJ1105-6107: something about adding source to background model that is very nearby. .
- PSRJ1648-4611 (what to do about nearby 2FGL soruce and other residual emission. Is this paper relevant: http://arxiv.org/pdf/1111.2043.pdf???)?
- What to do about emission from PSR J1023 at low energy???
- PSRJ0908-4913: waht to say about far localization?

See what OZLEM is doing

Describe how we present the point-like hypothesis for signifciant extended soures if the extension fails for some reason

1.4. Discussion

Maybe a pulsar physics person can fill in this discussion.

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A. Description of Auxiliary information for Off-peak Analysis

A more complete list of the results from the pipeline are contained in a supplimental `fits`-format table.

Here, we describe each column contained in the fits table:

- Column `TS_point` is the test statistic obtained at the best fit position of the assumed point-like source
- Column

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