DOUBLE GAMMA-RAY LINES FROM UNASSOCIATED FERMI-LAT SOURCES
MENG SU\textsuperscript{1,*}, DOUGLAS P. FINKBEINER\textsuperscript{1,2}

\textit{Draft version May 2, 2014}

ABSTRACT

Gamma ray emission from dark matter subhalos in the Milky Way has long been sought as a sign of dark matter particle annihilation. So far, searches for gamma-ray continuum from subhalos have been unsuccessful, and line searches are difficult without prior knowledge of the line energies. Guided by recent claims of line emission at 111 and 129 GeV in the Galactic center, we examine the coadded gamma-ray spectrum of unassociated point sources in the Second \textit{Fermi}-LAT catalog (2FGL) using 3.9 years of LAT data. Using the \textit{SOURCE} event class, we find evidence for lines at 111 GeV and 129 GeV with a local significance of 3.3\textsigma based on a conservative estimate of the background at $E > 135$ GeV. Other 2FGL sources analyzed in the same way do not show line emission at 111 and 129 GeV.

The line-emitting sources are mostly within 30 degrees of the Galactic plane, although this anisotropy may be a selection effect. If the double-line emission from these objects is confirmed with future data, it will provide compelling support for the hypothesis that the Galactic center line signal is indeed from dark matter annihilation.

\textit{Subject headings:} gamma rays — line emission — milky way — dark matter

1. INTRODUCTION

Although a wide variety of cosmological and astrophysical observations provide compelling evidence that nonbaryonic dark matter constitutes $\sim 80\%$ of the total matter in the Universe, we still know little about its nature (e.g. Bergstr"om 2012; Hooper & Profumo 2007; Bertone et al. 2005).

In many models of weakly interacting massive particle (WIMP) dark matter, particles annihilate and/or decay to gamma rays directly or indirectly. Gamma-ray photons at energies $E \gg 1$ GeV travel in straight lines without significant energy losses in the local Universe, allowing their spatial distribution to serve as a tracer of the dark matter distribution. Regions of high dark matter density such as the Galactic center, galaxy clusters, and dwarf galaxies have been suggested as possible sources. In addition, many DM subhalos in the MW may shine in gamma rays and have no counterpart at other wavelengths, making them promising sources (see recently e.g. Belikov et al. 2011, Ackermann et al. 2012, Mirabal et al. 2012 and references therein).

The primary challenge in such searches is to understand the background from conventional astrophysics well enough to distinguish a dark matter signal. A "smoking-gun" signal of annihilating dark matter would be the discovery of one or more gamma-ray lines. The line(s) could be produced by dark matter decays or annihilations into two photons, or two-body final states involving one photon plus a Higgs boson, Z boson, or other chargeless non-SM particle. No plausible astrophysical background can produce a line, although a narrow feature is possible (see Aharonian et al. 2012). In most models, the line flux is suppressed by a loop factor relative to the continuum, implying it is 2-3 orders of magnitude fainter (e.g. Bergstr"om & Ullio 1997). Although this is not true in all models (e.g. Bergstr"om et al. 1998, Bergstr"om 2000, Bertone et al. 2009, Jackson et al. 2010, Cline 2012), this theoretical prejudice led previous studies to focus on continuum searches. However, tentative evidence for gamma-ray line emission at $\sim 130$ GeV toward the inner Galaxy has been found with 3.3\textsigma significance after trials factor\textsuperscript{4} correction (Weniger 2012).

In our recent paper (Su & Finkbeiner 2012b), we have performed a study with various data analysis methods and obtained 6.5\textsigma local significance of the gamma-ray line structure, and 5.0-5.5\textsigma after trials factor (depending on whether we assume one line or two lines). In fact, we found two lines centered at 111 GeV and 129 GeV provide a better fit to the data.

The high significance of this result does not address concerns about instrumental artifacts, such as energy mapping errors that could give rise to spectral bumps and dips (Finkbeiner et al. 2012). Such concerns must be addressed by an independent analysis of photons from other parts of the sky. For example, detection of lines at 111 and 129 GeV elsewhere on the sky in multiple unassociated LAT sources, but \textit{not} in any class of associated LAT sources would rule out an energy mapping error in

\textsuperscript{1} Institute for Theory and Computation, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-51, Cambridge, MA 02138 USA
\textsuperscript{2} Center for the Fundamental Laws of Nature, Physics Department, Harvard University, Cambridge, MA 02138 USA
\textsuperscript{*} mengsu@cfa.harvard.edu

\textsuperscript{4} Also known as the “look elsewhere effect”
the LAT data processing as a source of the Galactic center lines. Even a lower significance detection would be interesting, because there is no trials factor for choice of line energies.

Many of the Fermi–LAT point sources are associated with counterparts at other wavelengths, including blazars (BL Lacs, Flat Spectrum Radio Sources (FSRS), etc.), other AGNs (Seyferts, Radio Galaxies, etc.), pulsars and binaries, and other Galactic sources (Nolan et al. 2012). Although substantially improved over the First Fermi–LAT catalog (Abdo et al. 2010a), there are still 344 sources in the 2FGL (∼15% of the total) without obvious counterparts at Galactic latitude |b| ≥ 5°.

Various statistical methods and theoretical scenarios have been suggested to classify and explain these unassociated sources (Ackermann et al. 2012a), including the existence of new types of source classes, e.g. dark matter subhalos. Numerical simulations suggest that within the Milky Way halo, dark matter subhalos form at all mass scales down to the simulation resolution. Less massive halos might show themselves as gamma-ray sources without significant emission at other wavelengths (Belikov et al. 2011, Ackermann et al. 2012b, Buckley & Hooper 2010). If such a signal were detected, it would be the first non-gravitational signature of dark matter.

In this work, we use 3.9 years of LAT data to study the gamma-ray spectrum of the unassociated point sources in the 2FGL catalog to search for gamma-ray line emission. We find that the energy spectrum shows two lines at 111
Fig. 2.— Same as Figure 1, but using the ULTRACLEAN event class.

In Section 2 we describe our LAT data selection and analysis procedure. In Section 3 we examine the spectral line emission by various statistical tests and we summarize our main findings in Section 4.

2. FERMI DATA SELECTION

In this section, we briefly describe our data selection and analysis procedure. We refer to our previous papers for more detailed information (Su et al. 2010, Su & Finkbeiner 2012a,b). The Fermi LAT is a pair-conversion telescope, in which incoming photons convert to $e^+e^-$ pairs, which are then tracked through the detector. The arrival direction and energy of each event are reconstructed, and the time of arrival recorded. The LAT is designed to survey the gamma-ray sky in the energy range from about 20 MeV to several hundreds of GeV. The point spread function (PSF) is about $0.8^\circ$ for 68% containment at 1 GeV and decreases with energy as $r_{68} \sim E^{-0.8}$, asymptoting to $\sim 0.2^\circ$ at high energy. It is convenient to distinguish between front-converting and back-converting events that convert in the front and back regions of the tracker, respectively. The 68% containment radius at high energy is $r_{68} \sim 0.15^\circ$ for front-converting and $r_{68} \sim 0.30^\circ$ for back-converting events, with some dependence on the incidence angle on the detector.

The LAT energy resolution (i.e. the half-width of the 68% containment region) is of order 10% over most of the energy range (see Fermi-LAT Collaboration 2012 for details). Around 100 GeV, the resolution is closer to 7% for high incidence-angle events, and twice that for normal incidence.

We use the latest publicly available data and instrument response functions, known as Pass 7 (P7_V6)5. We perform our analysis on both SOURCE and ULTRACLEAN events, and present figures based on each for comparison. The former has larger effective area and higher

5 Details at http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass7_usage.html
3. ANÁLISIS

Los simulados de alta resolución sugieren la existencia de estructuras de materia oscura jerárquicas a todos los escalones resueltos de masa (e.g. [Kuhlen et al. 2009; Pieri et al. 2008]). El final de la función de masa es visible en el Cielo de nuestro Galaxy como galaxias débiles, incluyendo las nubes Magallánicas. Menos subhaces poderosos podrían ser tan pequeños como para no ser visibles en otras longitudes de onda, pero brillarían solo a través de la aniquilación de los partículas de materia oscura en rayos gamma. Estas fuentes pueden parecer como fuentes asociadas Fermi-LAT en el catálogo 2FGL, que forma el fundamento para nuestra búsqueda.

3.1. Selección de fuentes

El catálogo Fermi-LAT 2FGL consta de 1873 fuentes (100 MeV-100 GeV), de las cuales 1290 están firmemente identificadas/asociadas y 575 (31%) son fuentes no asociadas (Nolan et al. 2012). Cortando a latitud galáctica \(|b| > 5^\circ\) para evitar la contaminación del disco galáctico resulta en 344 fuentes no asociadas. Dado que la emisión de materia oscura no se espera que sea no-variante en el tiempo, también eliminamos los 25 entre los 344 fuentes no asociadas que han sido marcadas con un índice de variabilidad > 41.6. Entonces seleccionamos eventos de fotones con energía en el rango 100-140 GeV y ángulo zenital menor que 105°. Incluimos tanto eventos FRONT como BACK convirtiéndolos. Entre los 319 restantes seleccionamos aquellas con al menos un fotón de 100-140 GeV dentro de 0.15/0.3° para FRONT/BACK convertidos, lo que resulta en 16 fuentes no asociadas para el evento SOURCE clases. La información detallada de estas 16 fuentes pueden ser encontradas en la Tabla [1].

En Nolan et al. (2012), se ha notado que 51% de las fuentes no asociadas han sido marcadas por diversos problemas (compared to 14% de las asociadas). Nos hemos esforzado por cortar en cada bit de bandera y no encontramos un impacto significativo en nuestros resultados. Para evitar la introducción de un factor de pruebas adicional, decidimos no cortar en cualquier bandera.

3.2. Espectro energético composite

Mostramos la energía del espectro de las regiones dentro de 0.15°/0.3° para FRONT/BACK convertidos eventos de dos maneras. En los paneles de izquierda de la Figura [1] y [2] mostramos la densidad de fotones binned en \(\log E\). La binning utilizada es igual a la del Fig. 16 de Su & Finkbeiner (2012b). Esta binning fue elegida para optimizar el señal en el 111 GeV y 129 GeV líneas en el centro galáctico, y no ha sido modificada para este estudio. En los paneles de derecha de la Figur [1] e [2] mostramos la densidad de fotones binned en \(E\). La binning utilizada es la misma como en la Fig. 16 de Su & Finkbeiner (2012b). Esta binning fue elegida para optimizar el señal en el 111 GeV y 129 GeV líneas en el centro galáctico, y no ha sido modificada para este estudio. En los paneles de derecha de la Figura [1] e [2] mostramos la densidad de fotones binned en \(E^2dN/dE\) para el distribución de eventos desempaquetados con la función de función de función de línea (LSF) (Edmonds [2011]; Su & Finkbeiner [2012b]). Cada una de estas representaciones presenta pros y contras. Los histogramas hacen que sea fácil de ver cómo muchos fotones contribuyen a cada bin, y permiten simples computaciones de likelihood de Poisson. Los espectros desempaquetados dan una sensación del espectro sin ningún
Fig. 4.— The inclination angle distribution of the 100-140 GeV photons in left panels of Figure 1 and Figure 2, i.e. for SOURCE and ULTRACLEAN events, respectively.

Fig. 5.— The energy spectrum of unassociated 2FGL sources which have a 100-140 GeV photon within 0.15°/0.3° radius for FRONT/BACK LAT events. The spectrum is obtained from the 2FGL catalog. Sources thought to be potentially confused with Galactic diffuse emission are shown with dotted lines. The dashed black line shows the average of all the spectra. Each band shows integral photon flux from [0.1-0.3, 0.3-1, 1-3, 3-10, 10-100] GeV respectively from the likelihood analysis in that band with fixed photon power-law index. A 2σ upper limit is shown if the source is not significant in a band.

Fig. 6.— The angular distribution of 100-140 GeV photons matching with unassociated 2FGL sources within 0.15°/0.3° radius for FRONT/BACK LAT events (shown with solid/blue and dash/red curve, respectively). The distribution is normalized by the annular area given a radius. The FRONT events shows more concentrated distribution than the BACK events, consistent with the expectation based on the point spread function. Both FRONT and BACK events suggest a central concentrated distribution.

arbitrary binning choices, and convolution by the LSF allows maximum sensitivity to faint signals. However, the spectrum is “twice convolved” (once by the instrument and once by the processing) making the lines blend together to an undesirable degree. In the following we use the binned histograms for analysis, and provide the smoothed spectra only for reference.

We plot the energy spectrum for photons near the 16 unassociated sources with a photon at 100-140 GeV for SOURCE (Figure 1) and ULTRACLEAN (Figure 2) event classes. While this selection obviously suppresses the spectrum outside of the 100-140 GeV range, there is no way it can rearrange photons in the 100-140 GeV win-
and subhalos as a function of the line fraction $f \equiv F_{129}/(F_{111} + F_{129})$. We find that the best fit ratio of the $129$ GeV line to $111$ GeV line is $1.5$, and the $2\sigma$ range of the line ratio is $[0.84, 4.5]$. See Section 3.3 for details.

3.3. Statistical significance

Even with low statistics (7 counts at $111$ GeV and 6 counts at $129$ GeV) it is possible to obtain a significant result if the backgrounds are low enough. Because WIMP annihilations can produce lower energy photons (final-state radiation, Z/W continuum, inverse-Compton, etc.) it may be incorrect to use lower energy emission to assess the background. However, at high energy there are very few photons in these sources, and there would be none from a $129$ GeV WIMP. As a compromise, we assume the background is a power law, fit its amplitude to high energy ($135 < E < 270$), but choose the power-law index so that lower energy emission is modeled approximately correctly (Figure 3).

We assess the Poisson probability of observing 13 (or more) SOURCE counts in the two spectral bins with the background estimate in the upper panel of Figure 8. This has a probability of $p = 0.00069$ corresponding to $3.2\sigma$. Removing sources to be potentially confused with Galactic diffuse emission (marked out in 2FGL) only mildly affect our results ($3.3\sigma$). The ULTRACLEAN events would give a much higher significance ($> 4\sigma$) if we could believe the background estimate, but it looks implausibly low.

3.4. Spatial distribution

The subhalo candidates identified in this work are mostly distributed at $|b| < 20^\circ$, at all longitudes. It is not clear whether this could be a selection effect, a fluke, or a hint about the true distribution of dark matter subhalos. On one hand, dark matter subhalos preferentially dragged into the Galactic disk may lead to disk-like configurations, e.g. the proposed “dark disk” (e.g. Bruch et al. 2009; Purcell et al. 2009). On the other hand, the distribution is not concentrated in longitude, so they may be nearby subhalos with lower mass, close enough to appear brighter than more massive subhalos, e.g. those hosting dwarf galaxies.

3.5. Radial profile

In Figure 6 we show the stacked angular distribution of 100-140 GeV photons, which are selected by matching with unassociated 2FGL sources within $0.15^\circ/0.3^\circ$ radius for FRONT/BACK LAT events, with respect to the source center provided by 2FGL. The distribution is normalized by the annular area at each radius. The FRONT events show a more concentrated distribution than the BACK events, consistent with the point spread function. Both FRONT and BACK events suggest a centrally concentrated distribution.

3.6. Line ratio

Our previous work (Su & Finkbeiner 2012b) found 4 (14) photons above background at 111 (129) GeV. This led us to expect the $129$ GeV line might be stronger, but this work finds the $111$ GeV to have slightly more counts: 6 (5) at $111$ (129) GeV above background. Are these results compatible?

In order to determine a confidence interval for the line ratio, we consider a total of $N$ photons for the doublet, with $k$ of them in the $129$ GeV bin, and the rest in the $111$ GeV bin. The binomial probability of observing $k$ of $N$ counts in this bin is

$$P_k(n, f) = \frac{N!}{k!(N-k)!} f^k (1-f)^{N-k}$$

where $f \equiv F_{129}/(F_{111} + F_{129})$ is the true fraction of doublet photons at $129$ GeV. Figure 7 shows this probability (i.e., the probability of observing $k$ counts given $N$ and $f$) as a function of $f$ for the GC, subhalos, and the product of the two.

To obtain a confidence interval, we find $f_{\text{low}}$ such that

$$P(k \geq x, n, f_{\text{low}}) = \sum_{k=x}^{N} P_k(n, f) = 0.025$$
with a complementary expression for \( f_{\text{high}} \). The 95% confidence interval (corresponding to \( 2\sigma \) confidence) is then \( 0.167 < f < 0.765 \) for the subhalos and \( 0.524 < f < 0.935 \) for the Galactic center. A significant range of \( f \) is allowed in both cases, so we can combine the counts from both and obtain \( 0.457 < f < 0.820 \) for the joint fit. This yields 95% confidence bounds on the line ratio \( 0.84 < F_{129}/F_{111} < 4.5 \). The data are consistent (at \( 2\sigma \)) with the lines being equally strong, but also with the 129 GeV line being 4.5 times as strong. Clearly more data will be required to measure the line ratio with high confidence.

4. DISCUSSION AND CONCLUSION

In this paper, we have reported evidence for line emission at 111 GeV and 129 GeV from unassociated Fermi-LAT point sources. The lines have a significance of \( p = 6.9 \times 10^{-4} \) or \( 3.2\sigma \) for a simple power-law background.
model. These results provide independent support for our previous claims of a double gamma-ray line in the Galactic center at the same energies \cite{SuFinkbeiner2012}. The double line emission is compatible with the scenario of a 129 GeV WIMP annihilating to $\gamma\gamma$ and $\gamma Z$, producing the two lines. As a test of systematics, we apply the same selection and analysis procedure to associated Fermi-LAT point sources, and find no evidence for lines at these energies. It is difficult to imagine instrumental systematics that could produce this double line emission only at the Galactic center region and the locations of unassociated point sources without affecting other regions of the sky. We find this evidence to be persuasive, but it cannot be considered conclusive until more data become available.

Further observations are essential, not only to firmly establish the existence of the lines, but to measure the line ratio. The ratio of $\gamma Z$ and $\gamma\gamma$ line strength depends only on the particle physics model, and is independent of the astrophysical uncertainties such as the dark matter distribution in the halo. The line pair is also compatible with a 141 GeV WIMP annihilating through $\gamma Z$ and $\gamma h$ for $m_\chi \sim 125$ GeV, as in the “Higgs in Space” scenario \cite{Jackson2010}. However, we have not found any significant gamma-ray line at $\sim 141$ GeV. In any case, additional data will be critical for measuring the line ratio, which is currently only poorly determined (Figure 7).

A possible change to the Fermi scan strategy could accumulate S/N on the double spectral lines in the Galactic center up to 4 times as fast as the current survey strategy, and it is crucial for studying the double line emission. We believe this could be done with only modest impact on other Fermi science objectives. With the highly effective area and low energy threshold of H.E.S.S II, it may be possible to confirm a spectral bump in the Galactic center fairly soon. However, the energy resolution of H.E.S.S. II is inferior to LAT at 129 GeV, and it may be difficult to resolve the doublet.

The 2FGL catalog is based on 24 months of LAT data, and an updated catalog based on 48 months would provide improved source parameters and associations, decreasing the background noise for the subhalo analysis presented here. Furthermore, multi-wavelength follow-up observations would be helpful to identify the nature of unassociated 2FGL sources and refine the list of associations.

By stacking the unassociated 2FGL point sources together, it might be possible to reveal the spatial profile of the gamma-ray distribution at 111 GeV and 129 GeV. One may in principle improve the positional information of these unassociated sources by using high energy photons and better quantifying the gamma-ray spatial profile. However, with $\sim 1$ photon per source at high energy, the details of the algorithm used for centroiding the sources are critical, and consideration of the spatial profile is beyond the scope of this work. We simply use the position provided by the Fermi 2FGL catalog.

Acknowledgments: We thank Christoph Weniger, Dan Hooper, and Neal Weiner for helpful conversations. We acknowledge the use of public data from the Fermi data archive at \url{http://fermi.gsfc.nasa.gov/ssc/}. This work would not be possible without the work of hundreds of people, over many years, to design, build, and operate Fermi. M.S. and D.P.F. are partially supported by the NASA Fermi Guest Investigator Program. This research made use of the NASA Astrophysics Data System (ADS) and the IDL Astronomy User’s Library at Goddard (Available at \url{http://idlastro.gsfc.nasa.gov}).

REFERENCES

Abdo, A. A. et al. 2010a, ApJS, 188, 405, 1002.2280
Abdo, A. A. et al. 2010b, ApJ, 712, 147, 1001.4531
Ackermann, M. et al. 2012a, ApJ, 753, 83, 1108.1202
Ackermann, M. et al. 2012b, ApJ, 747, 121, 1201.2691
Aharonian, F., Khangulyan, D., & Malyshiev, D. 2012, ArXiv e-prints, 1207.0458
Belikov, A. V., Hooper, D., & Buckley, M. R. 2011, ArXiv e-prints, 1111.2613
Bergström, L. 2000, Reports on Progress in Physics, 63, 793, arXiv:hep-ph/0002126
Bergström, L., & Ullio, P. 1997, Nuclear Physics B, 504, 27, arXiv:hep-ph/9706232
Bergström, L., Ullio, P., & Buckley, J. H. 1998, Astroparticle Physics, 9, 137, arXiv:astro-ph/9712318
Bertone, G., Hooper, D., & Silk, J. 2005, Phys. Rep., 405, 279, arXiv:hep-ph/0404175
Bertone, G., Jackson, C. B., Shaughnessy, G., Tait, T. M. P., & Vallinotto, A. 2009, Phys. Rev. D, 80, 023512, 0904.1644
Bruch, T., Read, J., Baudis, L., & Lake, G. 2009, ApJ, 696, 920, 0804.2896
Buckley, M. R., & Hooper, D. 2010, Phys. Rev. D, 82, 063501, 1004.1644
Cline, J. M. 2012, ArXiv e-prints, 1205.2688
Edmonds, Y. V. 2011, PhD thesis, Stanford University
Fermi-LAT Collaboration. 2012, ArXiv e-prints, 1206.1896
Finkbeiner, D. P., Su, M., & Weniger, C. 2012, in preparation
Hooper, D., & Profumo, S. 2007, Phys. Rep., 453, 29, arXiv:hep-ph/0701197
Jackson, C. B., Servant, G., Shaughnessy, G., Tait, T. M. P., & Taoso, M. 2010, JCAP, 4, 0912.0004
Kuhlen, M., Madau, P., & Silk, J. 2009, Science, 325, 970, 0907.0005
Mirabal, N., Frias-Martinez, V., Hassan, T., & Frias-Martinez, E. 2012, MNRAS, 424, L61, 1205.4825
Nolan, P. L. et al. 2012, ApJS, 199, 31, 1108.1435
Pieri, L., Bertone, G., & Branchini, E. 2008, MNRAS, 384, 1627, 0706.2101
Purcell, C. W., Bullock, J. S., & Kaplinghat, M. 2009, ApJ, 703, 2275, 0906.5348
Rajaraman, A., Tait, T. M. P., & Whiteson, D. 2012, ArXiv e-prints, 1205.4723
Reiprich, T. H., & Böhringer, H. 2002, ApJ, 567, 716, arXiv:astro-ph/0111285
Su, M., & Finkbeiner, D. P. 2012a, ArXiv e-prints, 1205.5852
Su, M., & Finkbeiner, D. P. 2012b, ArXiv e-prints, 1206.1616
Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044, 1005.5480
Weniger, C. 2012, ArXiv e-prints, 1204.2797
| Source name                  | RA  | Dec  | ℓ   | b    | Flags | σ    | Variability | Spec index | Radius | Spec type     |
|-----------------------------|-----|------|-----|------|-------|------|-------------|------------|--------|---------------|
| 2FGL J0341.8+3148c          | 55.5| 31.8 | 160.3| -18.4| 32    | 7.6  | 24.7        | 2.31       | 0.0706 | PowerLaw      |
| 2FGL J0526.6+2248           | 81.7| 22.8 | 182.9| -6.9 | 1     | 7.1  | 27.5        | 2.88       | 0.0641 | PowerLaw      |
| 2FGL J0555.9-4348           | 89.0| -43.8| 250.4| -28.0| 0     | 5.0  | 29.1        | 2.11       | 0.0994 | PowerLaw      |
| 2FGL J0600.9+3839           | 90.2| 38.7 | 173.2| 7.6  | 0     | 5.1  | 14.1        | 2.04       | 0.0490 | PowerLaw      |
| 2FGL J1240.6-7151           | 190.2| 71.9 | 302.1| -9.0 | 0     | 8.2  | 18.4        | 1.82       | 0.0458 | PowerLaw      |
| 2FGL J1324.4-5411           | 201.1| 54.2 | 307.8| 8.4  | 24    | 4.9  | 23.3        | 2.39       | 0.1126 | PowerLaw      |
| 2FGL J1335.3-4058           | 203.8| -41.0| 311.8| 21.1 | 0     | 4.6  | 11.2        | 2.13       | 0.0800 | PowerLaw      |
| 2FGL J1639.7-5504           | 249.9| -55.1| 331.8| -5.6 | 9     | 5.9  | 21.1        | 2.79       | 0.0568 | PowerLaw      |
| 2FGL J1716.6-0526c          | 259.2| -5.4 | 16.6 | 18.2 | 2080  | 6.8  | 25.7        | 2.43       | 0.1052 | LogParabola   |
| 2FGL J1721.5-0718c          | 260.4| -7.3 | 15.6 | 16.2 | 41    | 6.0  | 20.9        | 2.68       | 0.0795 | LogParabola   |
| 2FGL J1730.8+5427           | 262.7| 54.5 | 82.2 | 33.3 | 0     | 4.6  | 16.9        | 2.69       | 0.1258 | PowerLaw      |
| 2FGL J1844.3+1548           | 281.1| 15.8 | 46.3 | 8.7  | 4     | 12.5 | 29.8        | 2.43       | 0.0403 | PowerLaw      |
| 2FGL J2004.6+7004           | 301.2| 70.1 | 102.9| 19.5 | 0     | 9.5  | 36.8        | 1.97       | 0.0368 | PowerLaw      |
| 2FGL J2115.4+1213           | 318.9| 12.2 | 62.6 | -24.5| 0     | 5.1  | 25.3        | 2.38       | 0.0800 | PowerLaw      |
| 2FGL J2351.6-7558           | 357.9| -76.0| 307.7| -40.6| 0     | 4.1  | 20.8        | 1.92       | 0.0702 | PowerLaw      |

Note: — The table provides detailed information about the unassociated 2FGL point sources we have identified with at least one 100-140 GeV photon within 0.15/0.3° for FRONT/BACK events. The first column is the 2FGL catalog name in the format 2FGL JHHMM.m+DDMM, where 'c' indicates that the source is considered to be potentially confused with Galactic diffuse emission. The second/third column are Right Ascension (J2000) and Declination (J2000). The forth and fifth column are Galactic Longitude and Galactic Latitude. The sixth column is the flag parameter which indicate possible issues noted in detection or characterization of the source. Sources having no flags raised with value 0 are those without potential problems. The seventh column is the variability index, defined as the test statistic for the hypothesis that monthly averages of the source flux vary relative to the null hypothesis of constant flux. The TS is distributed as $\chi^2$ with 23 degrees of freedom, so a value greater than 41.64 indicates a > 99% chance of being a variable source, and we have removed these sources from our analysis. The eighth column shows the best fit for the photon number power-law index (for logarithmic parabola spectra it is index at the Pivot Energy) derived from the likelihood analysis for 100 MeV-100 GeV. The ninth column shows the average of semimajor/semiminor axis of the error ellipse at 68% confidence. Source detection significance in Gaussian $\sigma$ units is shown in the tenth column, which is derived from the likelihood Test Statistic for 100 MeV-100 GeV analysis. The eleventh column shows the best fit form of the spectral type. We note that only three sources have logarithmic parabolic spectral shape (two of them are marked with potentially confused with Galactic diffuse emission). Detailed explanation of parameters listed in this table can be found in Nolan et al. (2012).

APPENDIX

We show the same energy spectrum as in Figure 1 but with high incidence angle events only with $\theta > 40°$ in Figure 9. In Figure 10 we show that the 111 GeV and 129 GeV lines do not appear in the SOURCE minus ULTRACLEAN events, i.e. cosmic ray contamination is not a plausible explanation for the line emission. In Figure 11 and Figure 12 we show the unassociated/associated point sources by matching with LAT events of different energy range. We also compare with distributions of all the unassociated/associated sources. Selection effect is plausible explanation for the spatial distribution of selected unassociated sources shown in Figure 8.
Fig. 9.— Same as the upper left panel of Figure 1, but using only events with high incidence angle $\theta > 40^\circ$ which has better energy resolution to reveal the energy spectrum of unassociated 2FGL catalog. We found two gamma-ray line emission on 111 GeV and 129 GeV.

Fig. 10.— Same as the upper left panel of Figure 1, but using only events belongs to SOURCE class but not to ULTRACLEAN event. This selected set of events are dominated by cosmic ray events. We found no significant gamma-ray line emission on 111 GeV and 129 GeV ($0.47\sigma$ with background estimation using 100-500 GeV data).
Fig. 11.— The distribution of unassociated 2FGL sources selected by matching with LAT photons of different energy range. The panels from the upper left to lower right are for 150-500 GeV, 100-140 GeV, 60-100 GeV, 30-60 GeV, and 10-30 GeV, and for comparison all unassociated sources with $|b| > 5^\circ$ and variability index < 41.64.
Fig. 12.— The same as Figure 11 but for the associated 2FGL sources.