Joint Analysis of Fermi Gamma-ray Space Telescope and South Pole Telescope

1. Introduction

The Fermi γ-ray Space Telescope (Fermi) has surveyed the entire sky at the highest-energy band of the electromagnetic spectrum (0.2-300GeV) (Ackermann et al. 2011). The majority of Fermi sources have counterpart identifications from multi-wavelength large-area surveys, particularly in the radio and x-ray bands. However, around 35% of Fermi sources remain unidentified, a problem exasperated by the low resolution (~0.5 deg). Counterpart localization and characterization of these unidentified Fermi sources is one of the biggest challenges in gamma-ray astronomy. The South Pole Telescope (SPT) is a ten-meter diameter telescope optimized and dedicated to observations of the Cosmic Microwave Background (CMB), the relic radiation from the Big Bang. This unique millimeter-wavelength (mm) facility has completed a cosmological survey covering 2500 square degree of southern sky with arcminute resolution and mJy sensitivity at 1.4, 2, and 3 mm wavelength (Carlstrom et al. 2011). The mm regime is the most efficient means to identify unidentified Fermi sources, the majority of which are thought to be blazars at cosmological distances (Vieira et al. 2010). In this work, we cross-match sources from the Fermi and SPT surveys to characterize the mm properties of gamma ray sources and identify the positions and counterparts to previously unidentified Fermi sources.

2. Method and Analysis

2.1 Cross-Matching

The method for identifying the SPT counterparts of Fermi sources in this study is based on the evaluation of angular separation and corrected Poissonian probability (Browne & Cohen 1978; Downes et al. 1986; Biggs et al. 2011). The evaluation includes all the potential SPT counterparts nearby each Fermi candidate within the searching radius (~1 deg). The searching radius \( r_s \) is set twice large of Fermi beam (~0.5 deg) to guarantee all the possibility of having SPT counterparts. Given the possible SPT counterpart at angular separation \( r \), with flux density \( S \), we can obtain the surface density \( n(>S) \) and then calculate the expected number of events to find at least one candidate with at least \( S \) within \( r \):

\[
\mu = \pi r^2 n(> S)
\]

(1)

However, as we continue search till reach the searching radius, the following search would feed back the remaining similar events until no potential counterpart can be counted. Given the initial expected number, we can obtain the corrected expected number of similar events after several steps of differential derivation:
where the $\mu_{cri}$ is defined as the critical expected number, considering sources with critical flux density (above lowest detectable flux density) within the searching radius:

$$
\mu_{cri} = \pi r_s^2 n_{lim}
$$

$n_{lim}$ is the corresponding surface density of source with the lowest detectable flux. Therefore, the corrected Poissonian probability is

$$
p = 1 - e^{-\mu_{cor}}
$$

In both separation and probability space, the real correlation and random associations show the natural boundary to make the cuts. Using both parameters, association of SPT and Fermi sources can be more reliable.

**Figure 1:** **Left Panel:** Histogram of separation of potential correlated pairs within searching radius in SPT (150GHz) and Fermi association. This plot demonstrates the value of angular separation (~10arcmin) splitting the correlated and random associated sources. **Right Panel:** Flux-separation plot shows the two populations of correlated sources (red) and random associated sources (black) respectively. The criteria of correlation are determined by separation evaluation.
Figure 2: **Left Panel:** Histogram of the quantity referring corrected Poissonian probability modified by flux density distribution, where potential correlated pairs are within searching radius in SPT (150GHz) and Fermi association. Assuming Euclidean distribution of non-evolving sources, the flux density distribution would have a slope of index -2.5. So \( n(>S) \), the surface density of sources with fluxes greater than \( S \), is proportional to \( S^{-1.5} \). For \( p \ll 1 \) \( (p \propto n(>S) \propto S^{-1.5}) \), \( p \times S^{-1.5} \) gives flat distribution to decide the selecting criteria. The plot demonstrates the value of \( p \times S^{-1.5} \) (~10) splitting the correlated and random associated sources. **Right Panel:** Flux-probability plot shows the two populations of correlated sources (red) and random associated sources (black) respectively. The criteria of correlation are determined by probability evaluation.

![Plot 1](image1.png)

Figure 3: Separation-probability plot shows the distribution of two types of populations - correlated sources (red) and random associated sources (black). The correlated sources are strictly limited by both the separation evaluation and probability evaluation.

The analysis shows that about 95% of all the Fermi sources have SPT counterparts in 2500 deg\(^2\) survey region. SPT provides candidates associated with a large portion of unidentified Fermi sources (~45%).

![Plot 2](image2.png)

Figure 4: The plot is the 2500 deg\(^2\) SPT field (Story et al. 2013) map. In this region, black points represent SPT sources (4769); blue circles mark the position of the identified FERMI sources (129); green circles represent the unidentified FERMI sources with SPT counterparts (17); red circles represent the unidentified FERMI sources without SPT counterparts (21).

### 2.2 Multiwavelength Summary

Combining with published catalogs from large-area surveys, the same analysis with other surveys indicates that the mm waveband surveyed with the SPT is more efficient to identify...
Fermi sources than the Sydney University Molonglo Sky Survey (SUMSS) (Mauch et al., 2003) in the radio band (36 cm) and the ROSAT All-Sky Survey (RASS) in x-ray band. According to WISE γ–ray blazar Strip (WGS) in [3.4]-[4.6]-[12] µm 2-D projection (Massaro, 2012a), the evaluation of angular separation and corrected Poissonian probability provide more general associations other than only WISE blazar-like γ–ray sources.

Figure 5: **Left Panel:** The histogram of number density of sources in SPT (mm), SUMSS (radio), and RASS (x-ray) catalogs verses separation from Fermi sources. This plot demonstrates that the mm is the most efficient wavelength to identify γ–ray counterparts due to the high correlation between the mm and γ–ray emission, as well as the relatively low density of mm sources on the sky compared to radio and x-ray. **Right Panel:** Histogram of the probability of false associations between SPT, SUMSS, and RASS to the 167 Fermi sources in the SPT field. This plot demonstrates that using the mm to identify gamma-ray counterparts is the best. This method (p-value; see, e.g. Biggs et al 2011) takes into account the density of sources, the separation, and the fluxes of sources. Thus, the mm-wave counterparts are more secure, and have less false associations than x-ray or radio counterparts.

Figure 6: The WISE color plot ([3.4]-[4.6]-[12] µm) indicates the evaluation of separation and corrected Poissonian probability provide more general associations than WGS (Massaro, 2012a). Black dashed lines shows the boundaries of WGS. Green dots represent the SPT sources with WISE counterparts. Red cross demonstrates all the Fermi sources with SPT identification and WISE counterparts.
3. Conclusions
There are 167 FERMI sources in the 2500 square degree SPT field, where 140 of them (~ 84%) have SPT counterparts. There are 38 unidentified FERMI sources, where 17 of them (~ 45%) have SPT counterparts. This work demonstrated the promise of the mm-wavelengths to identify counterparts to γ-ray sources. This will have important implications for understanding the resolved gamma ray population as well as the diffuse γ-ray background.

![Figure 7](image)

Figure 7: Two panels of images illustrate the samples of unidentified Fermi sources with SPT identification. Blue circle indicates the Fermi 95% error ellipses; green contours represent Wide-field Infrared Survey Explorer (WISE) sources in 12µm; yellow contours pinpoint the SPT counterparts; red contours indicate the radio counterparts (SUMSS sources in 843MHz). **Upper Panel**: An unidentified Fermi sample (3FGL J0032.3-5522) with SPT identification. The left SPT 150 GHz image shows a SPT counterpart (SPT-S J003211-5522.4) in the beam of unidentified Fermi source. The right Digital Sky Survey (DSS) red image zooms in at the position of the SPT identification and indicates the existence of radio counterpart. **Lower Panel**: An unidentified Fermi sample (3FGL J2327.2-4130) with two SPT counterparts (SPT-S J232625-4140.3 & SPT-S J232804-4117.8). The first SPT 150 GHz image shows two SPT counterparts resolved in one Fermi beam. The second and third DSS red images zoom in at the positions of two SPT counterparts respectively and indicate the existences of radio counterparts.

References