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X-ray observations and the search for *Fermi*-LAT γ-ray pulsars

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The Large Area Telescope (LAT) on *Fermi* has detected $\sim$150 γ-ray pulsars, about a third of which were discovered in blind searches of the γ-ray data. Because the angular resolution of the LAT is relatively poor and blind searches for pulsars (especially millisecond pulsars, MSPs) are very sensitive to an error in the position, one must typically scan large numbers of locations. Identifying plausible X-ray counterparts of a putative pulsar drastically reduces the number of trials, thus improving the sensitivity of pulsar blind searches with the LAT. I discuss our ongoing program of *Swift*, XMM-*Newton*, and *Chandra* observations of LAT unassociated sources in the context of our blind searches for γ-ray pulsars.

1 Introduction

Since its launch, in June of 2008, the *Fermi* Large Area Telescope (LAT) has dramatically increased the number of known γ-ray pulsars. At the end of the *Compton Gamma Ray Observatory (CGRO)* era there were 7 *firm* detections [Thompson(2004)], while the Second $Fermi$ LAT Catalog of Gamma-ray Pulsars (2PC) contains 145 γ-ray pulsars detected in the first 3 years of the *Fermi* mission [Abdo et al.(2013)]. Almost a third (42) of the 2PC γ-ray pulsars were discovered in blind searches of LAT data (e.g. [Abdo et al. (2009b), Saz Parkinson et al.(2010), Pletsch et al.(2012)], See Figure 1). Radio follow-up observations of the these LAT-discovered pulsars failed to detect pulsations for all but a few of them (e.g. [Camilo et al.(2009)]), which suggests that a majority of the underlying population of young, isolated pulsars is, in fact, *radio quiet*. Thus, X-ray observations may prove to be the only alternative channel to learn about such pulsars, or even to identify them, prior to their discovery by the LAT.

1.1 LAT searches for pulsars

Blind searches for pulsars in LAT data are complicated by a number of factors, including the scarcity of photons [1] and the relatively poor point spread function (PSF) of the instrument, as well as its strong dependence on energy [2]. X-ray observations of LAT γ-ray sources significantly improve the sensitivity of pulsar blind searches by providing plausible counterparts with precise ($\sim$arc second) positions [Dormody et al.(2011)].

Blind searches for *even* isolated γ-ray pulsars are computationally intensive, as they involve a search over the fairly large parameter space of position, frequency, and frequency derivative. Searches for MSPs, in particular, are extremely sensitive to position. Typically, one must pick a position and *barycenter* the γ-ray photons to within 1", or better, of the true position of the (undiscovered) pulsar. Figure 2 demonstrates this sensitivity to the position by showing the drop in relative significance of the pulsation from the known MSP J2124–3358, when the offset in position is greater than a small fraction of an arc second. If the γ-ray source is an MSP, and we are able to detect *a priori* its X-ray counterpart, then our starting point is generally within at most a few arc seconds of the true pulsar position. Since typical uncertainties in the LAT positions are of order arc minutes, the gain in computer time achieved by scanning the X-ray (as opposed to the γ-ray) error region is of order 10^3. Aside from this gain in computational efficiency, however, restricting our blind searches to known X-ray positions has the added advantages of reducing the number of trials, thus improving the sensitivity of our searches.

The discovery of γ-ray pulsations in a LAT unassociated source first and foremost identifies the nature of the source. Its subsequent study, however, has numerous benefits: the timing analysis can lead to localizations of unprecedented (for γ-ray astronomy) accuracy, rivaling those of X-ray instruments, as described in [Ray et al.(2011)]. Follow-up X-ray observations can then unambiguously identify a coun-

[1] Typically only a few photons per day or, equivalently, one photon per thousands or even millions of rotations of the pulsar.

[2] The LAT PSF varies from several degrees at 100 MeV to a few arc minutes at 100 GeV.

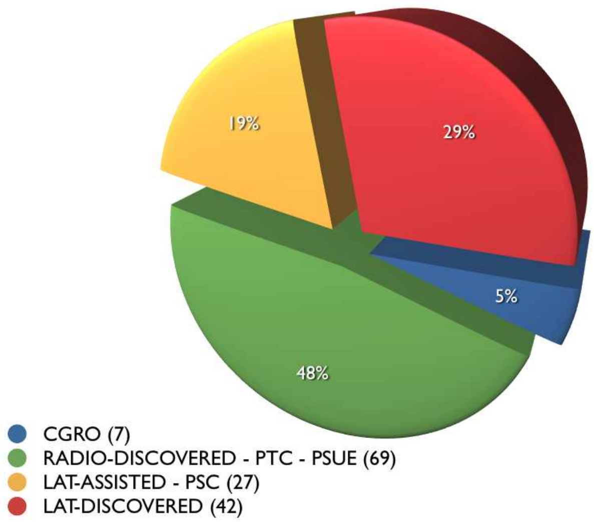

Fig. 1 **The γ-ray pulsar pie** – Distribution of the 145 γ-ray pulsars in the LAT 2nd Pulsar Catalog (2PC, [Abdo et al.(2013)]). In blue are *Compton Gamma-ray Observatory* (CGRO) γ-ray pulsars, known before the launch of *Fermi*. In green are γ-ray pulsars detected using radio ephemerides. In yellow are those discovered in radio searches of LAT unassociated sources, subsequently shown to pulse in γ rays (the so-called *LAT-assisted* γ-ray pulsars). In red are pulsars discovered in *blind searches* of LAT data.

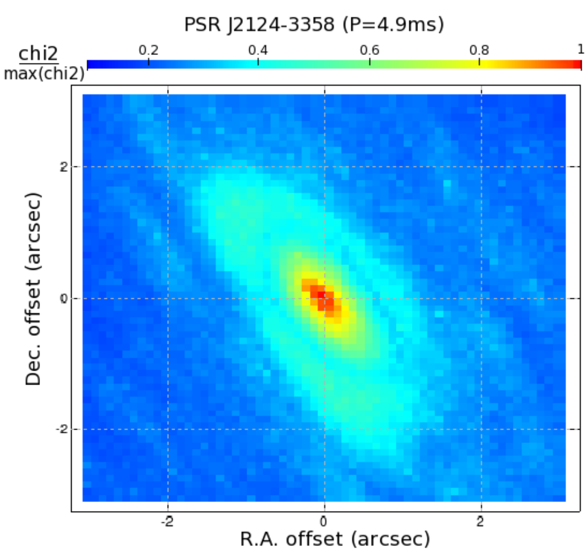

Fig. 2 Relative significance of the detection of pulsations from the isolated MSP J2124–3358. The normalized χ^2 is shown as a function of the offset from the radio position. The orientation of the ellipse follows ecliptic coordinates and the area satisfying $\frac{\chi^2}{\chi^2_{max}} > 0.5$ is approximately one square arc second, which illustrates the required accuracy for such searches.

terpart and its further study can tell us more about the nature of the compact object (e.g. its distance) or the pulsar population as a whole [Marelli et al.(2011)]. Further studies in γ rays (e.g. phase-resolved spectroscopy), in conjunction with theoretical modeling might also reveal further insights into some of the ongoing questions in pulsar physics (e.g. see Venter & Harding, in these proceedings).

In this paper, we describe our ongoing efforts to use *Swift*, *Chandra*, and *XMM-Newton* observations to enhance our blind searches for pulsars with the LAT.

2 The multi-wavelength nature of pulsars

Pulsars are thought to be rapidly-spinning highly-magnetized neutron stars. Although the vast majority of the $\sim$2000 known pulsars (including the first discovered) were found in radio, pulsars are the quintessential multi-wavelength (MWL) objects, having been detected across the entire electromagnetic spectrum, from the optical, to the X-ray and γ-ray bands [e.g. Thompson(2004)]. While optical pulsations are rarely detected [e.g. see Section 9, 2PC], there are currently over 100 known X-ray pulsars [Becker (2009)]. The nature of the X-ray emission can be varied, and can include thermal emission from the surface of the neutron star as well as magnetospheric emission. Even when optical and/or X-ray pulsations from a pulsar are not detected (often simply due to the faintness of such emission), it is fairly common to detect an optical or X-ray counterpart source at the location of the pulsar and the nature of such a source can lead to its identification as a neutron star (or at least a neutron star *candidate*).

The X-ray/γ-ray connection in the studies of pulsars has a long history. The first known *radio-quiet* pulsar, *Geminga*, was first detected as a bright unidentified γ-ray source by SAS-2 in 1972 but its true nature was only revealed 20 years later through the detection of pulsations in the X-ray band [Halpern & Holt (1992)], later confirmed to be present in the γ-ray band. Although subsequent analyses have shown that it could have actually been discovered directly in blind searches of the γ-ray data[3] [e.g. Ziegler et al.(2008)], undoubtedly it was the X-ray studies of this pulsar that led the way in improving our understanding of this enigmatic source [for a detailed review of Geminga, see Bignami & Caraveo(1996)]. More recently, we have an example of a different path: PSR J2021+4026 is a radio-quiet pulsar discovered in early blind searches of LAT γ-ray data [Abdo et al. (2009b)]. In this case, *Chandra* observations of a bright EGRET unidentified source led to a number of *plausible* candidates [See Figure 3, adapted from Weisskopf et al.(2006)]. Following the discovery of γ-ray pulsations, further *Chandra* observations, in conjuntion with the pulsar timing performed with the γ-ray data led to the identification of its X-ray counterpart [Weisskopf et al.(2011)], while a deep *XMM* observation of

[3] Possibly going as far back as the COS-B era.

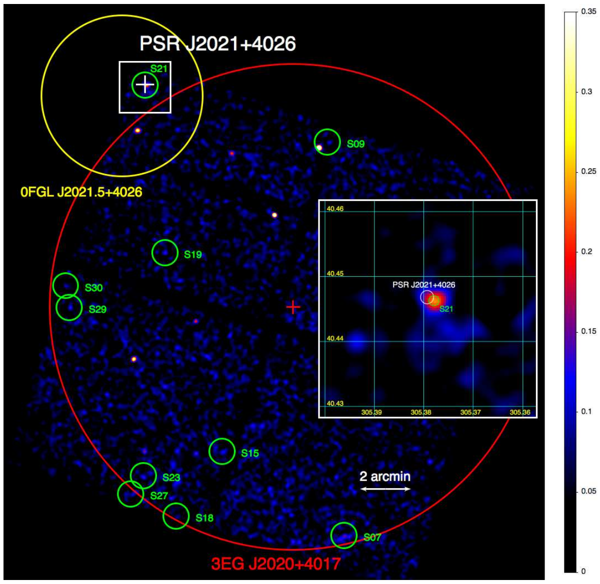

Fig. 3 *Chandra* 14.3 ks ACIS-I observation of the unidentified EGRET source 3EG J2020+4017 (PI: Weisskopf). The largest (red) circle represents the uncertainty in the EGRET position, while the smaller (yellow) circle in the top left represents the *Fermi*-LAT error circle with just 3 months of data (i.e. 0FGL). The numbering of the X-ray sources follows Weisskopf et al. 2006, with circled sources representing candidate X-ray counterparts. The one surrounded by a box (S21) represents the actual X-ray counterpart, whose X-ray position was used in the original discovery of the pulsar [Abdo et al. (2009b)]. The zoomed-in image shows the error ellipse obtained from timing the pulsar in γ rays, in good agreement with the X-ray counterpart position.

the X-ray counterpart managed to finally uncover X-ray pulsations [Lin et al.(2013)].

Pulsars (especially "young" ones) are naturally associated with supernova remnants (SNRs) and Pulsar Wind Nebulae (PWNe), both of which are important sources of radiation (including X-rays) in their own right. Hence, despite neutron stars often being inherently faint X-ray objects, pulsars can often reveal themselves through these other sources of unpulsed (most often extended) X-ray emission.

In short, although X-ray fluxes from most pulsars are extremely low, especially when compared to their γ-ray flux [Marelli et al.(2011)], the X-ray window remains one of the most fruitful channels for the discovery and subsequent study of pulsars. With the launch of *Fermi*, X-ray observations have become, if anything, even more important, as the population of *radio-quiet* neutron stars has vastly increased, along with our desire to understand these systems in the broader context of the overall neutron star population.

3 X-ray observations of LAT unassociated sources

From the beginning of γ-ray astronomy, a large number of γ-ray sources have been discovered with no known counterparts (e.g. Geminga). This is a natural consequence of the poor angular resolution of γ-ray instruments, relative to those in most other wavelengths. The first COS-B catalog, for example, contained 25 sources, of which $>$80% were unidentified. The Third EGRET Catalog contained $\sim$300 sources with more than 50% classified as "unidentified". With the advent of the LAT, the number of γ-ray sources has increased dramatically. Although still numbering in the hundreds, the fraction of sources considered *unassociated*[4] continues to fall: from 40% in the Bright Source List [0FGL, Abdo et al. (2009)], to 30% in the 1FGL catalog [Abdo et al.(2010)], and $\sim$25% in the 2FGL catalog [Nolan et al.(2012)]. This is in large part due to the significant improvement in the instrument characteristics of the LAT relative to past missions, but is also the result of the vast multi-wavelength campaigns that have been mounted to try to identify these sources, in particular in the radio [e.g. Ray et al.(2012)] and X-ray bands [e.g. Marelli et al.(2011)]. Figure 3 illustrates the dramatic improvement in source localization obtained with the LAT, relative to EGRET, which greatly facilitates multi-wavelength (particularly radio and X-ray) follow-up observations of these sources.

The nature of LAT unassociated sources can be investigated, to a certain extent, by comparing their properties to those of γ-ray sources in known classes. In particular, the two largest classes of γ-ray sources are blazars and pulsars. Fortunately, these sources differ greatly in their timing and spectral properties. Blazars are highly variable on long ($>$1 day) time scales and have power law spectra, while pulsars are fairly steady (although, see [Allafort et al. (2013)]) and have spectra that are better fit with a power law with an exponential cutoff. A number of techniques can be used to statistically classify sources into *pulsar candidates* or *blazar candidates*, by virtue of these spectral and variability characteristics [e.g.Ackermann et al.(2012)].

3.1 *Swift* follow-up observations of LAT unassociated sources

As part of a successful *Fermi* Guest Investigator Cycle 3 (later renewed in Cycles 4 and 5) program [Stroh & Falcone (2013)], we organized a campaign of follow-up observations of *Fermi*-LAT unassociated sources with *Swift*. Starting with the unassociated sources in the 1FGL catalog, our program was later expanded to include unassociated sources in 2FGL. Table 1 gives a summary of the *Swift* observations carried out to

[4] LAT catalogs distinguish between *identification* and *association* of a γ-ray source with a known astrophysical object, with the former requiring a measurement of correlated variability at other wavelengths.

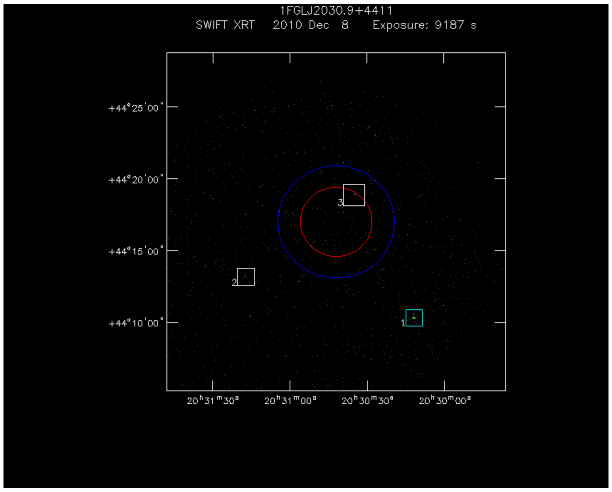

Fig. 4 *Swift* 9.2 ks observation of the LAT *pulsar-like* unassociated source 1FGL J2030.9+441, showing a number of plausible X-ray counterparts. For more details, go to `http://www.swift.psu.edu/unassociated/`.

Table 1 Swift X-ray observations of LAT *pulsar-like* unassociated sources (As of August 2013).

Catalog	# Sources (Unass.)	*Swift* Obs.	X-ray Sources (SNR>3)
1FGL	1451 (630)	251	544
2FGL	1873 (575)	179	198

date, as part of this program, along with the number of X-ray sources detected. The goals of this shallow survey are simply to identify plausible X-ray counterparts of the LAT unassociated sources. We previously determined which of these sources might be promising pulsar candidates (as described in the previous section), and typically observed these LAT sources for ∼10 ks, while the remaining unassociated sources (overwhelmingly blazar candidates, which generally have brighter X-ray counterparts) received only short (∼4 ks) observations. Figure 4 shows the results of a 9.2 ks *Swift* observation of the LAT *pulsar-like* unassociated source 1FGL J2030.9+441. The results of all the *Swift* observations are summarized in the publicly available web site: `http://www.swift.psu.edu/unassociated/`. We then proceeded to select all X-ray counterparts of the *pulsar candidates* and perform blind searches of the γ-ray data using the precise *Swift* locations. The LAT blind searches on these X-ray counterpart locations are still in progress and the results of such searches will be reported in a future publication.

3.2 XMM-*Newton* Observations

In addition to our *Swift* campaign, we proposed deeper observations with more sensitive X-ray missions such as *Chandra* and XMM-*Newton* of a few 'select' candidates. Our XMM campaign focused on trying to identify X-ray

Table 2 XMM X-ray observations of *pulsar-like* 2FGL unassociated sources

Target (2FGL)	duration (ks)
J1744.1–7620	26
J1036.1–6722	25
J1536.4–4949	18

Table 3 Chandra X-ray observations of LAT-detected SNRs with *pulsar-like* γ-ray emission

SNR (2FGL)	duration (ks)
G298.6–0.0 (2FGL J1214.0–6237)	20
G311.50.3 (2FGL J1405.5–6121)	13
G359.1+0.9 (2FGL J1738.9–2908)	11

counterparts of three bright high-Galactic-latitude LAT γ-ray sources which were plausible candidate radio-quiet MSPs (See Table 2). These targets were chosen as being extremely promising pulsar candidates (by some of the statistical measures alluded to in the previous section), apart from being relatively bright in γ rays. It was thus felt that they were *deserving* of the better angular and spectral characteristics of *XMM*. Indeed, one of our three targets (J1536.4–4949) subsequently turned out to host an MSP, discovered in a radio search of LAT unassociated sources carried out by the GMRT[5][Ray et al.(2012)].

3.3 *Chandra* Observations

The *Fermi* LAT has detected several dozen Supernova Remnants (SNRs) and many of the newly-discovered γ-ray pulsars are positionally coincident (and possibly associated) with SNRs. Indeed, the number of pulsar-SNR associations has grown dramatically thanks to *Fermi*. Disentangling the γ-ray emission due to the pulsar from that due to the SNR is crucial to explaining the nature of such emission.

Chandra can be extremely useful in identifying potential pulsar candidates in bright γ-ray sources with pulsar-like properties, and those which are already known to be associated with SNRs are therefore prime candidates to be targeted. In addition, the excellent angular resolution of *Chandra* raises the possibility of detecting extended X-ray emission from a PWN, making such a detection a strong indication for the presence of a young pulsar.

With this goal in mind, we proposed (and obtained) a number of *Chandra* observations of such sources, in the hopes of discovering the (probably radio-quiet) γ-ray pulsar associated with such SNRs (see Table 3). Figure 5, for example, shows the positional coincidence of the LAT source 2FGL J1214.0–6237 and SNR G298.6–0.0. The analysis of these X-ray observations is still in progress.

[5] `http://gmrt.ncra.tifr.res.in`

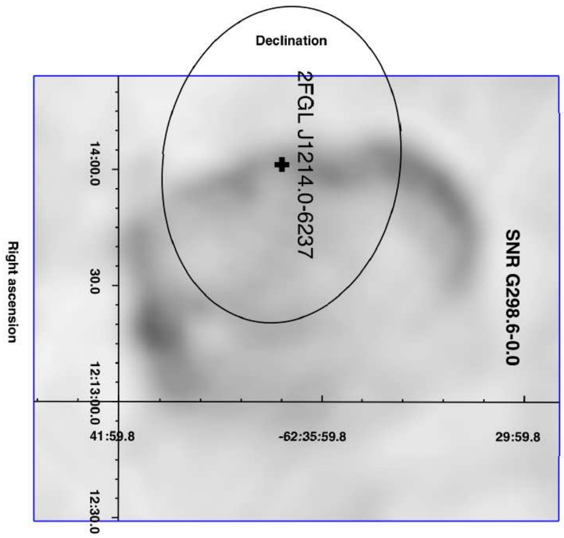

Fig. 5 843 MHz Radio continuum image showing the extent of SNR G298.6-0.0. The location of the nearby 2FGL source is shown with an error ellipse tracing out the 95% localization boundary. The ACIS-I field of view covers the entire image, including the 2FGL source.

4 Searches for *Black Widows*

Unfortunately, a majority of MSPs are in binary systems, adding an extra complication to the blind search for such pulsars. Indeed, over 85% of MSPs discovered in LAT sources fall in this category. In fact, a large number of these are in so-called *Black-Widow* (or Redback) systems. These systems have extremely tight circular orbits and are often subject to wide eclipses, making them quite challenging to detect in radio. Although no clear orbital modulation has been detected in the γ-ray light curves of these objects, optical (and sometimes X-ray) observations can clearly reveal the binary nature of the system.

Despite the fact that *Black Widow*-like binaries have almost circular orbits, thus requiring a search over “only” three additional orbital parameters, a full blind search of the γ-ray data would be unfeasible with current available computer power. However, an analysis of the X-ray and optical light curves, along with optical spectral observations and some modeling, can result in fairly robust estimates for at least two of the three additional parameters [e.g. Romani (2012)], thus making it possible to perform a *semi-blind* search of the LAT data. Such a search has already proven successful [Pletsch et al.(2012)], and more such searches are planned for the future.

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