Correlating the GeV & hard X-ray skies

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Summary: The preliminary results of the cross-correlation analysis of the *Fermi* and hard X-ray Source populations are reported. The level of correlation, the probability of false association and the dominant source classes are discussed.

Abstract

The Large Area Telescope on the *Fermi* Gamma-ray Space Telescope provides unprecedented sensitivity for surveying the high energy sky and has detected many sources in its 1st year of operations. The current generation of hard X-ray telescopes have been monitoring and surveying the keV sky for the past seven years providing the most complete catalogs in this energy band. Emission in the *Fermi* band is dominated by particle acceleration processes including shocks, jets and magnetospheric emission; the hard X-ray sky is dominated by accretion mechanisms. These are two physically different regimes and consequently those objects which are present in both energy regimes are interesting to investigate. We present a correlation analysis of the Fermi source population with the hard X-ray survey catalogs of *INTEGRAL* and *Swift*.

INTRODUCTION

The *Fermi*-LAT has been successfully surveying the entire sky with unprecedented sensitivity. Currently the internal *Fermi* catalog makes use of 11 months of data and detects over 1000 sources. Many of these sources are unidentified; one possible avenue for investigation is correlating the *Fermi* source list with the current hard X-ray surveys to identify targets for further investigation.

The *INTEGRAL*-IBIS survey has to date detected over 700 hard X-ray sources containing a variety of source types ranging from CVs to AGNs. The exposure is focussed in the Galactic plane and center. See the 4th IBIS/ISGRI catalog for details (Bird et al., 2009). *Swift*/BAT has also detected a large source population to date. The exposure of the *Swift* sky is more concentrated in the extra-galactic sky rather than the Galactic plane. The 22 month *Swift*/BAT catalog contains 461 sources with more than 50% associated with Seyfert galaxies (Tueller et al., 2009).

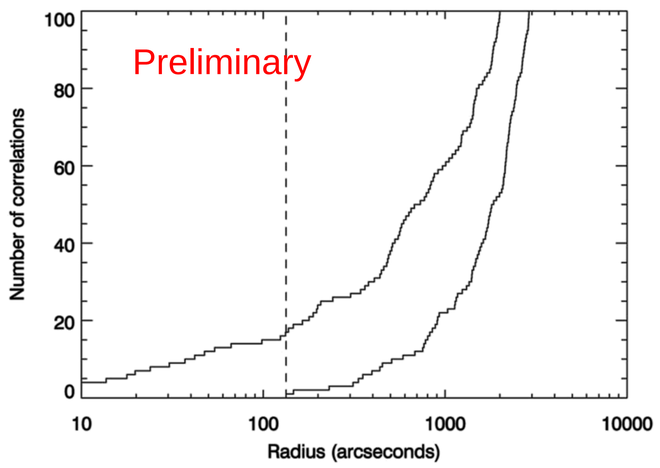

Figure 1: The number of objects matched at a given search radius between the *Fermi* internal catalog and the *INTEGRAL*-IBIS 4th catalog (left-most line). The right-hand solid line is the number of matches when using a faked source list . The dashed line indicates the limit where no spurious correlations are made.

Table 1: High confidence spatial associations between the internal *Fermi* catalog at the hard X-ray survey catalogs. This list should have minimal false association, with <1 source found by chance correlation

Fermi Source	Hard X-ray Source	l (deg)	b (deg)	Sep. (')	Fermi 95% error	INTEGRAL 95% error	Fermi TS	Hard X-ray significance	Hard X-ray catalog	Source type
SourceA	Mrk501	63.596	38.843	0.1	2.2	2.8	1607.5	11	INTEGRAL	BL Lac
PSRJ0534+2200	Crab	184.553	-5.786	0.1	0.9	0.2	78151.3	5625.3	INTEGRAL	PSR/PWN
SourceB	3C454.3	86.116	-38.185	0.3	1.3	1.2	31571	30.8	INTEGRAL	Blazar
SourceC	IGRJ20569+4940	89.335	2.777	0.3	5	4.4	73.7	6.5	INTEGRAL	AGN?
SourceD	3C273	289.945	64.355	0.3	2.5	0.5	5607.5	90.3	INTEGRAL	QSO
PSRJ0835-4510	VelaPulsar	263.553	-2.784	0.5	0.8	0.5	420835.6	89.1	INTEGRAL	PSR/PWN
SourceE	Mrk421	179.819	65.043	0.6	1.3	0.4	7868.7	151.1	INTEGRAL	BL Lac
SourceF	PKS1830-211	12.166	-5.700	0.7	2.5	1.2	1811	30.5	INTEGRAL	Blazar
LSI+61303	LSI+61303	135.676	1.082	0.9	1.6	2.8	6101.4	10.9	INTEGRAL	HMXB
SourceG	3C279	305.107	57.067	0.9	1.4	2.9	16254.7	10.7	INTEGRAL	Blazar
SourceH	CasA	111.751	-2.119	1.3	3.7	0.8	168.7	51.7	INTEGRAL	SNR
SourceI	1ES0033+595	121.006	-2.980	2	4.3	1.8	178.9	18.2	INTEGRAL	BL Lac
SourceJ	NGC1275	150.584	-13.273	2.2	1.9	2.7	3575.8	11.1	INTEGRAL	Radio Gal
SourceK	BLLac	92.600	-10.460	2.3	3.2	3.2	1078.2	9.2	INTEGRAL	BL Lac
SourceM	PKS1510-08	351.285	40.141	0.5	1.3	-	26344.9	6.1	Swift	QSO

METHODOLOGY

The internal *Fermi* catalog was filtered to exclude sources along the Galactic ridge ($|l| < 60^\circ$, $|b|<1^\circ$) as this is a crowded, challenging region which is not yet fully understood. Faint sources with a TS lower than 45 were also excluded. The Fermi source list was then correlated with the IBIS & BAT catalogs. Associations were made where source positions were consistent within their 95% errors. However faint sources inherently have larger position errors and hence increase the likelihood of a catalog source falling within it by chance.

Chance correlations were explored by creating a fake *Fermi* source population which was mirrored about the Galactic center and inverted in Galactic latitude. Figure 1 compares how many matches are made between the *INTEGRAL* catalog and the real and fake Fermi source lists with increasing search radii (see Stephen et al., 2005, 2006). No chance correlations are expected with the *INTEGRAL* catalog at source separations <2.3' and for *Swift* at <1.4'. Table 1 lists these high confidence associations where we expect <1 chance associations to occur.

However, up to radii of ~11' real associations are expected to be found, but these are contaminated with a number of chance associations. Approximately 10 are expected based upon this preliminary analysis. Table 2 lists these additional candidates which must be be treated cautiously as ~50% are not expected to be real.

Table 2: Potential spatial associations between the internal *Fermi* catalog at the hard X-ray survey catalogs. This list has a much higher chance of chance correlation, with the probability increasing with the separation between the matches. Approximately 10 matches could be achieved by chance.

Fermi Source	Hard X-ray Source	l (deg)	b (deg)	Sep. (')	Fermi 95% error	INTEGRAL 95% error	Fermi TS	Hard X-ray significance	Hard X-ray catalog	Source type
Source1	EtaCarinae	287.631	-0.644	3.2	2.4	5.5	1281.9	5.9	INTEGRAL	XB
Source2	3C345	63.446	41.028	6.9	3.6	-	1210.5	5.4	Swift	FSRQ
Source3	CenA	309.543	19.373	3	5.1	0.3	1064.1	220.9	INTEGRAL	Radio Gal
Source4	4C11.69	77.429	-38.576	2.8	3.8	-	963.0	5.1	Swift	FSRQ
Source5	QSOB1959+650	97.997	17.652	3.8	2.5	-	953.0	10.2	Swift	BL Lac
Source6	LS5039	276.614	-14.803	5	2.7	2.9	875.6	10.6	INTEGRAL	HMXB
Source7	PKS1127-14	275.293	43.678	2.1	6.6	-	624.7	5.6	Swift	Blazar
Source8	PSRB0540-69	279.625	-31.631	6.7	4.6	-	616.3	8.7	Swift	LMC source?
Source9	PKS0521-36	240.667	-32.758	4.5	7.4	-	558.2	7.1	Swift	BL Lac
Source10	XSSJ12270-4859	298.945	13.822	2.3	7	2.9	292.5	10.5	INTEGRAL	CV? LMXB?
Source11	QSOB0836+710	143.461	34.492	5.6	10	2.2	190.0	14.4	INTEGRAL	Blazar
Source12	4C04.42	284.896	66.059	3.3	10.1	3.3	152.7	8.9	INTEGRAL	Blazar
Source13	QSOB1933-400	359.129	-25.449	7.5	11.4	4.9	151.8	5.9	INTEGRAL	Blazar
Source14	SDSSJ074625.87+254902.2	194.644	22.957	5.2	9.1	-	145.1	8.2	Swift	Blazar
Source15	H1426+428	77.480	64.870	2.5	5.5	5.1	130.4	5.6	INTEGRAL	BL Lac
Source16	ESO323-77	306.175	22.260	10	13.5	3.3	97.6	9	INTEGRAL	Sy2
Source17	1RXSJ192450.8-291437	9.317	-19.737	7.9	10.7	4.4	90.0	6.6	INTEGRAL	Blazar
Source18	SWIFTJ0218.0+7348	128.834	11.876	8.1	19.4	4.2	84.2	6.9	INTEGRAL	BL Lac
Source19	SWIFTJ1656.3-3302	350.654	6.442	7.2	7.5	1.6	61.2	21	INTEGRAL	Blazar
Source20	4U0557-385	244.697	-26.473	10.8	12.2	5.4	48.1	5.3	INTEGRAL	Blazar
Source21	2MASXJ11363009+6737042	133.375	47.885	6.1	9.4	-	45.8	5.1	Swift	BL Lac

PRELIMINARY RESULTS

The physical emission processes which give rise to ~GeV emission and 10s keV emission are very different and hence we may expect *Fermi* to see a completely different source sample to that of the hard X-ray surveys. Indeed this appears to be the case as comparisons of ~1000 sources from both energy regimes yields only 36 ***possible*** matches.

The high confidence matches (Table 1) include 15 well known sources including 1 high mass X-ray binary, 2 bright pulsar/PWN systems and 11 AGN. However, it also includes a new *INTEGRAL* candidate AGN (Bird et al. 2009, Krivonos et al. 2007).

The potential match list (Table 2) includes an additional 21 sources, 17 of which are again possible AGN matches. However a number of additional binary systems are also found including the colliding-wind system Eta Carinae and the well known HMXB, LS 5039. PSR B0540-69 is matched to a Fermi source, however this is likely spurious as the Fermi emission has been previously reported as being from the LMC region, specifically 30 Doradus. Whilst all of these matches must be taken with scepticism they warrant further detailed scrutiny and investigation. However it is clear that the dominant population seen in these distinct energy regimes are the active galactic nuclei, specifically blazars. Surprisingly a Seyfert galaxy is matched, which is not expected to have HE emission, it is therefore likely that this can be explained away by chance association.