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IBIS search for possible 511 keV point sources in the Galaxy

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Although the first detection of a 511 keV emission from the center of the Galaxy, produced by electron-positron annihilation process, dates back to 1972, its astrophysical origin is still a mystery. The IBIS coded mask telescope gives us the opportunity to search for possible 511 keV point sources. These sources may be associated with objects such as galactic X-ray binaries or supernova remnants. Processing 5 years of IBIS data on time scales of days-months-years, we do not detect any sources of this type. For different classes of sources, 511 keV flux upper limits are estimated. If positrons originate from galactic compact objects, our result is consistent with the idea that a significant part of positrons propagates in the interstellar medium before annihilating away from the place of birth.

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1. Introduction

Since the seventies, when a $\sim$ 500 keV gamma ray radiation in the direction of the Galactic Center was detected with a balloon experiment (Johnson et al. 1972), we know that there is a large amount of positrons in our Galaxy. A few years later this 511 keV emission line, due to electron-positron annihilation, was measured with good accuracy thanks to the application of high resolution detectors. The 511 keV line width is of the order of keV. The astrophysical origin of these Galactic positrons is a quite complex topic. Electron-positron annihilation can take place in two ways, directly by producing two 511 keV photons or via the positronium atom, i.e. a bound state consisting of an electron and a positron. 25 % of them form a state with antiparallel spins (para-positronium), 75 % of them with parallel spins (ortho-positronium). While the first system decays in two 511 keV gamma ray photons, in the second case three gamma rays are produced with a continuum of energies up to a maximum of 511 keV. A simple consequence of this mechanism is that, by measuring of the line to continuum ratio in the spectrum one can estimate the fraction annihilation due to positronium atoms. Analyzing one year of INTEGRAL/SPI data, Jean et al. (2006) reports a positronium fraction of $(97 \pm 2)\,\%$.

The 511 keV emission is largely concentrated in the Galactic bulge, possibly with an asymmetric profile correlated with the distribution of LMXBs population (Weidenspointner et al. 2008). As a consequence of a flux of about $10^{-3}\,photons\,cm^{-2}\,s^{-1}$ measured in the Galactic Bulge (Knödlseder et al. 2005), we know that in the center of our Galaxy 10^{43} positrons must annihilate in one second. The lack of detection of a γ-ray continuum by COMPTEL/EGRET due to in-flight annihilation put a severe constraint on the positrons injection energy. A calculation of the γ-ray spectrum produced by the positron annihilation while they are still relativistic has shown that the emerging photon flux would exceed the COMPTEL/EGRET flux limit unless the positrons are injected into the interstellar medium with an energy below $\sim$ 3 MeV (Beacom & Yüksel 2006).

There is not any direct evidence for 511 keV emission from compact objects. However, due to SPI poor angular resolution, the INTEGRAL data are still compatible with a particular distribution of point sources. The IBIS imager, thanks to the fine angular resolution and the large field of view, gives us a unique opportunity to search for possible 511 keV point sources associated to known objects such as X-ray binaries or supernovae, or new ones.

2. Data sample and analysis

The IBIS data and software are delivered by the INTEGRAL Scientific Data Center (Courvoisier et al. 2003) in Geneva. Our data set consists of all the IBIS data accumulated until April 2007. In addition, our sample includes all the Core program data until April 2008. All the data that we have reduced correspond to 39413 IBIS pointings each lasting about 2000 s., i.e. a total observing time of about 80 Ms. The exposure map obtained with our sample is shown in fig. 1; we note that we have the best exposure (about 10 Ms) in the Galactic center region.

IBIS is a coded mask telescope (for a review of this technique see Caroli et al. 1987). The IBIS scientific data analysis, the so-called *Standard Analysis*, is reported by Goldwurm et al. (2003); we note that, as expected, the sensitivity goes as square root of the esposure. For the data reduction we use the release 7.0 of the Off-line Scientific Analysis (OSA) software.

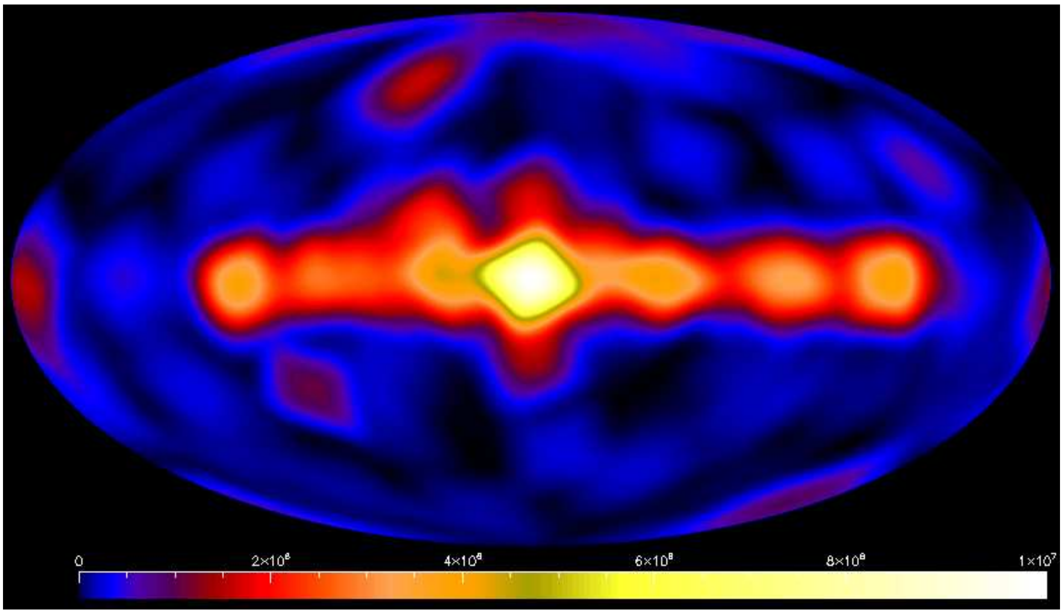

Figure 1 The exposure map for our data set. The deeper observation correspond to the galactic plane and the Galactic Center, where we reach with our data a 10 Ms exposure

3. Results and discussion

With our data analysis, we do not find any positive signal at 511 keV from point sources. In the center of the Galaxy (Sgr A*), with an exposure of 10 Ms, we estimate a 2σ 511 keV line upper limit of $1.6 \times 10^{-4} photons\, cm^{-2}\, s^{-1}$.

Analyzing data of single pointings, revolutions and Galactic Center visibility periods, we also searched for possible signals from Galactic compact object on timescales of hour, day, month. We still do not find any signal on all these timescales. In table 1 we report the observations of the Galactic center region and the 511 keV flux upper limits in for Sgr A*; on these Ms timescales our flux constraint is of the order of a few $10^{-4} photons\, cm^{-2}\, s^{-1}$. We note that, due to IBIS large field of view, we have similar constraints for all the IBIS sources located in the Galactic bulge.

Microquasars have been recently recently proposed by Guessoum et al. (2006) as candidate to explain the e+e- annihilation radiation. These sources can produce annihilation radiation by the jet interaction with the interstellar medium or the companion star (for mis-alligned jets). The 511 keV flux upper limits for microquasars detected by IBIS above 20 keV are reported in table 2.

Some of the atomic nuclei in supernovae produce positrons by their radioactive β^{+} decay. The supernovae are good candidate to explain the e+e- annihilation radiation also because the initial positrons energy is expected at about 1 MeV, in agreement with the constraint on the positron initial energy given by the in-flight annihilation. The possibility of detecting 511 keV point sources associated to the supernovae explosion is discussed by Martin et al. (2010), who compare the theoretical lightcurves with the SPI flux limit for a 511 keV narrow line. Significant line broadening could arise from the annihilation in a hot medium like the shocked regions of SNRs: for a temperature of 10^{7} K, the broadening is about 30 keV. The 511 keV IBIS flux upper limits for supernovae are reported in table 3.

Table 1. 511 keV 2σ Sgr A* upper flux limit in the Galactic Center visibility periods.

Period	Start Time (UT)	End Time (UT)	No. ScWs[a]	Sgr A* Exposure[b] (Ms)	Flux limit ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)
2003 Spring	2003-02-28	2003-04-23	1731	0.650	5.7
2003 Autumn	2003-08-10	2003-10-14	1717	1.872	3.2
2004 Spring	2004-02-16	2004-04-20	1862	1.046	4.5
2004 Autumn	2004-08-17	2004-10-27	2191	1.292	4.3
2005 Spring	2005-02-16	2005-04-28	2144	1.165	4.7
2005 Autumn	2005-08-16	2005-10-26	1667	0.790	5.9
2006 Spring	2006-02-09	2006-04-25	1869	1.501	4.1
2006 Autumn	2006-08-16	2006-11-02	1770	1.080	5.0
2007 Spring	2007-02-01	2007-04-22	985	0.347	9.2

[a]Each ScW lasts about half an hour

[b]Obtained from the exposure map. The exposure map, and in particular the value in the Galaxy depends both on the number of ScWs and the dithering patterns

Table 2. 511 keV 2σ flux upper limits for the hard X (E > 20 keV) microquasars detected by IBIS. These limits have been obtained with the exposure reported in Figure 1.

Source name	R.A. (deg)	Dec (deg)	Error[a]	F_{20-40}[b] (mCrab)	F_{40-100}[b] mCrab	2σ flux limit ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)	Type[c]
XTE J1550-564	237.745	-56.479	0.2	34.0 ± 0.1	55.3 ± 0.2	2.7	LMXB
Sco X-1	244.980	-15.643	0.2	685.7 ± 0.3	24.7 ± 0.3	3.7	LMXB
GRO J1655-40	253.504	-39.846	0.6	2.3 ± 0.1	2.7 ± 0.2	2.5	LMXB
GX 339-4	255.706	-48.792	0.3	40.7 ± 0.1	46.7 ± 0.2	2.6	LMXB
1E 1740.7-2942	265.978	-29.750	0.2	29.8 ± 0.1	36.6 ± 0.1	1.6	LMXB
GRS 1758-258	270.303	-25.746	0.3	58.8 ± 0.1	75.3 ± 0.1	1.6	LMXB
SS 433	287.956	4.983	0.5	10.4 ± 0.1	5.2 ± 0.2	2.4	HMXB
GRS 1915+105	288.799	10.944	0.2	296.8 ± 0.1	123.4 ± 0.2	2.5	LMXB
Cyg X-1	299.590	35.199	0.2	763.7 ± 0.2	876.7 ± 0.3	3.0	HMXB
Cyg X-3	308.108	40.956	0.2	196.5 ± 0.2	78.3 ± 0.3	2.6	HMXB

[a]Position error expressed as radius of 90 % confidence circle in arcminutes

[b]Fluxes averaged on the total exposure (Bird et al. 2007):
20-40 keV: $1\,mCrab = 7.57 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 1.71 \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$
40-100 keV: $1\,mCrab = 9.42 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 9.67 \times 10^{-5}\,ph\,cm^{-2}\,s^{-1}$

[c]Type identifiers: LMXB=Low Mass X-ray binary, HMXB=High Mass X-ray binary

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Table 3. 511 keV 2σ steady flux upper limits for the hard X (E > 20 keV) Supernova Remnants (SNR) reported in the 3rd IBIS catalogue.

Source name	R.A. (deg)	Dec (deg)	Error[a] (arcminutes)	F_{20-40}[b] (mCrab)	F_{40-100} mCrab	2σ flux limit ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)
4U 0022+63	6.319	64.159	3.6	0.7 ± 0.1	0.7 ± 0.2	2.3
PSR J1811-1926	272.827	19.417	2.9	0.8 ± 0.1	1.0 ± 0.2	14
IGR J18135-1751	273.395	-17.871	2.2	1.1 ± 0.1	1.7 ± 0.2	2.3
SNR 021.5-00.9	278.388	-10.579	1.2	3.3 ± 0.1	3.3 ± 0.2	3.0
AX J1838.0-0655	279.509	-6.916	1.5	1.9 ± 0.1	3.0 ± 0.2	2.9
Kes 73	280.338	-4.948	1.3	2.2 ± 0.1	4.2 ± 0.2	2.9
AX J1846.4-0258	281.596	-2.983	1.8	1.7 ± 0.1	2.4 ± 0.2	2.8
Cas A	350.848	58.815	0.9	4.1 ± 0.1	2.4 ± 0.2	2.5

[a]Position error expressed as radius of 90 % confidence circle.

[b]Fluxes averaged on the total exposure (Bird et al. 2007):
20-40 keV: $1\,mCrab = 7.57\times10^{-12}\,erg\,cm^{-2}\,s^{-1} = 1.71\times10^{-4}\,ph\,cm^{-2}\,s^{-1}$
40-100 keV: $1\,mCrab = 9.42\times10^{-12}\,erg\,cm^{-2}\,s^{-1} = 9.67\times10^{-5}\,ph\,cm^{-2}\,s^{-1}$

The 511 keV narrow line measured by SPI is generally explained by the idea that a fraction of positrons escapes from its birth place, loses energy and then annihilate in the ISM. The lack of IBIS detection of 511 keV from point sources is in agreement with this idea. However the details of this scenario are still poorly understood. Two basic questions are still open: where are the sources of positrons and how far from the birth place these particles travel before annihilate? We stress here that, depending on local conditions, a significant fraction of positrons can annihilate nearby their birth place in microquasars (Guessoum et al. 2006) and SNs (Martin et al. 2010).

With our data analysis, we do not find any positive 511 keV signal from these sources. In the Galactic Center region, we estimate a flux upper limit of the order of $2\times10^{-4}ph\,cm^{-2}\,s^{-1}$. An obvious consequence is that the new gamma ray instruments (see e.g. P. von Ballmoos presentation in this workshop) must have a better 511 keV line sensitivity to have a chance to detect some signal.

The SPI 511 keV data fit well with a diffuse 511 keV emission among the Galaxy, but they are also compatible with some distribution of point sources. In this case, for a total flux of $10^{-3}photons\,cm^{-2}\,s^{-1}$ the IBIS sensitivity tell us that we need at least 6 point sources to explain the Galactic positrons detected by 511 keV line.

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