MICROQUASARS' CONTRIBUTION TO THE GALACTIC POSITRON ANNIHILATION RADIATION

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ABSTRACT

Microquasars are-–by definition-–compact objects that frequently eject matter through their jets. Whether the jet content is leptonic or hadronic or a combination of both is, at present, uncertain and model-dependent. Assuming the jets are not purely hadronic, various models and methods allow one to estimate either the "typical" microquasars or the global galactic microquasar populations positron emissivity and thus see whether such a population (currently estimated at 100 in the Galaxy - Paredes [1]) would constitute a substantial contribution to the established 511 keV annihilation flux. Furthermore, one can attempt to compare the spatial distribution of Galactic microquasars (based on the scarce data available on the two dozen sources known today) and the spatial distribution of the annihilation flux as obtained by INTEGRAL/SPI.

We estimate the production rate of positrons in microquasars, both by simple energy considerations and using previously proposed models. We find that the collective emissivity of the annihilation radiation produced by Galactic microquasars may constitute a substantial contribution to the annihilation flux. The spatial distribution of microquasars leads to a Bulge/Disk ratio that is somewhat smaller than the lower limit inferred from INTEGRAL/SPI data. We stress that these results, although encouraging, suffer from the significant uncertainties in our present knowledge of microquasar properties and jet physics.

Key words: Gamma rays: theory – line: formation – ISM: general – X-rays: binaries.

1. INTRODUCTION: GALACTIC POSITRON SOURCES

Despite several decades of data gathering and analysis as well as theoretical modelling, the problem of galactic positron annihilation is far from being fully solved. Indeed, some of its fundamental issues, particularly the questions of positron origin and propagation, have remained mostly unsolved puzzles. In particular, the origin of the huge amounts of positrons produced in the Galaxy ($\sim 10^{43}$ $e^{+}\,s^{-1}$) is still eluding us. A large number of potential sources have been proposed over the years: cosmic ray interactions with the interstellar medium [2]; pulsars [3]; radioactive nuclei produced by explosive nucleosynthesis in supernovae [4] or novae [5]; compact objects housing either neutron stars or black holes [7] ; matter expelled by red giants [8] and Wolf-Rayet stars [6], [14]; gamma-ray bursts [10]; (light) dark matter [11], [12]; ; low-mass X-ray binaries [13]; hypernovae [15]; millisecond pulsars [16]; pair production from the collision of gamma-ray photons from "SMall Mass Black Holes" (SMMBHs) and X-ray photons from the Galactic Center black hole Sgr A* [17]; the Galaxy's supermassive black hole (Sgr A*), which can produce positrons either by proton-proton interactions when intense and energetic protons are released during the capture of a star [18], [19] or by photon-photon or photon-electron interaction when the intense and energetic photons are produced by a very active, high-accretion-rate disk around the black hole [20].

The recent mapping of the Galaxy at 511 keV [21], [22] has placed strong constraints on the positron candidate sources by way of a large Bulge/disk (B/D) ratio, which seemed to strongly exclude most of the earlier candidate sources, except perhaps Type Ia supernovae, low-mass X-ray binaries (LMXB's), and light dark matter; the map and high B/D ratio also led to new propositions of positron sources. However, many if not all of these propositions have their own difficulties; for example:

1) Although the *total positron emissivity of SNIa in the Galaxy* matches the observed one, the corresponding *bulge* emissivity is estimated (e.g. [13], [23]) to be an order of magnitude lower than required by SPI observations, and even if one takes into consideration the large systematic uncertainties on that estimate, the expected galactic distribution of SNIa's does not correspond to the high SPI B/D ratio (range), unless additional assumptions are made (e.g. important number of currently undetected SNIa's in the galactic bulge, or transfer of a large fraction of the disk positrons to the bulge through the galactic magnetic field – see [24]);

2) Low-mass X-ray binaries (LMXBs) display a spatial distribution considerably peaked toward the Galactic centre region [26], and their global energetics allow for a substantial positron production galaxywide [13], but the brightest of them (in X-rays) lie in the disk, not in the bulge of the Milky Way [13]; so if the positron emissivity correlates with X-ray emissivity (as is commonly assumed), it will be difficult to make the LMXB's somehow produce the positron annihilation map;

3) Dark matter particles as sources of Galactic positrons may or may not be able to reproduce the spatial "morphology" of the 511 keV radiation, *especially in the disk* if positrons from ^{26}Al and ^{44}Ti are found not to fully account for the annihilation radiation there, as preliminary investigations seem to indicate;

4) Positrons from Sgr A* (in the two scenarios mentioned above) may constitute only a limited fraction to the total required by observations; moreover, these models would be more appropriate if the annihilation radiation from the disk were very faint, which no longer appears to be the case [25].

Finally, we must note the important constraint that Beacom & Yüksel [28] have pointed out w.r.t. all models in principle: if the positrons are relativistic (E $\gtrsim$ 3 MeV), then the annihilation in flight of a fraction of them (which is very large when the medium is neutral) will produce continuum photons of high energies ($>$ a few MeV) that could be detected by instruments such INTEGRAL and COMPTEL (see also Yüksel [29]). This result places strong constraints on models, particularly those that have positrons produced at high energies and annihilating "in flight", i.e. while slowing down.

Let us consider the LMXBs scenario a little more closely; in such settings, positrons should be produced as e^+-e^- pairs in the inner regions of their accretion disks. Some of these pairs would annihilate locally, but a non-negligible fraction would be channeled out by jets—when these exist. In most cases, positrons would reach the ISM relatively far from their source, and they would propagate and annihilate, contributing to the diffuse 511 keV emission. In special cases, when the jets are strongly inclined ("misaligned") toward the plane of the binary system, positrons could periodically hit the atmosphere of the companion star where they would produce an annihilation signature, characterized, in particular, by its time variability and line profile (see Jean, Guessoum, Prantzos [27]).

We here therefore undertake to consider the fate of positrons ejected by microquasar jets. We first estimate the rate of positron production in jets, by reviewing estimates from other studies and by using simple energetics considerations; in that respect, we pay special attention to upper limits derived from the INTEGRAL-SPI measurements of positron annihilation fluxes from point sources in the Galaxy. We then consider the collective microquasar contribution to the flux of galactic annihilation radiation, which we find to be potentially substantial, especially in the central regions.

2. X-RAY BINARIES, MICROQUASARS, AND JETS

Microquasars are a subset of X-ray binaries (XRB's), which are systems containing a compact object (either a neutron star or a stellar-mass black hole) accreting matter from a companion star. A total of some 300 galactic X-ray binaries are currently known, about half of them are High Mass X-ray Binaries (HMXB's), in which the companion star has a mass ≥ 5 solar masses and where the mass transfer usually takes place by way of the strong stellar wind, and the other half are Low Mass X-ray Binaries (LMXB's), in which the companion has a low mass, and the mass transfer is carried out by Roche lobe overflow. Grimm, Gilfanov & Sunyaev [26] have shown that HMXB's tend to be distributed along the galactic plane, while LMXB's tend to be clustered in low Galactic longitudes. The number of XRB's brighter than 2×10^{34} erg/s is estimated at $\sim$700 in the Galaxy [26], [1].

Among the detected XRB's, 43 have now been found to exhibit radio emission, which is interpreted as synchrotron radiation. It is generally believed that the radio emission is evidence of jets. Of the 43 objects, 35 are LMXB's and 8 are HMXB's. Moreover, of the 43 systems, 16 are confirmed cases with resolved jets (Ribó [30], [1], Chaty [31]); these would then qualify as bona fide "microquasars", i.e. objects accreting from a companion star and ejecting a stream of relativistic particles. In addition to these 16 objects, 6 have also been recently reported as radio X-ray binaries/microquasars: IGR J17091-3624, IGR J17303-0601, IGR J17464-3213, and IGR J18406-0539 (Pandey et al. [32], [33], and Mioduszewski, Dhawan, & Rupen [34]), and X Nor X-1 and IGR J17418-1212 ([35] and [36], respectively). It is likely that all 43 radio-emitting X-ray binaries (REXB) are microquasars. The population of microquasars in the Galaxy is estimated at about 100 (Paredes [1], and the catalog of microquasars is expected to grow rapidly with the array of instruments and studies now investigating these objects (from radio to gamma rays).

Although jets of such systems were first observed in 1979 (in the peculiar object SS 433), microquasars were identified and imaged in the Galaxy only in 1992 when Mirabel et al. [37] performed high-resolution radio observations of the Galactic Center's "great annihilator" 1E1740.7 - 2942 and soon afterwards in GRS 1915+105 [38].

Our understanding of the conditions that lead to the emergence of jets in XRB's has been considerably improved by a number of very recent studies [39], [40], [41], [42]. First and foremost, a connection has been established between X-ray luminosity and jet formation: jets seem to appear when the accretion disk X-ray luminosity is low. Jets are apparently produced when the inner disk is replenished; there is a clear general pattern of steady jets in the "low/hard state" of the X-ray (microquasar) sources, while no jet is seen in "the high/soft state".

A useful unified model has thus been proposed by Fender, Belloni & Gallo [41], [42]. A relation between the power in the jet (when it exists) and the X-ray luminosity of a given source is derived: $L_{jet} = A_{steady} L_X^{0.5}$, with luminosities expressed in units of the corresponding Eddington luminosity. These authors argue that steady jets are produced when the X-ray spectrum of a source hardens beyond a certain value (which may be universal or vary somewhat from one source to another). The spectrum softens when the X-ray luminosity increases above about 1 % of the Eddington value; when this happens, the jet first increases in speed and then quickly gets suppressed and disappears.

There seems to be an agreement on the above relation between L_{jet} and $L_X^{0.5}$, which is supposed to hold for sources individually. On the other hand, there seems to be considerable uncertainty over the value of A_{steady} [43]; indeed, using various sources (e.g. XTE J1118+480) for "calibration", authors obtain values ranging from 0.006 as a lower limit (Fender, Belloni & Gallo [42]) to 0.3 (Malzac, Merloni & Fabian [44]), which Fender, Belloni & Gallo [42] take as an upper limit. In the case of transient jets, Fender, Maccarone & van Kesteren [43] conclude that the value of A_{trans} would range between 0.04 and 4.0, at least for black hole sources, which tend to exhibit jets that are about 10 times more powerful than those of neutron star jets, both in the steady and in the transient cases.

We should also note that, according to Heinz & Sunyaev [45], major "jet flares" have been observed (in sources like GRS 1915+105) at $L_X \gtrsim$ a few 10^{38} erg/s, such major flares would last a few days and recur several times a year; in addition, even more power can be found to be produced in microflare episodes that take place between the major flares. Moreover, all these timescales are much shorter than the propagation and annihilation timescales of positrons in the ISM [46], so that the frequency of the jet phenomena because unimportant.

A general correlation is also found between the velocity of the outflow and the X-ray luminosity of the accreting source: increases in X-ray luminosity tend to accelerate the jets, as long as the source remains in the low/hard state. Fender, Belloni & Gallo [42] further argue that the velocities of transient jets are significantly larger ($\gtrsim 0.87$ c) than those of steady jets ($\lesssim 0.7$ c). Jets with larger Lorentz factors have also been considered, but the standard cases are those presented in [42].

The particle content of the jets is among the major unresolved issues in studies of microquasars. Observations of emission lines in the case of SS 433 (Marshall, Canizares & Schulz [47]) suggest a substantial baryonic content of its jets. Several studies have considered the implications of a hadronic jet composition, either for the galactic cosmic ray content [45], [42], or for the synthesis of Li on the surface of the companion star [48]. Others have considered the gamma-ray and neutrino production at the surface of the companion by impinging high-energy protons [49]. On the other hand, arguments for e^+-e^- pair-dominated jets have been put forward, especially in cases involving the extraction of the spin energy of the black hole [50]. A strong argument in favor of such a leptonic composition is the repeated observations of highly polarized jets. Several leptonic microquasar models have been proposed in recent times, e.g. Bosch-Ramon and co-workers [51] [52], [53], Dermer & Böttcher [54]; see the review by Romero [55]. Some rather complex models have also been proposed, like "two-flow" models (pair beam surrounded by a mildly relativistic e^--p plasma) , or e^--p jets that later get loaded with pairs by interactions with high-energy photons (e.g. Scheck et al. [56] and references therein).

In the present treatment we consider microquasar jets channeling positrons (or e^+-e^- pairs) from the inner regions of the source's accretion disk into the ISM or towards the companion star (if the jet is "misaligned"). We also note that positrons can also be produced by hadrons from the jet colliding with nuclei (e.g. through p - p $\rightarrow$ p + n + π^+), but such processes would contribute only negligible amounts of positrons due to the small numbers of high-energy hadrons as well as the low values of the relevant cross sections.

In order to estimate the flux of the resulting annihilation radiation, the rate of positron ejection by the jets must then be determined.

3. RATE OF POSITRONS PRODUCED AND EJECTED THROUGH MICROQUASAR JETS

Electron-positron pairs are produced by $\gamma + \gamma \longrightarrow e^+ + e^-$ reactions in the high-temperature, high-density inner regions of the binary system's accretion disk. A fraction of the positrons annihilate close to the compact object, but when jets appear, they channel out a significant number of pairs. A few authors have attempted to model and estimate the production and ejection of pairs in those conditions.

In the model of Beloborodov [57] the pairs are cooled to energies of 1 – 10 keV and blown away by soft radiation to form a semi-relativistic wind. Depending on the compactness of the source ($l = L\sigma_T/m_e c^3 R$, where L and R are the power and radius of the emitting region, and σ_T is the Thomson cross section), the plasma will form an optically thin or thick atmosphere. The density of the outflow and the rate of ejection of electrons and positrons depend on the rate of production of pairs (which, in turn, depends on the photon "seed" spectrum and on the accretion disk model), the annihilation rate and the "escape efficiency" of the pairs. Under the assumption of an optically thin pair wind, where the pairs escape before they annihilate ($\tau_{esc} < \tau_{ann}$, with $\tau_{ann} \sim 1/n_e \sigma_T c$, where n_e is the electron density), Beloborodov [57] shows that the maximum pair luminosity is given by

$$L_{e^+e^-}^{\max} = \frac{2\pi m_e c^3 R}{\sigma_T} , \qquad (1)$$

which translates into a rate of pair injection in the jet of $\sim 4 \times 10^{41} \mathrm{s}^{-1}$. A substantial fraction of these pairs, perhaps up to 90 % (as argued by Misra & Melia [58]), would annihilate near the base of the jet, producing a broad and redshifted line (that is rather difficult to detect); as many as $\sim 10^{41}$ s^{-1} positrons are then expelled into the ISM generally or, occasionally, in the direction of the companion star.

In their model, Misra & Melia [58] suggest that the intense radiation field is responsible for the Compton acceleration of the pairs produced in the inner regions of the accretion disk. They find that a large rate of pairs (up to 6×10^{42} s^{-1}) stream outwards from the disk (at velocities of ~ 0.7 c), even after 90 % have annihilated near the base. One must note, however, that this large rate is obtained with an accretion rate of $\sim 5 \times 10^{-8} M_\odot$ yr^{-1}, a rate that can normally be attained only in episodic outbursts. Indeed, the model of Misra & Melia [58] was mainly aiming to reproduce the 1E 1740.7 -2942 "annihilation flare" of 1991.

In a different model, Yamasaki, Takahara & Kusunose [59] consider two-temperature accretion disks by taking into account the formation of relativistic pair outflows, in both AGN and microquasars. They show that in the inner regions of the disks, when the mass accretion rate becomes larger than about one tenth of the Eddington rate ($1.4 \times 10^{17} M/M_\odot$ g s^{-1} where M is the mass of the compact object) or $\sim 2 \times 10^{-10} M_\odot$ yr^{-1}, most of the viscously dissipated energy is converted into the thermal and kinetic energy of the electron-positron pairs. They obtain a maximum power of the pair outflow of 0.136 L_{Edd} for an accretion rate of $10^{-9} M_\odot$ yr^{-1} (assuming $M = 1 M_\odot$ and $R = 10 R_\odot$), which translates into a pair ejection rate of 2×10^{42} s^{-1}, assuming the jet is leptonic.

Another way of estimating the production of positrons is to consider the global energetics of microquasar jets in the Galaxy; starting from the following remarks:

- $\dot{N}_{e^+} \propto \mathrm{L}_{jet} \propto \mathrm{L}_X^{0.5}$;
- at $\mathrm{L}_X = 0.5\ \mathrm{L}_{Edd}$ one obtains $\dot{N}_{e^+} = 2 \times 10^{42}$ s^{-1} (Yamasaki, Takahara & Kusunose [59]), which in the following estimate we may use as a "yardstick"; and
- steady jets are produced at $\mathrm{L}_X = 0.01 - 0.1\ \mathrm{L}_{Edd}$ [41], [42];

one can then infer that the positron emissivity of a jet in the steady state lies in the range $\dot{N}_{e^+} \sim 4 \times 10^{40} - 9 \times 10^{41}$ e$^+$ s^{-1}, with 10^{41} e$^+$ s^{-1} as a reasonable average value.

One must also confront these estimates with the upper-limit constraints that can be inferred from the recent annihilation radiation measurements of INTEGRAL-SPI. Knödleseder et al. [21] have published 3-σ flux upper limits for a dozen galactic microquasars/LMXB's/HMXB's; we have completed the data for other sources of interest to us here. Table 1 lists the sources we have considered, with the corresponding SPI upper-limits on their 511 keV emission flux (taking the sources to be point-like) and inferred rates of positron injection, assuming that positrons do not annihilate far from the source. The bottom part of the table lists microquasar sources.

It can be seen that upper limits for the steady positron annihilation rate of individual sources are always $>10^{41}$ e$^+$s^{-1} (albeit with large uncertainties, due in particular to uncertain distance estimates), so the upper-limit rates inferred from INTEGRAL data do not clash with the average value derived from the works cited above.

From the different considerations and estimates presented above, it appears that a "canonical average" rate of $\sim 10^{41}$ e$^+$s^{-1} ejected by the microquasar jets is a reasonable "common denominator" value. We immediately note that with this average "canonical value" the ~ 100 microquasars that are believed to exist in the Galaxy [1] would produce a global annihilation emissivity near that measured by SPI (and previous instruments).

Another upper limit on the collective emission by galactic microquasars may be derived by considering the global energetics. Indeed, (i) the total luminosity of LMXRBs in the Milky Way is 2 - 3 10^{39} erg s^{-1} [26], while (ii) the luminosity of $\sim 10^{43}$ e$^+$ s^{-1} observed by SPI/INTEGRAL is $\sim 10^{37}$ erg s^{-1}, assuming the positronic jets are mildly relativistic (i.e. positrons have energies <1 MeV). Of course, as Grimm, Gilfanov & Sunyaev [26] note, the Galactic LMXRB population is dominated by a dozen bright sources (of $\sim 10^{38}$ erg s^{-1} each) lying in the disk. But the remaining fraction of $\sim$ 90 % is highly clustered towards the bulge (Fig. 1 in [26]), as required by the SPI data and noted in Prantzos [13], while their collective luminosity is 2 - 3 10^{38} erg s^{-1}, i.e. 20 times larger than required to explain the Galactic positron energetics. We note that those are precisely the low-luminosity (sub-Eddington) sources that may produce jets (see the discussion in Sec. 2). According to estimates by Paredes [1], based on current microquasar statistics, there are about 100 microquasars in the Milky Way, which corresponds to about 1/3 of the $\sim$ 300 LMXRBs in our Galaxy as estimated by Grimm, Gilfanov & Sunyaev [26]. Applying this correction factor of 1/3 to the microquasar energetics still leaves about 10^{38} erg s^{-1} available for positron production in their jets, i.e. about 6 times more than required by SPI data. We note at this point that some of the currently observed microquasars result from HMXRBs, but their fraction is rather small (less than 20 %) and does not affect the arguments presented here (see next section for a more detailed treatment). Moreover, we wish to stress the large (order-of-magnitude) uncertainty that exists in our current knowledge of the ratio between the energy that goes into positrons or into the jet (as a whole) compared to the energy that is radiated, an issue that is further complicated by the unknown lepton-to-hadron content ratio of the jet.

The simple estimate made in the previous paragraph implies that the ratio between the positron power and the X-ray luminosity of microquasars is, on average, about

Table 1. Limits on positron rates from SPI upper limits for XRB sources of interest. The positron rates were calculated assuming a positronium fraction of 95%. The bottom part of the table lists microquasar sources, the last two or three being misaligned ones.

Source	Type	Distance (kpc)	l (deg)	b (deg)	3σ Flux Limit $(10^{-4}\mathrm{cm}^2\mathrm{s}^{-1})$	Positron Rate $(\mathrm{e}^{+}\mathrm{s}^{-1})$
GX 349+2	LMXB	$\lesssim 10$	349.1	2.75	0.8	$\gtrsim 1.7 \times 10^{42}$
GX 5-1	LMXB	8	5.08	-1.02	0.7	9.4×10^{41}
Nova Muscae	LMXB	3	295.3	-7.07	2	3.8×10^{41}
A 0620-00	LMXB	2	209.96	-6.54	3.8	3.1×10^{41}
Cen X-4	LMXB	1.2	332.24	23.89	1.7	5.2×10^{40}
GRS 1915+105	LMXB	12.5	45.37	-0.22	1	3.3×10^{42}
Cir X-1	LMXB	10	322.12	0.04	1.1	2.3×10^{42}
Cyg X-3	HMXB	9	79.85	0.7	1	1.7×10^{42}
1E 1740.7-2942	LMXB	8.5	359.1	-0.11	0.9	1.4×10^{42}
GRS 1758-258	LMXB	8.5	4.51	-1.36	0.7	1.1×10^{42}
GX 339	LMXB	$\gtrsim 8$	0.68	-0.22	0.8	$\lesssim 10^{42}$
SS 433	HMXB	4.8	39.69	-2.24	0.9	4.5×10^{41}
LS 5039	HMXB	2.9	16.88	-1.29	0.9	1.5×10^{41}
Sco X-1	LMXB	2.8	359.1	23.78	1.5	2.4×10^{41}
Cyg X-1	HMXB	2.5	71.33	3.07	1	1.4×10^{41}
XTE J1118+480	LMXB	2.5	157.66	62.32	4.5	5.9×10^{41}
LS I $+61^o$ 303	HMXB	2	135.68	1.09	3.3	2.8×10^{41}
IGR J17091-3624	?	8.5?	-10.48	2.21	0.7	1.1×10^{42}
IGR J17303-0601	LMXB	8.5?	17.93	-1.61	0.9	1.4×10^{42}
IGR J17464-3213	LMXB	8.5?	-2.87	15.01	0.9	1.4×10^{42}
IGR J18406-0539	?	8.5?	26.67	-0.17	1	1.5×10^{42}
X Nor X-1	LMXB	8.5?	-23.09	0.25	1	1.6×10^{42}
IGR J17418-1212	?	8.5?	13.93	9.41	0.9	1.4×10^{42}
XTE J1550-564	Misaligned?	5.3	-34.12	-1.83	1.1	6.6×10^{41}
V4641 Sgr	Misaligned	9.6	6.77	-4.79	0.7	1.4×10^{42}
GRO J1655-40	Misaligned	3.2	-15.02	2.46	0.8	1.7×10^{41}

16 %. One must recall, however, that there is a relation between the two quantities, namely $\dot{N}_{e^+} \sim$ L$_{jet} \sim$ L$_X^{1/2}$ (see discussion and references above), which leads to more realistic expectations.

Indeed, taking the derivative of the cumulative X-ray luminosity function given by Grimm, Gilfanov & Sunyaev [26] for LMXRB's (see Eq. 15 in [26]) and assuming that 1/3 of LMXRBs are microquasars, one can derive a differential luminosity distribution function for microquasars:

$$dN/dL_X = 2.6 L_X^{-1.26}\,, \qquad (2)$$

where L$_X$ is in Eddington units (1.3×10^{38} ergs/s) and relates to L$_{e^+}$ as L$_{e^+}$ $=$ B L$_X^{1/2}$.

Now if the total positron power in the Galaxy is required to be 10^{37} erg/s (i.e. 0.1 in Eddington units), and using Eq. (2) above to integrate for the total power, one finds that B is between 0.9 and 1.6 % depending on the assumption made on the maximum X-ray luminosity of the microquasar (1 or 0.1 L$_{Edd}$, respectively), which are very reasonable figures.

Furthermore, having estimated B and thus obtained an analytic distribution function for the microquasars' positron emissivity, one can obtain the total rate of positrons emitted by all microquasars (of different luminosities) in the Galaxy by integrating dN/dL$_X$ against the luminosities and the rate of positrons emitted by each source, as obtained by Yamasaki, Takahara & Kusunose [59]. One then obtains N$_{e^+,tot}$ between 1.8 and 3.1 x 10^{43} e$^+$/s (for microquasar X-ray luminosities of 0.1 and 1 L$_{Edd}$, respectively), values that are very close to those inferred from observations and thus very encouraging in considering microquasars as possible contributors to the overall positron annihilation flux from the central galactic regions.

4. CONTRIBUTION OF MICROQUASARS TO THE GALACTIC POSITRON ANNHILATION RADIATION

Assuming that $\sim$ 100 microquasars exist in the Galaxy [1], and noting from the locations plot of the 22 microquasars presently known (Figure 1) that about half of them are in the central regions, i.e. $\sim \pm 25$ degrees from the GC, we can estimate the flux of annihilation radiation that can be expected from such a population of sources with jets ejecting $\approx 10^{41}$ e$^+$s^{-1} on average and compare it to the global galactic centre annihilation flux reported by Knödlseder et al. [21].

In what follows we will not distinguish between microquasars with "misaligned" jets (highly inclined with respect to the orbital plane) and "normal" ones (those with low inclination jets). Jets of misaligned microquasars (about 15-20 % of the total) hit the companion ∼10 % of the time (Butt, Maccarone & Prantzos [48]), and then only 1 of the ∼ 2 annihilation photons will emerge, the other being absorbed in the companion's atmosphere. The normal microquasars will pour out their positrons into the ISM, where the usual 2-3 photon production processes take place (see [46]). A more detailed treatment of the positrons from misaligned jets (including the interaction with the atmosphere of the companion and the resulting annihilation light curve) is given in [27].

The total flux of annihilating positrons coming from the inner Galaxy would be:

$$F = \frac{f_{\mu Q} N_{\mu Q} \dot{N}_{e+}}{4\pi D^2} \times 2 \times f_{\rm line} \; . \tag{3}$$

where $N_{\mu Q}$ is the total number of microquasars believed to exist in the Galaxy ($\sim$ 100), $f_{\mu Q}$ is the fraction of μQ's we assume to be in the inner regions of the Galaxy ($\approx$ 50%), $\dot{N}_{e+}$ is the rate of ejection of positrons from a typical jet (10^{41} s^{-1}), $f_{\rm line}$ is the fraction of photons emitted with the line energy (511 keV) as opposed to continuum (0 – 511 keV) energies, and D is the distance to the Galactic centre (8.5 kpc); $f_{\rm line}$ is obtained from $\frac{1}{4} f_{\rm Ps} + (1 - f_{\rm Ps})$, where $f_{\rm Ps}$ is the "Positronium fraction", i.e. the fraction of positrons that annihilate via formation of Positronium (the bound e$^+$-e$^-$ system), which has repeatedly been found in galactic annihilation radiation measurements to be ≈ 0.95 (see references given in Sec. 1);

With those parameter values, we obtain:

$$F \approx 5 \times 10^{-4} \; {\rm ph \; cm^{-2} \; s^{-1}} \tag{4}$$

This total flux is within a factor of 2 of the SPI-measured annihilation flux ($\sim 10^{-3}$ ph cm^{-2}s^{-1}), a result that is quite encouraging, considering the uncertainties on different parts of the problem (mostly due to our currently limited knowledge of microquasar jet energetics).

As noted in Sec. 1, the spatial distribution of the 511 keV flux detected by SPI-INTEGRAL puts strong constraints on candidate sources of positrons. Although far from complete at present, the spatial distribution of the available sample of known microquasars appears encouraging in that respect. Figure 1 displays the position and type (LMXB/HMXB) of the 22 currently known microquasars.

While fully aware that the current list represents only about one fifth of the microquasars believed to exist in the Galaxy, we can still attempt to determine a Bulge-to-disk (B/D) ratio of the annihilation produced by such sources and compare that with the limits obtained from SPI data [21], which inferred a rate of positron annihilation of $(1.5 \pm 0.1) \times 10^{43}$ e$^+$s^{-1} in the bulge and $(0.3 \pm 0.2) \times 10^{43}$ e$^+$s^{-1} in the disk.

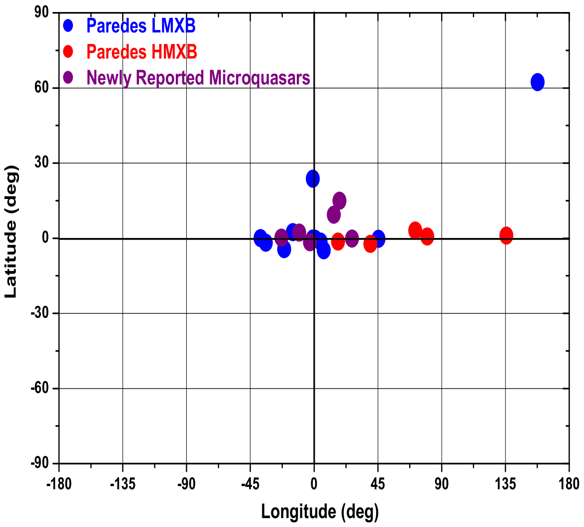

Figure 1. Microquasars (position and type) in the Galaxy.

Referring to Table 1, which lists the types, positions and distances of these microquasars, we note that roughly 80 % of them are LMXB's, about 15 % of which are in the halo, 35 % are in the disk, and about 50 % are in the bulge, while 20 % of the sources are HMXB's, ∼ 10% of which may be in the bulge and the rest in the disk. The canonical average rate of positron production has been taken to be about 10^{41} e$^+$s^{-1} by a typical jet from an LMXB microquasar, while for HMXB microquasars jets are ten times less powerful and thus about three times less productive in positrons (recall that $L_{e^+e^-} \sim L_{\rm jet} \sim L_X^{0.5}$). One must then take into consideration the confinement probability of positrons ejected from these sources; we note that: i) according to Jean et al. [60], positrons produced in the bulge do not escape, they end up annihilating in the bulge if their energy is below ∼10 MeV, which is the case for positrons produced by microquasars, if one ignores (as in this basic treatment) potential internal acceleration processes; ii) the scale height of LMXBs in the disk is ∼400 pc, while the gas has a scale height of ∼100 pc, so about 50 % of positrons produced by LMXB's there are ejected toward the disk and annihilate, while the rest (50 %) of the positrons are released in the halo and either contribute to a diffuse annihilation emission (unseen by spectrometers) or propagate following the galactic magnetic field lines toward the bulge (Prantzos [24]); iii) the escape fraction of positrons produced by HMXB's in the disk is unconstrained, and for simplicity we take it to be the same as that of positrons from disk LMXB's. With these fractions, the net rate of positrons annihilating in the bulge is found to be $\approx 4.1 \times 10^{42}$ e$^+$s^{-1} (about one third the SPI bulge rate), while the net rate of positrons annihilating in the disk is found to be $\approx 1.7 \times 10^{42}$ e$^+$s^{-1}; this would give a B/D ratio of 2.4, which is somewhat smaller than the lower SPI limit (B/D)$_{SPI} \geq 3$, indicating that positrons produced in the disk are escaping in large(r) fractions than assumed here. More encouraging still is the fact that more recent morphological studies of the annihilation radiation (Weidenspointner et al. [61]) seem to indicate a lower value for the B/D ratio than was inferred from the earlier INTEGRAL-SPI data, a trend that would make the microquasar hypothesis even more attractive.

One can also turn these estimates around and use the SPI data to set limits on positron production rates from microquasars. (Note that since we are taking a canonical average value of positron production rate for all LMXB microquasars and assuming the HMXB microquasars to produce only one third as many positrons, for luminosity reasons as explained above, the B/D ratio is independent of the jet positron rate and cannot help set constraints on it, at least in our simple model.) Assuming the ratios of LMXB/HMXB microquasars and the escape fractions given in the previous paragraph, we find that the SPI limits would be violated if positrons are produced at steady rates greater than $\sim 3 \times 10^{41}$ $e^{+} s^{-1}$.

Furthermore, we note that our model easily satisfies the Beacom & Yüksel [28] constraint since our positrons have kinetic energies between 2.5 keV and 660 keV (jet speeds range from 0.1 c to 0.9 c), so their annihilation in flight does not produce detectable continuum emission of photons at higher energies.

5. SUMMARY AND CONCLUSIONS

Since the detection and subsequent studies of Galactic positron annihilation radiation, the origin of the positrons that produce the large flux and map of that emission has remained a major puzzle in high energy astrophysics. In this work we have proposed and investigated the possibility of Galactic microquasars (XRB's that exhibit jets in an intermittent way) as sources of positrons.

We thus first reviewed our current knowledge of microquasars, which has greatly increased in the past few years, and emphasized the most important features of these objects, particularly as they relate our problem. The correlation between the power of the jet and the X-ray luminosity of the compact object is the most important of these features; we have stressed, in particular, that the ratio between the two, often assumed to be small, is highly uncertain. Moreover, the content of the jets, leptonic or hadronic (i.e. electron-positron pairs vs. protons and pions), remains largely unknown at present. Some of the implications of a hadronic content have been explored elsewhere ([48], [49]); we have explored here the consequences of a leptonic content.

In the main part of our treatment, we evaluated the rate of positron ejection by the microquasar jets, based on various models proposed in the literature, but also on simple arguments of energetics relating the total power of the positrons in the jets to the estimated total X-ray luminosity of the "low luminosity - hard spectrum" galactic LMXRBs. We found that a value of 10^{41} $e^{+} s^{-1}$ could be considered as a "canonical average", albeit with large (and difficult to evaluate) uncertainties. We then estimated the total annihilation flux produced by positrons from microquasars in the inner Galaxy and found it to be about half that measured by SPI/INTEGRAL. The spatial morphology of the corresponding flux received on Earth depends on the assumed large scale distribution of Galactic microquasars, which is very poorly known at present; we found that the distribution of the currently available (incomplete) sample appears encouraging in that respect, with a B/D of about 2.4 (with large uncertainties), which is now quite close to the values inferred from the most recent analyses of SPI data. Finally, we constrain the rate of production of positrons by microquasars on the basis of the SPI flux results: we find that the SPI limits would be violated if positrons are produced at steady rates greater than $\sim 3 \times 10^{41}$ $e^{+} s^{-1}$.

In summary, we have shown in this study that microquasar jets may constitute important sources of the Galactic annihilation radiation. In a related study [27], we show that special "misaligned" microquasars can be interesting point sources of 511 keV emission; and although the expected fluxes are only within range of the next generation of gamma-ray detectors, such a detection (or lack therefore) can constitute an important confirmation, rejection, or constraint-setting experiment for our proposed scenario.

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