On the Origin of the 511 keV Emission in the Galactic Centre

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ABSTRACT

Diffuse 511 keV line emission, from the annihilation of cold positrons, has been observed in the direction of the Galactic Centre for more than 30 years. The latest high-resolution maps of this emission produced by the SPI instrument on INTEGRAL suggest at least one component of the emission is spatially coincident with the distribution of \(\sim 70 \) luminous, low-mass X-ray binaries detected in the soft gamma-ray band. The X-ray band, however, is generally a more sensitive probe of X-ray binary populations. Recent X-ray surveys of the Galactic Centre have discovered a much larger population (>4000) of faint, hard X-ray point sources. We investigate the possibility that the positrons observed in the direction of the Galactic Centre originate in pair-dominated jets generated by this population of fainter accretion-powered X-ray binaries. We also consider briefly whether such sources could account for unexplained diffuse emission associated with the Galactic Centre in the microwave (the WMAP ‘haze’) and at other wavelengths. Finally, we point out several unresolved problems in associating Galactic Centre 511 keV emission with the brightest X-ray binaries.

Key words: dark matter; compact objects; X-ray binaries; Galactic Centre; accretion, accretion physics; jets

1 INTRODUCTION

Emission at 511 keV, the characteristic signature of positron annihilation, has been observed in the direction of the Galactic Centre (GC), since the 1970s. Apparently diffuse gamma-ray emission at approximately this energy was first detected in 1970 by the balloon-borne experiments of the Rice group (Johnson, Harnden, \& Haymes 1972; Johnson \& Haymes 1973; Haymes et al. 1975; preliminary indications were also reported in Haymes et al. 1969) and was confirmed as positron annihilation emission in 1978 by the balloon-borne experiments of the Bell-Sandia group (Leventhal, MacCullum, \& Stang 1978; Leventhal et al. 1980). High-energy balloon experiments and space observatories through the early 1990s continued to detect the 511 keV emission; however the relatively low spatial resolution of these detectors prevented determination of the true location and distribution of the emission (see Purcell et al. 1997, Jean et al. 2003, or Teegarden et al. 2005 for a summary of these early observations). Specifically, from these data it is unclear whether the emission is truly diffuse, or if it originates either from a single discrete source (e.g. Sgr A* or 1E1740.7-2942, “The Great Annihilator”) or from a small number of discrete but unresolved sources. Some early detections suggested time variability in the signal, indicating a small number of discrete sources, but these variations were not confirmed in subsequent observations (e.g. Purcell et al. 1997; Teegarden et al. 2005).

With the advent of space observatories of increasing sensitivity, spectral coverage, and spatial resolution, the resultant improvement in data quality now provides much stronger constraints on the origin of the emission. In particular, observations of the GC by the SPI spectrometre on the satellite INTEGRAL (the INTErnational Gamma-Ray Astrophysics Laboratory) have recently produced the most detailed map of the anomalous 511 keV emission to date (Knödlseder et al. 2005; Weidenspointner et al. 2006, 2007). The SPI/INTEGRAL map clearly shows this emission arising from the central \(\sim 1.5 \) kpc \((l < 10^{\circ})\) of the Galaxy, with a fainter component of 511 keV flux detected from the remainder of the Galactic disk. The smoothness of the emission constrains the number of discrete sources responsible to be in excess of \(\sim 8\) (Knödlseder et al. 2005), as do point source limits of \(1.6 \times 10^{-4} \) ph cm\(^{-2}\) s\(^{-1}\) from searches with
the IBIS imager on INTEGRAL (de Cesare et al. 2006). Most recently, Weidenspointner et al. (2008) have detected a longitudinal asymmetry in the disk component of the emission, which matches the asymmetry in the distribution of the brightest low-mass X-ray binaries (LMXBs) detected by the IBIS instrument on INTEGRAL, suggesting that these ~70 objects may account for much of the disk component of the 511 keV emission.

Diffuse emission from the Galactic Centre, unaccounted for by known sources, has also been observed at several other wavelengths, notably high-frequency radio (21–63 GHz) with WMAP (Finkbeiner 2004a) and soft X-rays (1–10 keV) with e.g. HEAO and Chandra (Worrall et al. 1982, Muno et al. 2004). The origin and nature of the diffuse emission is puzzling in each case. In the case of the diffuse X-ray component, a population of discrete but unresolved point sources was originally postulated as a possible source of the emission (see e.g. Skibo et al. 1997, Valinia & Marshall 1998).

With the advent of high-resolution X-ray imaging using Chandra, a large new population of low X-ray luminosity sources has indeed been identified in the central 2°×0.8′ of the GC (300×120 pc at a GC distance of 8.5 kpc; Wang et al. 2002, Muno et al. 2003, Muno et al. 2006). Many of these ~4200 discrete X-ray sources are likely to be accreting binaries, including high and low mass X-ray binaries and cataclysmic variables. However, it is worth noting that these detected sources only account for 10% of the previously observed diffuse 2-10 keV emission (Ebisawa et al. 2001, Muno et al. 2003), so an even larger population of still fainter sources (with $L_X < 10^{31}$ erg s$^{-1}$) could exist at the GC (but see Muno et al. 2004 who argue that the spectral characteristics of the remaining diffuse X-ray emission are inconsistent with a stellar X-ray source origin). In any case, it is not clear how much these new populations might contribute to the diffuse flux at lower (e.g. WMAP) or higher (e.g. INTEGRAL) energies.

In this paper, we consider the hypothesis that jet outflows from X-ray binary systems (XRB), which are accretion-powered mass-transferring binaries containing a black hole (BH) or neutron star (NS), are the main source of the 511 keV emission in the GC. This idea has been explored previously by various authors, notably Ramaty & Lingenfelter (1979), Prantzos (2004), Knödlseder et al. (2005), and Guissoumi et al. (2006). These previous studies generally focused on the large-scale discrete jet ejections produced by the class of luminous black hole XRBs known as “microquasars”. However, it is now thought that luminous black hole XRBs much more commonly produce lower-luminosity “steady” jets, and that these outflows are “on” for a substantially greater fraction of the XRB duty cycle than the large-scale ejection events (Gallo et al. 2006). We note that neutron star X-ray binaries are, in principle, also possible sources of jet positrons. The fraction of low magnetic field NS XRBs with outflows could be as high as ~100% (Fender 2006; Migliari & Fender 2006). However, they show a different scaling than black hole XRBs between X-ray luminosity and radio luminosity (i.e. $L_R \propto L_X^{0.7}$ in BH systems and $L_R \propto L_X^{1.4}$ in NS systems; Migliari & Fender 2006). As a result of this scaling, the jets from quiescent neutron star X-ray binaries are likely to be several orders of magnitude weaker than those from quiescent BH X-ray binaries, if one assumes the same scaling relations continue into quiescence.

More likely, though, is that the scaling relation becomes even steeper for neutron stars as they fade more deeply into quiescence than the current radio flux limits allow us to probe; the emission from the faintest neutron star XRBs is generally dominated by thermal crustal emission from cooling neutron stars, rather than by accretion power (e.g. Rutledge et al. 2001).

Also, while some luminous high-mass X-ray binaries (HMXBs) have been observed to emit jets (e.g. Cyg X-1, Cyg X-3), these systems are predominantly located in the Galactic disk (Grimm et al. 2002). Thus these canonical BH HMXBs – of which there are only a few known in the entire Milky Way – are not a class of objects which can cause an excess of high-energy flux in the Bulge relative to the Galactic disk. Recent INTEGRAL observations have detected a population of lower-luminosity, X-ray hard, high-mass XRBs including highly-obscured HMXBs and “supergiant fast X-ray transients”, a number of which are located in the Bulge (Chaty et al. 2008). However, there is as yet no evidence for jet outflows in these HMXBs. Furthermore, the nature of the compact objects in these systems is currently not known; but we note that of those canonical HMXBs for which the nature of the compact object has been identified, the majority contain neutron stars rather than black holes. Finally, in a detailed study of the spatial distribution of INTEGRAL-detected XRBs (including the new highly-obscured systems), Lutovinov et al. (2005) find that the angular distribution of HMXBs in the inner Galaxy is significantly different from that of LMXBs – specifically, LMXBs are clearly the dominant population within the Bulge, significantly overabundant as compared with the HMXBs in this region. Thus while we cannot rule out a high-energy flux contribution in the Bulge from these newly discovered low-luminosity HMXBs, we will not consider them further here.

Therefore in this paper we primarily consider jets from low-mass black hole binaries. It seems plausible that steady, low-luminosity outflows from Galactic BH XRBs contribute substantially to the annihilation line emission, and possible also to the diffuse emission observed at other wavelengths.

The outline of the paper is as follows. In section 2, we first review the 511 keV observations of the GC and discuss possible sources for the positrons. In section 3, we outline a simple model for positron production in (quiescent) LMXB jets. In section 4, we briefly examine the unexplained diffuse GC emission observed at microwave and X-ray wavelengths, and consider whether this emission could also originate in outflows from low-luminosity LMXBs. In section 5, we discuss the recent association of the disk component of the 511 keV emission with bright LMXBs detected by IBIS, pointing out some unresolved problems with this association. We conclude by proposing several observational tests that may help elucidate the nature of the population responsible for the 511 keV emission.

## 2 UNEXPLAINED EMISSION FROM THE GALACTIC CENTRE

### 2.1 Observations

Since its initial discovery almost 40 years ago, our picture of the annihilation emission from the GC has gradually become
clearer. The emission amounts to $\sim 10^{-3}$ photons cm$^{-2}$ s$^{-1}$, coming from a region roughly $10^7$ in radius around the GC. Assuming the mean distance to the positron sources is the distance to the GC, 8.5 kpc, this flux corresponds to an integrated luminosity of $10^{43}$ photons/s emitted within a region 1.5 kpc in radius. After initial suggestions of temporal variability in the flux, extensive observations over the 1990s have ruled this out at any substantial level (see Purcell et al. 1997 for a summary of this evidence).

The detailed spatial distribution of the emission has become much clearer since observations first by OSSE on CGRO, and then more recently by SPI on INTEGRAL. The most recent analyses of 4 years of SPI/INTEGRAL data (Weidenspointner et al. 2008) suggest two main components: a central bulge and an asymmetric disk. The bulge component is reasonably well described by a single Gaussian with a FWHM of 6°, but even better described by a superposition of two Gaussians of FWHM of 3° and 12°, or alternately a compact, symmetric bulge component from $R = 0$–0.5 kpc, and an extended shell of emission from $R = 0.5$–1.5 kpc. The disk component is now detected at $\sim 14\sigma$ in 4 years of SPI, and appears to be asymmetric at 3.8σ significance (Weidenspointner et al. 2008), with 1.8 times more flux at negative longitudes than at positive ones. The total flux from the disk is $\sim 7 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$, i.e. comparable to the bulge flux. There is also marginal evidence for emission more than 1.5 kpc from GC (Knödlseder et al. 2005), possibly extending out as much as 40°–5 kpc (Bouchet et al. 2008), though detection here is hampered by the very uneven exposure maps of INTEGRAL away from the GC. On the other hand there has been no significant detection of the emission more than 40–50 degrees away from the GC (Teegarden et al. 2005; Weidenspointner et al. 2007).

Detailed analysis of the annihilation line profile, the positronium continuum below 511 keV, and the spectrum of the diffuse gamma-ray background at higher energies place further limits on the origin of the line. INTEGRAL and COMPTEL measurements of the diffuse background at 1–10 MeV indicates that the positrons must be produced at relatively low energy, since otherwise in-flight annihilation of relativistic positrons off background electrons would produce a visible bump in the spectrum. This constraint on the injection energy, first identified by Agaronyan & Atoyan (1981), places an upper limit of $\sim 3$ MeV on the mass of a light dark matter candidate producing positrons through annihilation in a neutral medium (Beacom & Yüksel 2006; note that in this case internal bremsstrahlung in the annihilation process also contributes to the high-energy emission). Allowing for a partially ionized medium (and for production mechanisms without associated internal bremsstrahlung emission), the more general limit on the injection energy is $\sim 4$–8.5 MeV (Sizun, Cassé, & Schanne 2006, 2007). Furthermore, low-energy positrons rarely annihilate directly; instead the majority form positronium, a short-lived bound system composed of an electron-positron pair. Positronium then decays either from the singlet ("para-positronium", spins anti-parallel) state, via the emission of two photons at 511 keV, or from the triplet ("ortho-positronium", spins parallel) state by the emission of three photons, leading to a continuum below 511 keV. Detailed analysis of the line profile and line-to-continuum ratio can constrain the properties of the medium in which the positrons propagate and annihilate. The recent analyses of Churazov et al. (2005) and Jean et al. (2006) indicate that the dominant emission source cannot be located in the very hot or very cold components of the ISM, but that annihilation probably occurs in the warm neutral and ionized medium.

Given these constraints and the expected lifetimes for positrons in different components of the ISM, the implication is that positrons are either produced in, and annihilate in, the warm medium, or are produced in the hot medium but propagate further and annihilate in the warm medium at the edge of hot bubbles. In the former case they would travel only 50–100 pc ($\sim 0.5°$ at GC) from their source before annihilating, and in even in the latter they would annihilate within $\sim 250$ pc of their source (Jean et al. 2006). Thus, in the absence of large-scale magnetic fields (which could cause the positrons to propagate even further from their sources; Prantzos 2006) the spatial extent of the observed emission implies sources distributed over a similar area on the sky.

2.2 Possible Positron Sources

Since its discovery, many possible sources have been invoked to explain the 511 keV emission from the Galactic Centre. A number that were initially consistent with early detections are now disfavoured, given more accurate maps and flux measurements. Some sources, e.g. cosmic rays interacting with the intergalactic medium (Ramaty et al. 1970; Lingenfelter & Ramaty 1982), or populations of young stellar objects such as pulsars (Sturrock 1971), or supernovae or Wolf-Rayet stars (via the radioactive nuclei they produce – Clayton 1973; Ramaty & Lingenfelter 1979; Sigmone & Vedrenne 1988; Woosley & Pinto 1988; Lingenfelter & Ramaty 1989; Milne et al. 2002), would produce a more flattened distribution on the sky, inconsistent with the bulge component. Some other possible candidates, e.g. Sgr A* (Lingenfelter & Ramaty 1982; Rees 1982; Obermeyer 1989; Ramaty et al. 1992), a single GRB or hypernova at Galactic Centre (Lingenfelter & Huetter 1984), or a population of classical novae (Purcell et al. 1997), should appear as a single point source and/or show temporal variability (although models where stronger emission of positrons from Sgr A* occurred at some time in the past may be possible – see Cheng, Chernyshov & Dogiel 2006 and 2007; and Totani 2006). While some of these sources may account for part of the annihilation flux (e.g. the radioactive decay of $^{26}$Al from young massive stars should account for 20-30% of the 511 keV emission in the central part of the Galactic disk; Bouchet et al. 2008), the majority of the 511 keV flux now seems most likely to come from a distributed population of faint sources that traces the old stellar bulge. We refer the reader to e.g. Knödlseder et al. (2005) for further discussion of the alternatives.

Of sources associated with old stellar populations, type Ia SNe are too rare to account for much of the flux. Hypernovae/GRB progenitors (Cassé et al. 2004) or GRBs (Pari- zot et al. 2005; Bertone et al. 2006) might produce enough positrons, but it is not clear they could necessarily reproduce the smoothly distributed emission seen by SPI. Another possibility worth mentioning is pulsars. Rotationally powered pulsars are well known to produce high energy particles. In recent years, it has become clear through the observation of a synchrotron nebula around the pulsar 1957+20 (Stappers et al. 2003) that even millisecond pulsars (MSPs) can have...
significant pair-dominated winds. Given their considerably larger numbers compared with young pulsars, especially in regions of old stellar populations like the Galactic Bulge, the pair flux from MSPs should dominate the total pair flux from pulsars, and it has been shown that reasonable parameter values for pulsar numbers and pair flux rates can reproduce the observed annihilation line rate (Wang, Pun & Cheng 2006). Thus MSPs are a plausible source of the 511 keV line emission. However, pulsars are expected to produce very high energy (>10 MeV) positrons; but as noted earlier, the INTEGRAL and COMPTEL measurements of the diffuse 1-10 MeV background indicate that the positrons responsible for the observed annihilation line must be produced at relatively low energy, as otherwise a visible bump in the spectrum from in-flight annihilation of relativistic positrons would be observed (Agrononyan & Atoyan 1981). Thus we will not consider MSPs further in this paper.

Finally, a large number of more exotic possibilities have been suggested to explain the 511 keV emission. They include annihilation of an MeV-scale particle, such as “light” dark matter (Boehm et al. 2004); sterile neutrinos or pseudoscalar relics with masses < 100 MeV (Picciotto & Pospelov 2005); decays of axions (Hooper & Wang 2004), sub-GeV scale neutralinos (Gunion et al. 2006; Bird et al. 2006), or other supersymmetric particles (Takahashi & Yanagida 2006); Q-balls (Kasuya and Takahashi 2005), mirror matter (Foot & Silkadze 2005), moduli (Kawasaki & Yanagida 2005; Kasuya and Kawasaki 2006), superconducting cosmic strings (Ferrer & Vachaspati), droplets of superconducting quark matter (Oaknin & Zhitnitsky 2004; McNeil, Forbes, & Zhitnitsky 2008), TeV-scale particles with an excitation at the MeV scale (Finkbeiner & Weiner 2007; Pospelov & Ritz 2007) or small, accreting black holes (Titarchuk & Chardonnet 2006).

3  A MODEL FOR POSITRON PRODUCTION IN LMXB JETS

3.1 Emission from Accreting Binaries

Over the past decade, multiwavelength observations of X-ray binaries have clearly shown that these systems produce relativistic jet outflows, analogous to those observed in AGN and quasars (see Fender 2006 for a review). There are known accreting binary populations in the GC, and there is increasing evidence that all accreting sources containing black holes and neutron stars have a compact, steady jet outflow during their “hard” states, when their X-ray luminosity is relatively low (indeed, there is evidence that these compact jets are also present during the “quiescent” state when the source X-ray luminosity is extremely low; Gallo et al. 2006, 2007). Several (perhaps all) BH XRBs also have transient powerful, large-scale, extended jets, which are associated with the transition between the “hard” or “quiescent” states and the X-ray luminous “high/soft” state. These large-scale ejection events are episodic but their duty cycle is poorly known; however, it is clear that most BH XRBs spend less time in the transitional regime where the large-scale jets are emitted than in the lower X-ray luminosity hard (or quiescent) states. We therefore focus here on the low-luminosity steady jets.

Extending the results of deep X-ray surveys of the central Galactic Bulge (Wang et al. 2002, Muno et al. 2003, Muno et al. 2006) to the entire Bulge, we would expect roughly 10^5 X-ray point sources similar to those detected by the Chandra surveys. While a large fraction of these are likely to be cataclysmic variables (see e.g. Muno et al. 2003), a few percent of the sources are likely to be quiescent low-mass BH X-ray binaries, sources which trace the older stellar population of the Galaxy and thus are observed to be concentrated in the inner Galaxy. Such quiescent systems might be good candidates for the jet positron source, consistent with known point sources down to 10^{38} ergs/s. These jets could be sources of high-energy electrons and protons, and also, as they interact with the ISM, of positrons.

Alternatively, this could be done by low energy cosmic ray injection in jets with associated acceleration to high energies in the jet-ISM interaction sites (e.g. Heinz & Sunyaev 2003; Fender, Maccarone & van Kesteren 2005; Heinz & Grimm 2005). These two distinct components would in turn produce diffuse emission across the electromagnetic spectrum via positron annihilation, synchrotron emission, and perhaps heating of the ISM. This solution is preferable to many of the more exotic scenarios, which require fine tuning to avoid constraints on positron production at energies above ~10 MeV, and cannot simultaneously produce both low-energy positrons and high-energy electrons and protons. (Light dark matter, for instance would produce the former, whereas conventional heavy dark matter would generate the latter via pion production.)

3.2 Positron power from jets

The jets in low/hard state or quiescent X-ray binaries are thought to be mildly relativistic (see Gallo, Fender, Pooley 2003). While there are some arguments that the data on XRBs do allow for higher jet velocities in the low/hard states (Heinz & Merloni 2004), additional indirect evidence supports the former assertion. The giant jet ejections that take place at transitions from hard to soft states are well explained by a jet speed that increases as the state transition proceeds, leading to a shock of the faster jet material against the recently ejected slower material (Vadawale et al. 2003; Fender, Belloni & Gallo 2004). Furthermore, the jets in low luminosity active galactic nuclei are typically two-sided, while those in high luminosity AGN are typically one-sided, consistent with the idea that Doppler boosting is a more important effect in high luminosity AGN than low luminosity ones.

We thus take a jet speed of 0.7c, meaning that the kinetic luminosity of the jet is about 0.4mc^2. This gives \( \dot{m} = 3 \times 10^{14} \text{ g/sec} \) for a jet power of about 10^{35} ergs s^{-1}, typical in the quiescent systems whose X-ray luminosities are about 10^{32} ergs s^{-1}. Theoretical studies suggest a range of 1000-10000 for the number of quiescent BH XRBs in the entire Galaxy (Romani 1992; Portegies Zwart, Verbunt & Ergma 1997). From this range, we derive an estimate of 10^{38-39} ergs/sec of total kinetic power input into the Galactic interstellar medium (ISM) from quiescent black hole XRBs. Since roughly 1/3 of the stellar mass of the Milky Way is in the Bulge, and low mass XRBs are good tracers of stellar populations (Gilfanov 2004), this results in an estimate of \( \sim 300-3000 \) BH in the Bulge itself. We can then
estimate that the kinetic power injected by quiescent BH X-ray binaries into the Bulge is about $3 \times 10^{37} - 3 \times 10^{38}$ ergs/s, and that the total mass injected into the Bulge ISM from these jets is about $10^{37} - 10^{38}$ g/s, yielding a total proton injection rate of about $5 \times 10^{40-41}$ per second. If we see $\sim 10^{-3}$ photons/s cm$^2$, then this means we see $10^{38}$ 511 keV photons per sec. If we assume that 3/4 of the annihilations go through the 3-photon positronium channel, then we need $2 \times 10^{43}$ positrons/s produced to get the $10^{38}$/s 511 keV photons needed (75% produce no 511, 25% produce two 511 photons). We thus need a pair to proton ratio of about 40–400 to account for the observed 511 keV luminosity.

The best attempts at estimating the pair fractions for jets come from active galactic nuclei. It has been shown by Sikora & Madejski (2000) that excessive pair fractions in quasar jets would lead to a strong bump in the soft X-rays due to the bulk Compton upscattering of the thermal photons from the accretion disk of the quasar, in contrast to observations. On the other hand, for lower luminosity AGN, which are more likely to be analogous to the quiescent BH X-ray binaries discussed here, the situation is less clear – these still could be pair-dominated as they do not have strong thermal accretion disks to contribute photons for upscattering. Comparisons in M87 between the bulk kinetic power observed from jet-intracluster medium interactions and the synchrotron luminosity argue that there must be a large number of leptons per unit kinetic power, and hence that the pair fraction must be large (Reynolds et al. 1996; Dunn, Fabian & Celotti 2006). Reynolds et al. (2006) also find that the pairs in these jets are most likely to be predominantly cold (i.e. the energy spectrum for the electrons has no low energy cutoff, so that the number density is dominated by electrons with low enough energies to satisfy the constraint discussed in section 2.1, that high energy pairs would produce excessive emission in $\sim$ MeV range via in-flight annihilation).

Guessoum, Jean, & Prantzos (2006) have estimated the production rate of positrons in “canonical” jet-producing microquasars, based on the energetics and models of these luminous XRBs which have been presented in the literature; we summarize their results here. They use an average value of $10^{43}$ pairs/sec from a luminous microquasar producing “steady” jets (e.g. in the low/hard state, rather than the large-scale episodic jets) at $L_X \sim 0.01-0.1L_{Edd}$. Using an estimate of $\sim 100$ for the total number of microquasars in the Galaxy, together with the Galactic positional distribution of observationally-confirmed microquasars, they derive an estimate of $\sim 4.1 \times 10^{42}$ positrons/s for the rate of annihilating positrons in the Bulge. They note that the positron production rate they derive is smaller than what is inferred from the INTEGRAL 511 keV observations. Comparing their results with ours, we see that their calculated positron injection rate from luminous microquasars within the Bulge – a fairly small population, of order $\sim 40$ sources – is an order of magnitude smaller than the $2 \times 10^{43}$ positrons/s we calculate as being produced by quiescent BH XRBs in the Bulge – a population we estimate to have $\sim 3000$ members. As such, in the scenario we describe in this paper, the quiescent BH XRBs would be the dominant source of the Bulge 511 keV emission, although the luminous microquasars would also make a significant contribution.

From one year of INTEGRAL/SPI observations, Knödlseder et al. (2005) found that the spatial distribution of 511 keV luminosity shows a Bulge-to-disk (B/D) ratio of 3-9, which is higher than the mass of the Galaxy in general. Subsequently, using two years of INTEGRAL/SPI data, Weidenspointner et al. (2007) revised this ratio downward to a range of 1-4. Since there exist mechanisms for producing 511 keV emission in the Galactic Plane which involve young stars not present in the Bulge, any viable mechanism for producing the bulk of the 511 keV emission in the Bulge must be one in which a larger amount of annihilation per unit mass comes from the Bulge than from the Galactic Plane. At first glance, this seems to represent a problem for our model, in which we suggest that 1/3 of the quiescent BH XRBs are located in the Bulge; if the remaining 2/3 are simply assumed to be in the Galactic disk, then the 511 keV luminosity B/D ratio would be 0.5, well below the lower end of the range determined by Weidenspointner et al. (2007).

However, this simple calculation neglects two important factors, highlighted by Guessoum et al. (2006). First, a significant portion of the Galactic LMXB population is located in the Galactic halo, distinct from the Bulge and disk LMXB populations. Grimm et al. (2002) find that 25% of the total number of LMXBs in the Galaxy are located in the halo. They also find that 1/3 of bright LMXBs are located in the Galactic Bulge, consistent with the expectation from the stellar mass distribution of the Galaxy discussed above. Thus if we assume that the quiescent black hole XRBs described here have a similar distribution to canonical luminous low mass XRBs, we expect $\sim 1/3$ in the Bulge, $\sim 1/4$ in the halo, and the remainder to be located in the disk. The halo sources are physically located well outside of the Bulge and the Plane; thus they will not significantly contribute to the 511 keV luminosity in the spatially-constrained Bulge and inner disk areas (within $R \sim 1.5$ kpc of the Galactic Centre) over which the 511 keV emission has been detected (Weidenspointner et al. 2008). Removing the halo sources results in a B/D luminosity ratio of 0.8 – still below the lower limit of Weidenspointner et al. (2007). (Note that Guessoum et al. also made an estimate for the number of luminous microquasars in the halo, and removed those sources before calculating their Bulge-to-disk luminosity ratio.)

The second factor, as discussed by Knödlseder et al. (2005), is that the scale height of XRBs in the Galactic disk is about 700 pc (Jonker & Nelemans 2004), considerably larger than that of the gas in the Galaxy, and that this can have profound effects on the inferred rate of positron production in different parts of the Galaxy. If positrons are injected into gas poor parts of the Galaxy, they may travel fairly large distances before annihilating, yielding a situation where the distribution of locations for positron annihilation is not the same as the distribution of locations for positron production. The largest effect would be to transfer positrons from production sites several gas scale heights above the Galactic Plane into the halo or Bulge before they undergo annihilation. Following Guessoum et al. (2006), if we estimate that 50% of positrons produced in the disk escape into the halo and/or propagate along field lines towards the Bulge, while all positrons produced in the Bulge are retained and annihilate therein (see e.g. Jean et al. 2006), then we must reduce the disk 511 keV luminosity by 1/2. Combining this factor with the Bulge and disk population estimates above, we now find a B/D 511 keV luminosity ratio for the quiescent BH
XRB population of $\sim 1.6$, well within the range for the B/D ratio found by Weidenspointner et al. (2007). Finally, we note that some positrons which escape from the disk may end up annihilating in the Bulge, rather than in the halo, resulting in a still larger B/D ratio.

Therefore, it seems plausible that the 511 keV emission could come from the jets of quiescent (X-ray faint) black hole X-ray binaries. The requirements to make this happen – (i) that the jets have $\sim 100$ positrons per proton; (ii) that there are on the order of 3000 quiescent BH X-ray binaries in the Bulge; and (iii) that the pairs are mostly cold – are all within the range of reasonably standard assumptions and well within the range of observational constraints.

### 3.3 Predicted Emission at Other Wavelengths

We first introduce a few standard assumptions about jet kinetic power from accreting binaries, and its relationships with observables such as radio and X-ray luminosities. The kinetic power input into a relativistic jet is assumed to be a constant fraction of the accretion power:

$$L_K = f \dot{M}. \quad (1)$$

This follows in a straightforward manner from the standard mechanisms for producing jets by extracting either the spin energy of the central black hole (Blandford & Znajek 1977), or the rotational energy of the accretion disk (Blandford & Payne 1982), provided that the height to radius relation for the accretion disk does not change as a function of accretion rate (e.g. Livio, Ogilvie & Pringle 1999; Melter 2001).

Based on the results of standard synchrotron theory (e.g. Blandford & Königl 1979; Falcke & Biermann 1995; Heinz & Sunyaev 2003), it is normally assumed that the observed radio luminosity from a jet is proportional to its kinetic luminosity to the 1.4 power:

$$L_R \propto L_K^{1.4}. \quad (2)$$

Next, it is assumed that black holes at low accretion rates (in the hard or quiescent states) are radiatively inefficient, because they can advect energy across their event horizons, leading to a scaling of the bolometric luminosity on the square of the mass accretion rate (Narayan & Yi 1994)

$$L_{X,bh} \propto \dot{M}^2; \quad (3)$$

whereas neutron stars, with their solid surfaces, cannot advect matter or energy, leading to a linear proportionality between mass transfer rate and luminosity:

$$L_{X,ns} \propto \dot{M}. \quad (4)$$

The resulting expectations are that black holes should have a radio luminosity which depends on the X-ray luminosity to the 0.7 power, assuming that the radio emission comes from the jet, and the X-ray emission comes from an advection-dominated accretion flow:

$$L_R \propto L_K^{4.0} \propto \dot{M}^{1.4} \propto L_{X,bh}^{0.7}. \quad (5)$$

Similarly, neutron stars should have a radio luminosity which scales as the X-ray luminosity to the 1.4 power. Both these correlations are indeed observed; see e.g. Corbel et al. (2003) and Gallo, Fender & Pooley (2003) for the case of black holes, and Migliari and Fender (2006) for the case of neutron stars.

The kinetic energy input into the ISM from black hole X-ray transients in quiescence can then be estimated based on their X-ray luminosities. The characteristic X-ray luminosities of quiescent BH X-ray transients are $10^{32}$ ergs/sec. Jets are likely to take away a substantial fraction of kinetic power in the low/hard state (e.g. Malzac, Merloni & Fabian 2004), but, given that state transitions between the radiatively efficient high/soft state in which little or no jet power is seen, and the radiatively inefficient low/hard state in which there is a steady jet, do not correspond with abrupt luminosity changes, the jet power cannot be much greater than the radiated power at the state transition (Maccarone 2005b). Therefore, the best estimate of the jet kinetic power is that it scales with $L_X^{0.8}$, as predicted by the model, with the normalization fixed such that the jet power and the X-ray luminosity are equal at the state transition luminosity which is typically about 2% of the Eddington luminosity (Maccarone 2003). Such arguments have been used to estimate that the total kinetic power input into the ISM from bright XRBs is about $10^{39}$ ergs/sec (Fender, Maccarone & van Kesteren 2005; Heinz & Grimm 2006), while the kinetic power input from quiescent black hole X-ray binaries may be $10^{38–39}$ ergs/sec (as derived in Section 3.2; see also Maccarone 2005a). (Note that we use this power estimate based on the theoretical numbers of the BH XRB population rather than using the luminosity function derived from observed bright BH X-ray transients, as the latter option would involve extrapolating the luminosity function to X-ray luminosities 3–6 orders of magnitude lower than what has been directly measured for the bright sources.) Since the total kinetic power in jets from quiescent BH X-ray binaries is likely to be of the same order as that from the most luminous systems, and the quiescent systems will be more strongly concentrated in the Bulge than will the luminous XRBs (a population which includes HMXBs as well as LMXBs), it is to be expected that a substantial fraction of the Bulge positrons come from quiescent black hole X-ray binaries.

### 3.4 Observational Constraints at Other Wavelengths

Finally, we note two other diffuse components in the Galactic Centre that may be related to the annihilation radiation.

#### X-ray:

In the bulge core, diffuse Chandra emission amounts to $2 \times 10^{36}$ ergs/s, with a spectrum equivalent to an 8 keV thermal plasma over the 17x17 sq. arcmin Chandra field (Muno et al. 2004). The observed spectral shape is indicative of a truly diffuse component rather than originating from a collection of unresolved discrete sources. The flux limit of the Muno et al. (2003) X-ray survey is $\sim 10^{31}$ ergs/s. Normal stars have luminosities of $\sim 10^{35}$ ergs/s or less, and so at least 10$^9$ normal stars would be needed to account for the diffuse emission component. However, 10$^9$ stars are all the (solar mass) stars in the Bulge, not just those within the central 40 square parsecs covered by the Muno et al. Chandra survey. It has been argued that this
plasma can be thermally maintained by low energy cosmic ray heating (Yusef-Zadeh et al. 2007). Could these cosmic rays possibly come from the X-ray binary jets themselves? The energetics should be adequate. One question is whether this fraction of the energy actually comes out in cosmic rays, rather than just leading to bulk kinetic motions of the gas at the collisional interface of the jets.

**Microwave:**

WMAP finds a likely synchrotron background with an integrated luminosity of about $2 \times 10^{36}$ ergs/sec in the 23-61 GHz frequency range from a region 20–30 $^{\circ}$ in radius around the Galactic Centre region (Finkbeiner 2004a). The total power emitted at these frequencies is estimated to be between $1-5 \times 10^{36}$ erg s$^{-1}$. Assuming a distance of 8.5 kpc, this corresponds to a flux level between 3000 and 15000 Jy. We note that there are large uncertainties in this estimate, given the need to subtract many other contributions, including thermal dust, spinning dust, thermal bremsstrahlung emission and synchrotron from electrons accelerated in SNe shocks, from the microwave maps. Moreover, use of the WMAP internal linear combination (ILC) dust extinction template leaves much uncertainty in possible spatial variations of the composition-dependent frequency sensitivity of the dust emissivity. Nonetheless, the signal has generated interest given its possible connection to exotic processes such as the annihilation of massive WIMPs (Finkbeiner 2004b; Hooper, Finkbeiner & Dobler 2007), or states of ‘excited’ dark matter (Finkbeiner & Weiner 2007).

The reported haze flux level cannot be produced from core emission from individual black hole X-ray binaries – as previously discussed, no more than about 3000 quiescent BH XRBs are thought to be in the entire GC region (e.g. Romani 1992; Portegies Zwart, Verbunt & Ergma 1997), meaning that the flux of the typical source would have to be ~1 to several Jy. Sources above even 100 mJy would be well-known radio sources at lower frequencies (since they would likely be flat spectrum sources, or sources whose flux density drops with increasing frequency), and an excess of such sources would be clear from existing radio surveys. The typical flux of a quiescent low mass X-ray binary in the radio at the Galactic Centre distance should be $\sim$ 10–20 $\mu$Jy (see e.g. Gallo et al. 2006 for the faintest known system of this sort; Hynes et al. 2004 for V404 Cyg, the brightest one). Given $\sim$3000 BH with an average quiescent radio flux level of $\sim$100 $\mu$Jy, the integrated luminosity of those outflows at WMAP wavelengths would be far less than that of the WMAP GC haze (even if the haze flux has been significantly overestimated). This may support the interpretation of the haze emission source as relativistic electrons, produced by annihilating 100 GeV dark matter particles (Finkbeiner 2004b; Hooper, Finkbeiner & Dobler 2007).

### 4 DISCUSSION

It thus seems reasonable that most or all of the Galactic Centre 511 keV emission line could come from low luminosity BH X-ray binaries. We note that this scenario is not required, since the positron-to-proton ratios for X-ray binary jets are largely unconstrained by observations. What about the contribution from high luminosity (“canonical”) XRBs? We need to estimate the fraction of the overall 511 keV line flux that can be accounted for by the well-studied canonical jet sources, and correspondingly the percentage of the flux which needs to be accounted for by the low luminosity population. However, if we only consider black hole XRBs, since (as previously discussed) the NS jet flux is too small, then at any given time there are only a few active luminous hard state black holes which would contribute to the 511 keV emission. But in this case, if a significant fraction of the overall 511 keV flux originated from a hundred of sources, and if the positrons do not propagate and annihilate far from their production sites, we would expect to see these individual sources in the 511 keV flux maps - the 511 keV line emission would not appear to be as smooth as it does.

There is no convincing evidence for time variability of the 511 keV line. It is clear that the mechanism proposed here-- summed emission from hundreds to thousands of sources of roughly equal importance -- should predict low variability levels in the 511 keV emission. It is less clear whether this would be true from many of the other mechanisms proposed which rely more heavily on a smaller number of sources. However, temporal variability is not useful for distinguishing the total number of sources if the characteristic positron lifetime is $10^5$ years as suggested by Ferrer & Vachaspati (2005). Only spatial variability would be useful in this case.

Weidenspointner et al. (2008) suggest that an asymmetry in the 511 keV emission is correlated with an asymmetry in the LMXB distribution around the inner Galaxy. The asymmetry argument is that the disk 511 keV flux is asymmetric, and so is the hard LMXB population, with the same ratio between halves (positive and negative galactic longitudes) of the disk. Furthermore, the number of objects (~70) times a plausible mean flux per source ($10^{-5}$ photons/cm$^2$/s each) gives the right total disk flux ($7 \times 10^{-4}$ photons/cm$^2$/s); thus the luminous hard LMXBs may be the source of the disk flux, if not the ($\sim 10^{-3}$ photons/cm$^2$/s) Bulge flux (note that the latter corresponds to a larger luminosity, since the Bulge is further away; overall it should be 3-9 times the disk luminosity).

While the positional asymmetries in the known luminous X-ray binary distribution do appear to be in the same sense as the asymmetry in the 511 keV emission, it is not clear that the asymmetry in the Bulge component of the X-ray binary population is real. The inner 20$^{\circ}$ of the Galaxy show only a 1.5$\sigma$ asymmetry - 30 (negative longitude) versus 18 (positive longitude) sources. In other words, given a total of 48 sources, the probability of having $\geq$30 sources at negative latitudes is 5.6%. We note that at least eight of the X-ray binaries in the INTEGRAL catalog (5 at negative longitudes, 3 at positive) used by Weidenspointner et al. (2008) in their determination of the asymmetry are “foreground” sources, with known distances which are not consistent with being in the Galactic Bulge (Jonker & Nelemans 2004). If the 511 keV emission is physically associated with the population of hard XRBs, as is suggested by the asymmetry, then the observed enhancement of 511 keV flux in the central region of the Galactic Plane is simply a projection effect along our line of sight towards the GC, which coincidentally results in an apparent concentration of 511 keV line emission within...
Thus in this scenario, the 511 keV enhancement is not physically associated with the Galactic Bulge itself, and the morphology and intensity of the 511 keV map is dependent upon the longitudinal location of bright, hard XRBs. However, we note that GRS 1915+105, which is almost certainly the strongest emitter of positrons from jets outside of the innermost region of the Bulge, is on the other side of the Galaxy (at positive galactic longitude) from the bulk of the INTEGRAL sources and the observed 511 keV enhancement (which are at negative galactic longitudes).

The asymmetry interpretation has at least 4 distinct problems:

(i) The LMXB luminosity function is steep near the lower end; changing the sensitivity limit of the IBIS catalog would change the positive/negative longitude number ratio.

(ii) Integrating flux down the luminosity function, the asymmetry also depends on the catalogue limit, in that the total flux asymmetry is actually the reverse of the number asymmetry, at least at high luminosities.

(iii) A few sources (e.g. GRS 1915+105) are responsible for much of the flux; if this is always true, then the numbers of objects in the catalog may not mean much; a few bright sources could determine how many positrons are produced at any given time (i.e. the total flux need not correlate with the number of objects over the IBIS limit).

(iv) Since LMXB X-ray emission is time-variable, there is no indication that any current asymmetry in numbers or flux would be constant in time.

Fig. 1a shows the cumulative (20-100 keV) luminosity function for all 72 Galactic LMXBs within \( \pm 10^\circ \) latitude of the Plane in the catalogue of Bird et al. (2007), divided up into objects at positive and at negative longitudes (solid and dashed lines respectively). Note this scale height excludes high-latitude luminous LMXBs such as Sco X-1. Fig. 1b shows the integrated flux contributed by binaries over a given flux limit for each of these samples.

Clearly the longitudinal asymmetry in number counts is sensitive to the lower flux limit of the catalogue; here, this is set to the INTEGRAL/IBIS 20-100 keV detection limit. The current integrated flux is dominated by a small number of bright sources, with the majority of the sources in the INTEGRAL catalogue being just at the flux detection limit. Given the recently identified large population of X-ray faint XRBs discussed above, it is clear that there are many lower luminosity sources below the INTEGRAL detection threshold. The asymmetry in the source number counts could thus easily be an artifact of the flux bias of the INTEGRAL sample. Therefore the source numbers used to determine the positional asymmetry could be greatly changed by a slight change in the flux cutoff (to either higher or lower luminosities). Cutting objects below 10 mCrab, for instance, would produce no asymmetry at all, while cutting at a high flux limit would produce more sources at positive longitudes. So overall, the observed positional asymmetry seen in the INTEGRAL catalogue, with its instrumentally-determined bias towards luminous sources, may not be significant even if the observed current 20-100 keV flux were to correlate exactly with the 511 keV flux.

Furthermore, the integrated flux from LMXBs in the catalogue is dominated by objects at positive longitudes at all flux limits (Fig. 1b), although admittedly this is mainly due to the strong contribution from the single brightest source, GRS 1915+105. Thus the asymmetry in the number of sources does not agree with the asymmetry in the total flux from the INTEGRAL catalogue sources – there is...
more integrated flux where there are fewer sources (positive longitudes), and less integrated flux where there are more sources (negative longitudes).

The fact that the current “snapshot” distribution of the integrated flux does not match the 511 keV asymmetry may in itself not be problematic for the Weidenspointner et al. (2008) hypothesis, since the timescale for positrons to annihilate and produce 511 keV emission is $\lesssim 10^7$ years. However, we note that a large fraction of the sources observed by INTEGRAL and used to “find” the positional distribution asymmetry are transients. In addition, those X-ray sources which we call “persistent” merely means that the sources have been consistently luminous over the $\sim 35$ years of observational X-ray astronomy, which provides very little information about the persistence of their luminosity over the $10^5$ year timescale of photon interaction. Thus the current apparent positional asymmetry is merely a snapshot in time, and does not constitute evidence that the total absolute numbers of 511 keV-producing binaries in the direction of the inner Galaxy – including those currently in quiescence, which are likely to be the majority – at negative longitudes is larger than at positive longitudes.

Over the long lifetime of positron interaction, the integrated flux from all sources which become active during that time may indeed be larger at negative longitudes than positive ones, resulting in the observed asymmetry in the 511 keV emission. To determine this, however, we would need to be certain that there is a true asymmetry in the distribution of all positron-producing XRBs in the inner Galaxy - not just during the current epoch, when only a small fraction of such XRBs are observed to be active and luminous. We would have to assume that the asymmetric distribution of currently luminous XRBs - a sample of $\sim 70$ sources - reflects an underlying asymmetry in the overall distribution of all XRBs - on the order of $\sim 3000$ BH binaries - which would contribute to the 511 keV emission over $10^5$ years. While this is certainly possible, it cannot be considered conclusive, as it is dependent upon both the arbitrary lower flux cutoff of the INTEGRAL catalogue (set by the instrument sensitivity rather than by any intrinsic property of the sources themselves) and the arbitrary time of observation (e.g. the modern era of high-energy astronomy).

A much deeper census of the black hole X-ray binary population, which explores down to the quiescent luminosity of these sources ($\lesssim 10^{32}$ erg/s), is needed in order to search for a true asymmetry in the physical distribution of jet-emitting XRBs in the inner Galaxy. Such a census would require both a deep X-ray survey and infrared follow-up observations to identify stellar counterparts to a representative sample of the X-ray sources, in order to conclusively determine which sources contain black holes. It would then be possible to assess whether or not the asymmetry in the 511 keV flux is due to an intrinsic spatial asymmetry in the number of XRBs which episodically exhibit large X-ray luminosities integrated over the timescale for 511 keV production.

If stellar sources do account for 511 keV emission, it is unlikely that they would show up as point sources at higher spatial resolution at other wavelengths than the X-ray, as the positrons likely propagate a significant distance ($\sim 50-250$ pc, which is $\sim 0.5\degree - 1.5\degree$ at the GC; Jean et al. 2006 – but see also Prantzos et al. 2006, which suggested a larger distance) before annihilating. For the brightest of the low-luminosity sources ($10^{35}$ erg/s), we could perhaps detect a flat near-IR spectrum which would not be consistent with the flux of a mass donor star alone, but which instead would denote the presence of another component - e.g. a jet outflow. It is not clear if there is enough sensitivity in the mid-IR for ground-based observations e.g. at 4 and 8 microns to detect the flux from these sources. Similarly, for sources with this X-ray luminosity, high frequency (8.6 GHz) radio emission might be detectable (e.g. with the VLA) to search for the flat spectrum signature associated with the steady jets from hard state X-ray binaries.

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