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# An asymmetric distribution of positrons in the Galactic disk revealed by γ-rays

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**Gamma-ray line radiation at 511 keV is the signature of electron–positron annihilation. Such radiation has been known for 30 years to come from the general direction of the Galactic Centre[1], but the origin of the positrons has remained a mystery. Stellar nucleosynthesis[2–4], accreting compact objects[5–8], and even the annihilation of exotic dark-matter particles[9] have all been suggested. Here we report a distinct asymmetry in the 511-keV line emission coming from the inner Galactic disk (~10–50° from the Galactic Centre). This asymmetry resembles an asymmetry in the distribution of low mass X-ray binaries with strong emission at photon energies >20 keV ('hard' LMXBs), indicating that they may be the dominant origin of the positrons. Although it had long been suspected that electron–positron pair plasmas may exist in X-ray binaries, it was not evident that many of the positrons could escape to lose energy and ultimately annihilate with electrons in the interstellar medium and thus lead to the emission of a narrow 511-keV line. For these models, our result implies that up to a few times $10^{41}$ positrons escape per second from a typical hard LMXB. Positron production at this level from hard LMXBs in the Galactic bulge would reduce (and possibly eliminate) the need for more exotic explanations, such as those involving dark matter.**

The main clue as to which of the sources of positrons are most important is expected to come from the distribution on the sky of the annihilation line radiation. With existing instrumentation, the emission appears to be diffuse; no point sources of annihilation radiation have yet been detected[10–13]. The 511-keV flux from the bright Galactic bulge region has been well measured to be about $1 \times 10^{-3}$ photons $cm^{-2} s^{-1}$ (refs 1, 10, 14, 15), and its spatial distribution is well established to be symmetric about the Galactic Centre, with an extent of ~6° (full-width at half-maximum)[10,15,16]; these conclusions are unchanged by the present work. However, no firm conclusion as to the origin of the positrons has been possible because of the limited angular resolution and sensitivity of previous γ-ray instrumentation, and the complications arising from uncertainties in the distribution of potential positron sources and in the distribution and content of gas; uncertainties also exist in the structure and strength of magnetic fields in the Galaxy, and in the physics of positron diffusion and thermalization.

Annihilation radiation from the disk is more difficult to study because of its lower surface brightness[14,16], but it potentially provides complementary clues to the positron production processes involved. Only a few instruments have been capable of spatially resolving the (inner) disk emission from the brighter bulge emission. The sparse measurements that exist agree that the annihilation emission from the disk is strongest in the inner Galaxy, and simple models assuming symmetry suggest that it is brightest in the longitude range $|l| < 18$–$35°$ (refs 15–17). The latitude extent of the disk emission is still poorly constrained[14,16]. Using more than four years of data from the SPI imaging spectrometer on the INTEGRAL satellite (Supplementary Information), we have obtained new results on the disk component of the 511-keV emission that have important implications for the origin of positrons in the Galaxy. We not only clearly detect narrow 511-keV line emission from the inner Galactic disk[16], but we observe a distinct and surprising asymmetry in its distribution. This asymmetry is revealed in sky maps (Fig. 1a), in model fitting (Fig. 2), and in spectra of the inner disk emission (Fig. 3).

We have quantified the asymmetry using model fitting (Fig. 2). Our best estimate is that the flux from the inner disk at $-50° < l < 0°$ exceeds that from the inner disk at corresponding positive longitudes by a factor of about 1.8; a symmetric distribution (equal fluxes) can be excluded at the 3.8σ confidence level (Supplementary Information). The fluxes in these negative and positive longitude bands within 10° of the Galactic plane are $(4.3 \pm 0.5) \times 10^{-4}$ photons $cm^{-2} s^{-1}$ and $(2.4 \pm 0.5) \times 10^{-4}$ photons $cm^{-2} s^{-1}$, respectively. The uncertainties quoted here are 1σ statistical errors. No significant emission is yet detected from the outer disk ($|l| > 50°$). We have searched for systematic effects, such as background variations on orbital or other timescales, that might mimic the observed flux asymmetry, but after extensive efforts we have found none. It cannot be due to differences in exposure on the two sides of the Galactic Centre, which are rather similar—for example, the exposures in the Galactic plane around $l = -25°$ and $l = +25°$ differ by less than 10% (see Supplementary Information for details). Although this is the first time that such an asymmetry has been reported, we find that it is not inconsistent with measurements by previous, less-sensitive, instruments[15,17] (Supplementary Information).

Our results for the fluxes from the inner disk region and their asymmetry are not changed significantly if the bulge model is replaced by a halo component (comprising the emission peak at the Galactic Centre and fainter emission extending far beyond the bulge region), which provides an equally good description of the data[16]. Their robustness has been further demonstrated by using additional alternative models and subsets of observations to test in particular for the possibility that an asymmetry in the bright central emission influences conclusions about the disk emission further out. In all cases, the conclusion that the disk emission is asymmetric remains significant (Supplementary Information).

The distinct asymmetry in the annihilation flux from the inner disk is unexpected. It is in the opposite sense from, and much larger than, any difference that might be expected due to the Galactic stellar bar, whose closest limb is at positive longitudes[18]. A part of the inner disk flux must come from positrons associated with the $^{26}Al$ decay chain

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that leads to a 1,809-keV γ-ray line. Using the 1,809-keV line flux, which has been relatively well established with COMPTEL[19,20] and SPI[21], and which is much more symmetric than the 511-keV emission seems to be, we predict a corresponding 511-keV emission that amounts to $(28 \pm 7)\%$ of the emission that we see in the inner disk (Supplementary Information). Thus the dominant (non $^{26}$Al) source of disk positrons must have an asymmetry of about 2.2, not 1.8. The asymmetry cannot be due to differences in the column densities of the interstellar medium (ISM) in which the positrons annihilate. Both 21-cm radio observations and measurements of high-energy γ-rays from cosmic-ray interactions indicate that typical ISM column densities on either side of the Galactic Centre are equal to within about 10%. Furthermore, spectroscopy of the 511-keV line emission from the two sides of the inner Galactic disk (see Fig. 3) suggests no differences in line shape that might indicate that the flux difference is associated with differing conditions in the ISM. We therefore propose that the annihilation asymmetry is in some way linked to the positron production.

As previously noted, X-ray binaries containing accreting stellar-mass black holes or neutron stars have been considered as possible candidates for sources of the positrons, partly because their concentration towards the Galactic bulge is similar to that seen in annihilation line radiation. If positrons escape with an energy of about 1 MeV, their lifetime in the ISM before they slow down and annihilate is thought to be $\sim 10^5$ years (ref. 22; for an ISM density of $1\,\mathrm{cm}^{-3}$). The distance traversed in this time depends critically on the structure of the magnetic fields, but studies suggest that typically they do not diffuse more than about 100 pc from their sources[22,23], corresponding to $\sim 1^\circ$ at the distance of the Galactic Centre. Hence one would expect the annihilation radiation produced to be diffuse but to follow the large-scale distribution of the sources.

Our observed asymmetry in the 511-keV line emission from the Galactic disk suggests an association with X-ray binaries, specifically with LMXBs. Whereas LMXBs seen at lower (<20 keV) X-ray energies are approximately symmetrically distributed in the inner Galaxy, for reasons that are still not understood the distribution of LMXBs in the inner Galaxy seen in hard X-rays exhibits an asymmetry (Fig. 1b) that becomes more and more distinct with increasing energy. High-mass X-ray binaries do not, by contrast, show any significant imbalance. The number of LMXBs in the INTEGRAL/IBIS catalogue[24] at negative longitudes (45) is higher than that at positive longitudes (26) by a factor of 1.7. At higher energies[25], and particularly if one uses flux-weighted counts, the ratio becomes even larger (for example, for LMXBs detected above 100 keV we find a flux-weighted ratio of 2.8), but the statistical uncertainties become large. The differences cannot be attributed to differences in the IBIS survey sensitivity in the two regions, which are small ($\lesssim 10\%$). A Kolmogorov–Smirnov test shows that the Galactic longitude distribution of hard LMXBs follows very well that of our asymmetric 511-keV flux model but not the best fit symmetric one (the maximum distance between the normalized integral distributions being such as to occur with chance probability of 41% in the former case, but only 2.1% in the latter—see Supplementary Information for

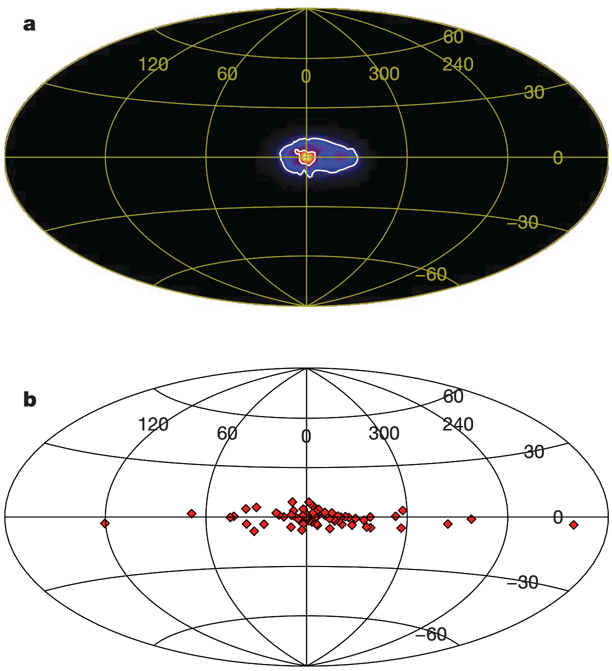


**Figure 1 | A sky map in the 511-keV electron–positron annihilation line, and the sky distribution of hard LMXBs.** In both maps, the Galactic Centre is at the origin, the Galactic plane is along the equator; Galactic longitude and latitude are shown in degrees. **a**, The 511-keV line map. The bright bulge region is prominent, as is the distinct asymmetry in the flux from the inner disk; contours correspond to intensity levels of $10^{-3}$ and $10^{-2}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. The map is based on observations with the imaging spectrometer SPI on board the INTEGRAL satellite, and uses data obtained during 'guaranteed time' for the first 4.3 years of the mission and publicly available data from 'guest observer' observations for the first 3.3 years, supplemented by observing time awarded to the authors. The map was obtained using a MREM (Multi-Resolution Expectation Maximization) image deconvolution algorithm[28]. During the iterative image reconstruction, a filter is applied to the image correction to suppress artefacts due to statistics noise. Such filtering implies that low surface brightness emission which is still detectable by model fitting may not be present in the image, as is the case for some of the disk emission. **b**, The sky distribution of the hard LMXBs detected at energies above 20 keV with INTEGRAL/IBIS[24], showing the resemblance to that of the 511-keV annihilation line in **a**.

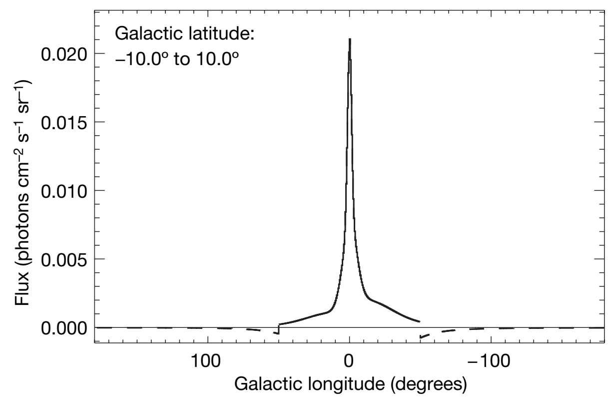


**Figure 2 | The longitude profile of a model for the sky distribution of 511-keV electron–positron annihilation line radiation for Galactic latitudes $|b| < 10^\circ$.** The model was obtained by fitting to the same observations from which the map depicted in Fig. 1a was derived. The asymmetry in the annihilation flux from the inner disk is again evident. The depicted sky model consists of six components. The bright bulge was described by a superposition of two gaussian distributions located at the Galactic Centre. For the disk, a parameterized model of the Galactic distribution of the stellar population was used[29]. The parameters of the bulge and disk components were determined by fitting to our observations (see Supplementary Material for details). This disk model was then divided into four longitude intervals with boundaries at $-180^\circ$, $-50^\circ$, $0^\circ$, $50^\circ$ and $180^\circ$. The two gaussians representing the bright bulge overlap with the two longitude intervals covering the inner disk region. This model was compared with the observations, finding the normalizations of the six components that best reproduce the data, using maximum likelihood as the test statistic. In this particular model, the normalizations of the two outer disk components are negative, but insignificant. Other models that provide equally acceptable fits to the data all lead to the same conclusions about the asymmetry in the inner disk region (and none of them attributes significant emission to the outer disk region). The solid lines show the model in the inner Galaxy; the dashed lines show the model in the outer Galaxy where formally the fit gives a negative, but not significant, flux.


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details). We cannot, of course, exclude the possibility that the similarity of the distributions arises by chance. However, if the present asymmetric hard LMXB activity is typical of that over the $10^5$ year expected lifetime of positrons in the ISM, these systems could explain the observed flux asymmetry in the 511-keV line. We note that it is possible that the IBIS sources considered here are not representative of the full source population of hard LMXBs, which may comprise at least a few hundred members (as inferred from lower energies) in all of the Galaxy[26]. A full evaluation will require a more complete inventory of hard LMXBs in the Galaxy and a detailed population-synthesis study beyond the scope of the present work.

The most natural explanation of an association between positron emission and hard X-ray binaries lies in the large numbers of positrons that are expected to be produced by $\gamma$-$\gamma$ interactions in the hot innermost region of accretion disks. Some of these positrons may escape the inner dense regions in bipolar jets of electron–positron pair plasmas. Alternatively, the pair plasma could escape through wind outflow. The implied positron production rate per hard LMXB is of the order of $10^{41}\,s^{-1}$. This is well within the wide range that has been suggested (see ref. 6 and references therein). In terms of energy, assuming that they have a kinetic energy of $\sim$1 MeV, the escaping positrons would represent less than 1% of the hard X-ray luminosity of the LMXBs. The average 511-keV line flux per system is about $10^{-5}$ photons cm$^{-2}$ s$^{-1}$, which is still well below upper limits that have been derived for selected objects[6,10,11].

If hard LMXBs are responsible for most of the positron production in the Galactic disk (that part not accounted for by $^{26}$Al decay), then it is natural to ask whether the strong concentration of such systems around the Galactic Centre can explain the bulge component for the 511-keV emission. We estimate that they would account for about half of it. Although the expected contribution is uncertain (because of the limited number of objects involved) and we cannot exclude that it all arises in this way, our best fit models do suggest that there is additional bulge emission beyond that expected on a *pro rata* basis. This is consistent with our previous finding that it is difficult to explain all of the disk and bulge emission with positrons from LMXBs because their concentration towards the centre is insufficient[10]. Perhaps the hard LMXBs in the bulge contribute more positrons or a smaller fraction of them escape to large distances. Even if an additional bulge component is needed, there are many possible astrophysical positron sources that could contribute, such as type Ia supernovae[27] or the supermassive black hole Sgr A* (refs 7, 8). Hence there may be no necessity to invoke exotic explanations such as the annihilation of dark matter[9].

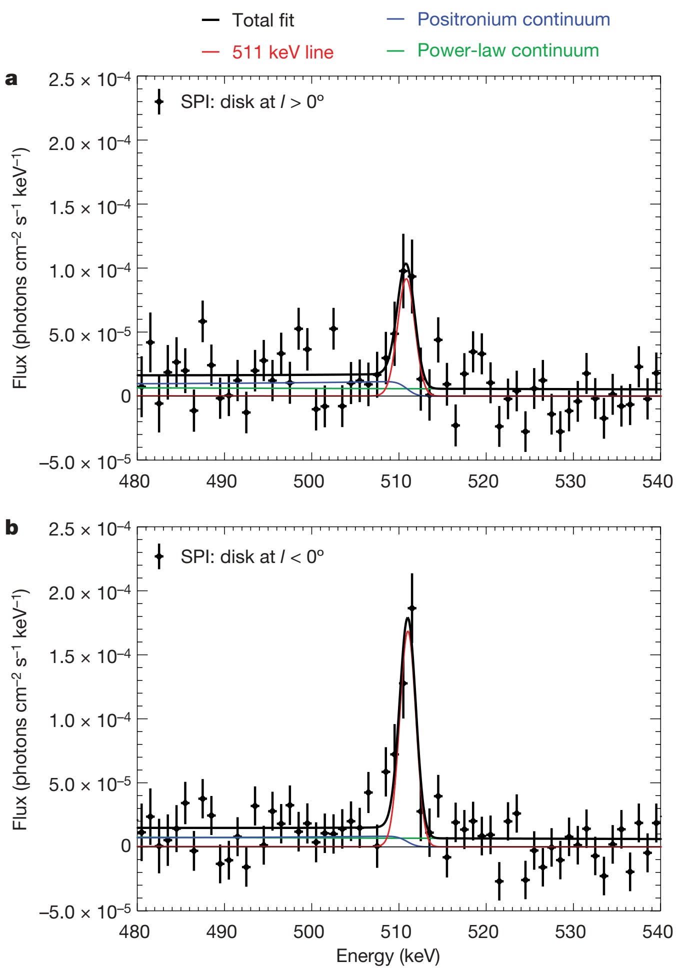


**Figure 3 | Energy spectra of the $\gamma$-ray emission from the inner Galactic disk.** The difference in the 511-keV electron–positron annihilation line flux from the inner Galactic disk in the longitude intervals $0^\circ < l < 50^\circ$ (**a**) and $-50^\circ < l < 0^\circ$ (**b**) is apparent; this difference is also seen in Figs 1a and 2. The spectra were determined by fitting to the data, in each energy bin, the 6 spatial components illustrated in Fig. 2. Error bars, 1 s.d. As the normalizations of each of the 6 model components are fitted individually, the spectra represent the disk emission despite the fact that the two gaussian bulge components spatially overlap with the two components representing the inner disk. The energy spectra were described by three emission components—the positron annihilation radiation, being the sum of a (narrow) 511-keV line (red) and the positronium continuum emission (blue), and a power law (green) representing the continuum emission from the Galactic disk due to cosmic-ray interactions in the ISM. The total spectrum is indicated in black. The similarity of the spectral distribution of the annihilation radiation from both sides of the inner disk suggests that the flux difference is not associated with differing conditions in the ISM.

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