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The influence of Galactic stellar structures on 511 keV positron annihilation morphology

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A thesis submitted for the degree of
Masters of Science

29 August 2014
I would like to dedicate this thesis to my friends, my family and my loving partner Fiona, without whom life would be like a broken pencil. Pointless.
Acknowledgements

I would like to formally thank my supervisors, Laurent Bouchet for kindly providing reduced 511 keV data used in this analysis, our anonymous reviewer for detailed corrections on the paper submitted to MNRAS based on Chapter 4, Pierrick Martin for invaluable advice and expert knowledge regarding positron propagation, Sanjib Sharma for Galaxia and the Denison Award provided by the University of Sydney for most of my candidature.
Statement of Originality

This thesis, to the best of my knowledge, contains no copy or paraphrase of work published by another, except where duly acknowledged in the text. Contributions from collaborators are as follows:

- Laurent Bouchet provided the 511 keV data used in Chapter 4.
- Sanjib Sharma provided the code, “Galaxia”, used in Chapter 4; a tool used to efficiently sample stellar density functions, as defined by the Besançon model, and stellar properties, as defined by Padova isochrones.

I hereby declare that I have not submitted this material, either in full or in part, for a degree or diploma at this university or any other institution.

10/12/2015
Statement of Attribution

Chapter 1 is a brief introduction to the thesis and its purpose written by Muazzam Ali.

Chapter 2 is an introduction to gamma ray instrumentation reviewed and written by Muazzam Ali. Figures; 2.2, 2.3, 2.4 and 2.5 were created by Muazzam Ali and all other figures are referenced in the text.

Chapter 3 is in part an introduction to positron production and observation in the Galaxy and in part research and original analysis of Galactic positron nucleosynthesis; reviewed, researched and written by Muazzam Ali. In Chapter 3.2.1, the expected Galactic positron yield from nucleosynthesis of $^{26}$Al, $^{44}$Ti and $^{56}$Ni are calculated and discussed by Muazzam Ali. In Chapter 3.3, the expected Galactic positron yield from Supernovae type Ia, Core-collapse Supernovae and Asymptotic Giant Branch stars; all-sky distribution maps and histograms of Supernovae remnants, low-mass X-ray binaries, high-mass X-ray binaries, Microquasars, Pulsars, Carbon Monoxide and Dust shown in Figures 3.3, 3.4, 3.5, 3.6, 3.7, 3.8 and 3.9, were created by Muazzam Ali from existing surveys referenced in text.

Chapter 4 is an original research chapter entirely modelled, plotted and written by Muazzam Ali. 511 keV data were obtained from Laurent Bouchet. Stellar distributions are generated by Muazzam Ali using the “Galaxia” code developed by Sanjib Sharma. All-sky flux distributions and all results are modelled, produced and generated using algorithms developed by Muazzam Ali.

The bulk of this research and parts of Chapter 3 were submitted to the Monthly Notices of the Royal Astronomical Society as a paper entitled “The influence of Galactic structures on positron annihilation and propagation” on the 15th of June 2012. On the 2nd of July 2012, the paper was accepted with major revision requested; it has since not been revised and resubmitted and will have to be submitted anew. The submitted paper is attached as an appendix; it was modelled, plotted and written entirely by Muazzam Ali, where some ideas, advice and support were given by the listed co-authors.
Chapter 5 is a conclusion to the thesis and discussion of future work written by Muazzam Ali.

10/12/2015
Abstract

Galactic positrons are mostly observed indirectly from the products of their annihilation. The 511 keV photons produced by their annihilation remain the most convincing probe into their origin as they move relatively unperturbed through the interstellar medium. Presently, observations of these $\gamma$-rays are conducted exclusively by space-borne instruments to avoid the atmospheric background but these measurements can be difficult, costly, and, due to the energies involved, have inherently poor resolution. The current iteration of one such experiment is ESA's INTEGRAL satellite which measures $2 \times 10^{43} \, e^+ \, s^{-1}$, primarily originating from the central region of the Galaxy with a low-flux background permeating the disc; there have been suggestions that the $e^+$ flux favours negative longitudes in either the peak or the disc flux. These observations have revealed no obvious source that can account for the radiation, and the source of Galactic positrons is still intensely debated. This study takes a holistic approach to the problem, focusing on the nature and limitations of $\gamma$-ray observations, the large scale distribution of stars involved in positron nucleosynthesis in the Galaxy and positron propagation in the interstellar medium. We use detailed density models of stars and their Galactic distribution, including the bulge/bar, thin and thick discs, to produce a density-dependent measurement of the expected flux from positron nucleosynthesis in these stars. After introducing positron propagation, we generate maps of relative Galactic annihilation flux for our models and correlate these to observations of Galactic 511 keV morphology, investigating the connection between stellar distribution and positron annihilation morphology. While considering negligible $e^+$ diffusion in the bulge/bar, we find that the natural peak in luminosity flux to be at $l_0 = -0.35$ deg, for a bulge/bar tilt angle of 11.1 deg, at a FWHM of 6 deg. This produces a negative to positive flux ratio of 1.1, providing a mechanism for a central 511 keV flux asymmetry. Although this asymmetry is unconfirmed, our results suggest that a smooth distribution of $e^+$ annihilation sources in an extended population can be attributed to the natural distribution of stars in the Galaxy without requiring any asymmetric sources. Furthermore, we perform a best-fit between our models of relative $e^+$ flux and Galactic disc and 511 keV data, finding a best-fit for stars in the Galaxy older than 8 Gyr, i.e., classes of older stars with a diffusion length of 1.5 kpc. Although, this trend in age has a low statistical significance and could suggest a combination of young and old sources cannot be ruled out. Finally, given a diffusion of 1.5 kpc, the initial $e^+$ kinetic energy we estimate to be between 100 – 200 keV. For positron nucleosynthesis, this energy corresponds most closely to the radioactive decay of...
$^{22}\text{Na}$, which occurs predominantly in novæ, and $^{26}\text{Al}$, from massive stars. Additionally, if we consider that positrons partially lose momentum when escaping their supernovæ sources, there may also be contributions from $^{56}\text{Ni}$ and $^{44}\text{Ti}$. 
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Galactic positrons $e^+$ are only observed indirectly from the products of their annihilation (Prantzos et al., 2011). Since its launch in 2002, the spectrometer aboard the INTEGRAL satellite, SPI, has observed the all-sky 511 keV positron annihilation signal. From these data it is estimated that there are $\approx 2 \times 10^{43} e^+ s^{-1}$ annihilating in the Galaxy. SPI has an angular resolution of $\approx 3$ deg and the all-sky morphology of the signal indicates a high bulge to disc luminosity ratio and hints at an asymmetry towards negative longitudes (Weidenspointner et al., 2008). Although there are possible sources that can account for the majority of the $e^+$ flux, at present there is no obvious $e^+$ source that can account for the Galactic 511 keV morphology. This could either mean that the source of positrons is yet to be conclusively identified or that positrons may diffuse far from their sources before annihilation. The only source of 511 keV to be directly observed is the sun (Murphy et al., 1987), but positrons are also seen indirectly by the $\gamma$-rays produced in the radioactive decay of elements.

The major issue in positron research is the inherently poor resolution of experiments which can detect them, making it extremely difficult to identify point sources of annihilation. Constructing models that predict positron production and propagation and comparing them to observations is a useful tool to help us better understand likely sources of positrons in the Galaxy. In Chapter 2, we explore the basics of $\gamma$-ray detection including experimental techniques, telescopes and limitations. There are many sources and observations that have been linked to positron production in the Galaxy. In Chapter 3, we explore 511 keV line and continuum observations and discoveries, positron production processes in the Galaxy, including sources of positron nucleosynthesis, and explore the large scale distribution of these stellar sources in the Galaxy. In Chapter 4, through detailed models of stars and their Galactic distribution, we produce models of stellar $e^+$ production by nucleosynthesis stars and, after considering positron propagation, we compare $e^+$ stellar sources in our model to the observed Galactic 511 keV $e^+$ annihilation flux. The discussion and conclusions are presented in Chapter 5.
The sky has been revealed to be rich in high-energy phenomena. The most compact and energetic objects in our universe, such as neutron stars, stellar and massive black holes, supernovæ, active galactic nuclei (AGNs), γ-ray bursts (GRBs) and cosmic rays all have large emissions in the γ-ray spectrum. Some of these, such as radio pulsars, quasars and GRBs have their peak luminosities at γ-ray energies. From pioneering balloon experiments to the space-based detectors to the hundreds of square kilometre arrays on the ground, we have been able to explore the nature of these objects, the most energetic in the universe.

In this chapter we review experimental techniques and obstacles, processes responsible for producing γ-rays, past and present experiments and finally discoveries, implications and the future. It is only from this background that we will be able to provide detailed insight into how the 511 keV positron annihilation line signature can be connected to the source of Galactic positrons.

2.1 Introduction

The energy band of γ-ray astronomy begins at the rest energy of an electron, 511 keV to the current observation limits of \( \sim 100 \) EeV. The field can be separated into two broad observational domains; space-borne/high altitude and ground based. Space-borne/high altitude covers energies ranging from 500 keV to approximately 100 GeV. In this energy range γ-rays cannot penetrate the Earth’s atmosphere without being absorbed and scattered, and so can only be detected above the atmosphere using satellite or high-altitude balloon experiments. Ground based observations begin at energies above 100 GeV and end at the highest energy particles that have ever been detected, cosmic rays at 100 EeV. In this energy range, huge showers of particles are produced in the atmosphere due to incoming γ and cosmic rays which we detect from ground based telescopes.
2.2 Instrumentation obstacles

Although γ-ray astronomy has opened a new and fascinating window in astronomy, it has developed quite slowly as a field of astronomy. This is primarily due to three factors: first, fluxes from celestial objects are low, sometimes orders of magnitude lower than for other energy ranges; second, conversion lengths of γ-rays in detector materials are high, hence, massive and large area detectors are essential for observations; third, the use of reflection and refraction in order to focus a beam is not practically feasible at γ-ray energies above 500 keV, which is why the angular resolution achieved by existing telescopes is inferior for γ-rays than other fields in astronomy (Schönfelder, 2001).

In every band of the electromagnetic spectrum astronomical telescopes make use of the fact that the cosmic rain of photons can be concentrated by reflection or refraction, so that the dimensions of the actual photon detector are a small fraction of the telescope aperture. Above a few MeV there is no efficient way of reflecting γ-rays; hence the dimensions of the γ-ray detector are effectively the dimensions of the γ-ray telescope (Weekes, 2001).

2.2 Instrumentation obstacles

2.2.1 The atmosphere

Fundamental problems arise for γ-ray observers performing astronomical observations below ∼ 100 GeV. The primary issue is the opaqueness of the atmosphere at these energies. At 1 MeV, the absorption probability for a γ-ray is > 99.8% (Schönfelder, 2001), therefore cosmic γ-rays cannot be observed directly at the surface of the Earth. Direct measurement γ-ray telescopes, then, must be brought above the atmosphere. Once above ∼ 100 GeV, indirect observations can be performed with ground based telescopes.

2.2.2 γ-ray fluxes

Another obstacle for observation of celestial γ-rays are their relatively low flux. The energies of γ-rays are millions of times more than optical photons, therefore fewer γ-rays are needed to transport this energy. Although these are the most energetic processes known in the universe, the number of γ-rays generated are small compared to other regions in the EM spectrum, leading to low γ-ray fluxes. These low fluxes mean that γ-ray telescopes must have a large effective area and long observation times in order to collect sufficient γ-rays. Furthermore, γ-rays are highly penetrating particles with small cross sections and therefore require thick detectors with sufficiently high stopping power to achieve a reasonable detection probability (area matter density of the order 10 g cm$^{-2}$ (Schönfelder, 2001)). So γ-ray telescopes consist of large heavy detectors, making space-based observations via balloon or rocket difficult. It therefore follows that, due to the large detector size, there is a substantial increase in the intrinsic background of the telescope.
2. GAMMA-RAY ASTRONOMY

2.2.3 Intrinsic background and suppression

At high altitudes, \(\gamma\)-ray telescopes are permanently irradiated by cosmic rays and other particles in the radiation belts of the Earth. These often interact with the telescope material producing excited nuclei, prompt \(\gamma\)-rays, neutrons and delayed \(\gamma\)-rays. The charged particle background causes ionisation along the path travelled in the material, which can be combated by surrounding the detector with a thin (usually plastic) scintillator. When a charged particle passes through the scintillator, a light pulse is emitted and measured by photomultipliers. Using the anti-coincidence method most, if not all, of the charged particle background is removed. The neutral background, from neutrons and \(\gamma\)-rays, is much more problematic, to the extent that distinguishing neutrons from \(\gamma\)-rays is a difficult exercise. A particle with enough energy incident on the telescope material can cause the activation of atomic nuclei and the decay of natural radioactive elements. The interaction depends on the amount of matter and the reaction cross sections, so reducing both of these is a primary concern.

Passive suppression techniques, such as surrounding the instrument in lead or similar, are effective \(\gamma\)-ray absorbers but also effective producers. Adding more lead increases absorption and production of \(\gamma\)-rays, which makes the whole process redundant and ultimately acts to increase the intrinsic background. Instead, active suppression techniques are employed using high density high stopping power scintillator materials, for example, CsI and NaI on the SMM (Forrest et al., 1980).

The significant neutral background component from neutron induced \(\gamma\)-rays is removed by using a technique called pulse shape discrimination (PSD). \(\gamma\)-rays produce electrons via their electromagnetic interactions and neutrons produce protons via their nuclear interactions. This produces distinct light-pulse patterns due to the differing decay times of the \(\gamma\)-rays produced in the scintillator materials, which can be measured and used to suppress the overall neutron induced \(\gamma\)-ray background.

![Figure 2.1: The relative importance of the major forms of \(\gamma\)-ray interactions with matter as a function of energy and atomic number of the material involved (Murthy and Wolfendale, 1993).](image)
2.3 Gamma-ray processes

Gamma-rays are neutral, high energy, highly penetrating particles. The only way to gain information about on their energy and origin is to induce an interaction in the detector material and observe the results. The three main processes that occur are the photoelectric effect, Compton scattering and pair production, all of which are dominant at different energies, as shown in Figure 2.1. In all three processes charged particles (e\(^+\), e\(^-\)) are created which can then be measured by particle detectors; a \(\gamma\)-ray detector must have a sufficiently high density (stopping power) to increase the chance of an interaction and must also generate a sufficient number of charged particles for measurement.

2.3.1 The photoelectric effect \((E \lesssim \text{300 keV})\)

The photoelectric effect occurs when a \(\gamma\)-ray interacts with a bound electron in such a way that it transfers all of its energy to the electron. Some of the energy is used to overcome the electron binding energy and the remainder is transferred to the freed electron as kinetic energy and a tiny amount of recoil energy to the atom to conserve momentum. The newly created photoelectron is absorbed into the active material of the detector, which emits a small output pulse, the amplitude of which is proportional to the energy deposited by the photoelectron. By adding this to the electron binding energy (which appears as characteristic x-rays) in coincidence, the resulting output pulse is proportional to the total energy of the incident gamma ray (Reilly, 1991).
Figure 2.4: Pair production; incident photons near an atomic nucleus are annihilated producing electron positron pairs.

2.3.2 Compton scattering \((300 \text{ keV} \lesssim E \lesssim 8 \text{ MeV})\)

In Compton scattering, a photon interacts with an unbound electron and can gain all or part of the energy and momentum of the \(\gamma\)-ray. In practice the \(\gamma\)-ray may Compton scatter several times before eventually undergoing photoelectric absorption. In each scatter, the electron gains some of the energy as kinetic energy and the \(\gamma\)-ray will change direction. Due to the various interactions that can occur, there is a loss of information of the incident \(\gamma\)-ray and in this way, Compton scattering is considered the most complex of the three interactions, and hence the most complicated for detectors (Weekes, 2001).

2.3.3 Pair production \((E \gtrsim 8 \text{ MeV})\)

Pair production involves the complete annihilation and energy transfer of \(\gamma\)-rays to \(e^+ - e^-\) pairs;

\[
h \nu \rightarrow e^+ + e^-.
\]  

(2.1)

The positrons predominantly annihilate with an electron to produce two more \(\gamma\)-rays, which then go on to Compton scatter or suffer photoelectric absorption in the material of the detector. By measuring the energy of the \(e^+ - e^-\) pair and taking into account their rest mass, the \(\gamma\)-ray energy can be estimated (Weekes, 2001).

2.4 Detection properties

2.4.1 Angular Resolution \((\Delta \Omega)\)

The angular resolution or imaging capability of a telescope refers to the obtainable spatial resolution of the incoming particles to be detected. The usual method for imaging high energy X-rays employs the use of passive collimators, high density materials which can absorb the incoming photons with a high cross section of interaction. As discussed in Section 2.2.3, when used in \(\gamma\)-ray detectors, the secondary particles emitted within the passive collimator materials
generate background radiation which can be quite difficult to combat and ultimately results in a reduced angular resolution. Thus, passive collimators are not used exclusively in γ-ray telescopes. Instead, the use of active collimators in scintillator materials is employed (see Section 2.2.3), although imaging resolutions is still only at 12 arc seconds at best (the IBIS imager aboard INTEGRAL, Winkler et al., 2003).

2.4.2 Energy Resolution ($\Delta E$)

Gamma-rays detected in a spectroscopic system produce peaks in the spectrum, the width of which are determined by the energy resolution of the detector. Again, due to the background present at γ-ray energies, the energy resolution is quite poor and the background difficult to combat. Typical energy resolution is quoted with respect to the γ-ray energies being observed. For example, one of the highest energy resolution detectors is the Spectrometer aboard INTEGRAL (SPI, Winkler et al., 2003), which has $\Delta E/E \approx 0.2\%$ between 20 keV and 8 MeV OR an energy resolution of $\Delta E \approx 0.4$ keV at 20 keV and $\Delta E \approx 160$ keV at 8 MeV.

2.4.3 Detector efficiency

Detector efficiency refers to the probability of interaction of the γ-ray with the detector producing a count. It is a measure of the required exposure time at a particular energy, where high-efficiency detectors produce spectra in less time than low-efficiency detectors.

2.5 Detectors and Telescopes

In discussing telescopes and the detection techniques used to observe γ-rays, with a focus on the 511 keV positron annihilation line, the word ‘telescope’ refers to devices which combine multiple detector types and techniques to detect γ-rays more effectively. The composite function may be to improve angular or energy resolutions by minimising backgrounds or it may increase the effective energy range of the telescope. Some commonly used γ-ray telescopes and their function are described below.

2.5.1 Scintillators

Scintillation refers to the process whereby an incident γ-ray is absorbed in a material, resulting in the emission of a lower energy photon (desirably in the optical energy range). There are two types of scintillators; organic and inorganic. The former are based on atomic energy level transitions, while the latter are based transitions between the conduction and valence bands in the lattice structure of a crystal.

Organic scintillators can be in gas, liquid or plastic form. They generally have poor stopping power due to their low densities, thus have small cross sections of interaction with photons. However, due to their fast response times, they are ideal for use in the anticoincidence method.
of charged particle background rejection (e.g. plastic in the SMM and EGRET aboard CGRO, Forrest et al., 1980; Kanbach et al., 1988) and also in some cases the neutron PSD rejection method (see Section 2.2.3) in Compton telescopes (Schönfelder et al., 1993).

An electron in an inorganic scintillator gets excited into the conduction band with the passage of a charged particle through the lattice structure of the material, leaving behind a hole. When the electron eventually recombines with the vacant hole, depending on the incident energy of the γ-ray, a photon of a particular wavelength is emitted. In the ideal case, there would be perfect excitation, recombination with the lattice and the emitted photon would have a high intensity lying in the visible spectrum (for easy detection by photomultiplier tubes, PMT). Pure inorganic crystals are not ideal as they are inefficient at recombination, due to the large valence/conduction gap, and the emitted photons lie outside the visible wavelength (Schönfelder, 2001). By introducing small amounts of impurities (activators), that is by doping the inorganic crystals, the emission of visible photons can be enhanced.

After the visible photon is emitted, it suffers photoelectric absorption in the photocathode of the PMT which measures the magnitude of the charge deposited (see Figure 2.5). The initial number of photoelectrons liberated at the photocathode is proportional to the amount of light incident on the phototube, hence is proportional to the amount of energy deposited in the scintillator by the initial γ-ray (Reilly, 1991). This is an efficient process, but the main disadvantage of scintillators is their relatively poor energy resolution caused by photoelectron creation requiring at least 100 eV leading to an energy resolution of just a few percent.

**OSO-3 (E ≳ 50 MeV)**

In 1967, the Orbiting Solar Observatory (OSO-3) replaced the first γ-ray satellite Explorer-XI, which was decommissioned after only a four month run in 1962 (Kraushaar and Clark, 1962). Its primary instrument was an X-ray telescope aimed at observing solar flares and the cosmic diffuse X-ray background, but it also had a γ-ray instrument which operated for 16 months before a tape recorder failure. Like Explorer IX, OSO-3 was aimed at detecting γ-ray energies above 50 MeV. To achieve this, its construction consisted of three key elements, a stacked
scintillator crystal (CSI/NaI) sandwiched by layers of tungsten and a lucite Čerenkov detector, both of which allowed the reduction of the solid angle between the $e^+ - e^-$ pairs and obtain the incident $\gamma$-ray directions, and a plastic anti-coincidence scintillator shield to remove the CPB (See Figure 2.6). OSO-3 succeeded in detecting 628 $\gamma$-rays and these results provided the first piece of evidence to suggest the existence of a cosmic diffuse $\gamma$-ray background (Kraushaar et al., 1972).

Figure 2.6: The OSO-3 telescope (Kraushaar et al., 1972).

2.5.2 Solid-state detectors ($E \gtrsim 4$ MeV)

In solid-state detectors, the $\gamma$-rays are identified by the charge produced from the photon interactions directly. The active volume is a semiconductor material in which liberated electrons
and holes can move freely. When a photon ionises an electron-hole pair, electrodes detect the ionisation charge which gets converted to a voltage pulse. The $\gamma$-ray energy resolution of these detectors is better than that of scintillation detectors; only a few eV are necessary for the generation of an electron-hole pair in a semiconductor. Solid-state detectors offer several other important advantages; they are small in size, they offer fast response time and have a high absorption probability. However, a disadvantage is they are difficult to use in space due to sensitivity to radiation damage and the need for low-temperature operation.

Solid-state detectors are produced mainly in two crystal configurations: coaxial and planar. The most commonly encountered detectors are coaxial; their radial electric field makes them better for fast timing applications, and they achieve large detection efficiencies. Planar crystals have either a rectangular or a circular cross sectional area, achieve the best energy resolution and are preferred for detailed spectroscopy analysis. Table 2.1 gives a summary of common semiconductor materials and their properties. The most commonly used material in gamma-ray astronomy is High Purity Germanium (HPGe), due to ideal electronic characteristics of a low energy gap which allows for high energy resolution when taking measurements. However, this also leads to ineffectiveness at room temperatures. Due to the small band gap energy, many electron-hole pairs are generated from thermal excitation creating a large leakage current which is higher than the one produced by the $\gamma$-rays to be measured. Therefore, Ge detectors must be cooled to very low temperatures, requiring expensive cooling mechanisms. Silicon has a low photoelectric efficiency which makes it effective at measuring low energy $\gamma$-rays less than 50 keV but sensitivity to high energy $\gamma$-rays is greatly reduced.

Other solid-state detection media besides germanium and silicon have been applied to gamma-ray spectroscopy. It would be advantageous to have high-resolution detectors operating at room temperature, thereby eliminating the cumbersome apparatus necessary for cooling the detector crystal. Operation of room-temperature semi-conductor materials such as CdTe, Hg12, and GaAs has been extensively researched (Sakai, 1982).

### 2.5.3 Pair-tracking spark chambers ($E \gtrsim 30$ MeV)

These telescopes are designed to work for energy ranges above 30 MeV (Pinkau, 2009), where the dominant interaction process of the $\gamma$-ray photons is pair production. Interactions within the stack of metal plates produces electron and positron pairs which travel through the spark
chamber, ionising the gas along their flight path. This method is known as “pair-tracking”. Specifically, the telescope consists of: the conversion region, a stack of thin metal plates with high atomic number e.g. tungsten and tantalum; a pair tracking device, which is a gas-filled spark chamber thin metal plates or wires; and the telescope device, two plastic scintillators. After the spark chamber, the pair interacts with two thin plastic scintillators producing photons which are measured by phototubes. Using the coincidence method, a trigger pulse is generated along the electron positron ionisation trajectory. This pulse is used to fire the spark chamber by applying a high voltage to its wires or metal plates. Because of the inertia of the ionisation of the gas within the spark chamber, a spark will break through along the ionisation path. The positions of these sparks can be recorded optically or electronically. Electron-positron pairs form V-shape tracks and the direction of the incident $\gamma$-ray can be reconstructed from the bisector of the angle (Schönfelder, 2001).

The ingredients of the spark chamber gas degrade with each recorded event, as they are cracked by the sparks. This reduces the sensitivity of the instrument as the tracks become less well traced and reconstruction becomes difficult and inaccurate. Replacing the gas can combat this issue, however, when used on satellites, the chamber’s lifetime is limited by the amount of gas available on board. The basic structure of a pair-tracking telescope is a spark chamber, surrounded by an anti-coincidence shield (combating the charged particle background), a Čerenkov detector integrated with the trigger (distinguishes between upward and downward moving $e^+$ and $e^-$) and a calorimeter where the electrons and positrons can deposit their final energies (Schönfelder, 2001). The most recent pair-tracking spark chamber is the EGRET satellite shown in Figure 2.7.

### 2.5.4 Compton telescopes ($0.1 \text{ MeV} \lesssim E \lesssim 10 \text{ MeV}$)

Compton telescopes are devices designed for operation in the 100 keV to 10 MeV range (Weekes, 2001). They consist of two detectors placed in series: a primary $\gamma$-ray Compton scatters in the material of the first detector, and is then absorbed in another Compton scatter in the second detector. There is also an anti-coincidence scintillator around the second detector to remove the charged particle background. Because of the wide range of angles that the scattering may
have after interaction with the first detector, the angular resolution is quite poor. However, the wide field of view makes them very powerful for all-sky surveys (Schönfelder, 2001). The basic improvement to the single-stage process saw these telescopes widely used in the early years of γ-ray astronomy (Weekes, 2001). The first Compton telescope ever built had an angular resolution of 30° and an energy resolution of ∼50% (Herzo et al., 1975; Schönfelder et al., 1973). Schönfelder (1982) had an angular resolution of ∼10° and energy resolution ∼25%.

The satellite instrument COMPTEL, was the most successful application of a Compton telescope. It was the first breakthrough in low energy γ-ray which was previously only conducted on balloon borne experiments (Schönfelder, 2001). The primary γ-rays are incident within ±40° of the telescope axis; they first Compton scatter in the upper detector, a low-Z liquid scintillator, and then enter the lower detector, a high-Z NaI(Tl) scintillator. Each detector consists of seven modules and the separation between the two layers is 1.5 m. A varied time of flight can be used to discriminate against upward going particles. In addition, all of the detectors are surrounded by thin plastic anti-coincidence scintillators which respond to charged particles. If the energy deposited in the upper and lower modules is measured, then the direction of the incident γ-ray can be determined with an angular resolution of 3-5° and an energy resolution of about 5-10%.

From studies with the imaging Compton telescope instrument (COMPTEL) aboard the Compton Observatory (1991 - 2000), $^{26}$Al emission has been mapped all along the plane of the Galaxy (see Figure 3.2). From these measurements it was concluded that massive stars dominate $^{26}$Al production (Diehl et al., 1995). $^{44}$Ti nucleosynthesis was also observed in the Galaxy for the first time (Schönfelder et al., 1973).
2.5.5 High energy γ-ray astronomy \((E \gtrsim 50\text{ GeV})\)

At high enough energies γ-rays can penetrate the atmosphere and be detected through secondary phenomena. When charged particles created during pair-production enter the atmosphere at speeds higher than the local speed of light, Čerenkov photons are emitted and observed by ground based photomultipliers. γ-rays at energies even higher, produce huge pair showers and are observed even before Čerenkov photons are emitted using scintillation techniques.

High energy \((\gtrsim 100\text{ TeV})\) Cosmic rays, consisting of about 90\% protons, 9\%α-particles, 1\% electrons and other heavier charged nuclei, incident on the atmosphere can also produce these observable phenomena, thus it can be challenging to differentiate between incident cosmic rays and γ-rays. Much like γ-rays, lower energy cosmic rays can be observed through primary detection techniques in space and experiments sometimes share the same instruments.

2.6 The International Gamma-Ray Astrophysics Laboratory (INTEGRAL)

Launched in 2002, ESA’s INTEGRAL mission was to image and observe spectra of high energy X-rays and low energy γ-rays. It achieves this through two primary instruments; an imager and a spectrometer.

The INTEGRAL Imager on-Board the INTEGRAL Satellite (IBIS), observes from 15 keV to 10 MeV with an angular resolution of 12 arc mins (Bird et al., 2010). The Spectrometer for INTEGRAL (SPI), observes radiation between 20 keV and 8 MeV with an angular resolution of \(~3\text{ deg FWHM}\) and an spectral energy resolution of 2.1 keV FWHM, both at 511 keV (Vedrenne et al., 2003).

INTEGRAL has been able to conduct all-sky observations of low and high-mass X-ray binaries and Microquasars etc; measure \(^{26}\text{Al}\) throughout our galaxy, demonstrating that the Milky Way produces, on average, about two supernovae per century; and produced an all-sky 511 keV positron annihilation emission distribution, indicating Galactic longitudinal asymmetry mapping and imaging 511 keV and continuum (Weidenspointner et al., 2008). The details of 511 keV observations will be explored and discussed extensively in Chapter 3.

2.7 Discussion

At low energies (keV - MeV), the atmosphere interferes with γ-rays entering the upper atmosphere, and as such telescopes in balloons and satellites are used to observe these photons. This can take years of planning, can be quite costly and limiting to the scale and lifetime of the instrument. At high energies (GeV - TeV), we can measure the products of γ-rays interacting
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with the atmosphere to determine the origin and energy of the incident particles. In this way, the atmosphere of the Earth can behave like a giant telescope for high energy photons and cosmic rays. These two approaches enable the sources of the highest energy processes in the universe to be explored. For a brief history of γ-ray astronomy see Appendix A.

This study focuses on 511 keV and source Galactic positrons, which currently relies on data from the SPI, the spectrometer aboard the INTEGRAL satellite. While the INTEGRAL mission continues, it is well past its expected lifetime and the future of this field research will require the development of a successor to SPI/INTEGRAL. One such proposal is the higher resolution DUAL experiment (Boggs et al., 2010). It is composed of a Wide-field Compton telescope (WCT) and a broad band Laue-Lens Telescope (LLT) maintained by two separated spacecraft flying in formation at the lens’ focal distance. The novel focusing instrument has a proposed energy resolution of $< 1\%$ at 511 keV due to the smaller volume of the focal plane and the reliable background subtraction possibility.

There is also the possibility of observing a signal from electronic transitions of Positronium that occur at lower energies, e.g Ps $\alpha$ (1.313 $\mu$m) and Ps Ly$\alpha$ (2413 Å). At these wavelengths the atmosphere is quite bright in OH, but through OH suppression or space-based observation with the proposed James-Webb Space Telescope, it may be possible to probe high energy phenomena with the increased resolution of low energy telescopes (Ellis and Bland-Hawthorn, 2008; Mohorovičić, 1934). At present though, the data obtained by the INTEGRAL spacecraft is the most accurate measure of the positron interactions occurring deep within the Galactic centre.
Galactic positrons have only been observed indirectly from the products of their annihilation (Prantzos et al., 2011). At high γ-ray energies, positrons are observed as ‘cosmic rays’ where their origin and energy can be traced quite easily (Hinton, 2009; Sinnis, 2009). However, at low γ-ray energies they are only observed by the 511 keV photons produced by their annihilation which is much more difficult to trace (Prantzos et al., 2011). The 511 keV observations indicated a large flux coming from the Galactic centre and led to the hypothesis of a single major source of Galactic positrons, e.g. the Galactic Super-Massive Black Hole (SMBH), Sgr A*, acting as a ‘Great Annihilator’. However, spectroscopic observations from the CGRO/OSSE in the 1990s indicated that the X-ray flux of the SMBH was too low to be responsible for the associated 511 keV flux (Prantzos et al., 2011). While this issue would be later circumvented by the possibility of Sgr A* variability and a non-steady state 511 keV signal, the difficulty is that there is no obvious source accounting for the observed 511 keV morphology (Prantzos et al., 2011).

In modelling positron sources, due to the large uncertainties involved and the complicated nature of the processes that occur (Weidenspointner et al., 2008), a convenient simplification is to assume minimum propagation from birth to annihilation. This simplification is not unreasonable because some Galactic environments can cause catastrophic energy loss and subsequent annihilation (Jean et al., 2009). However, since its launch in 2002, SPI aboard the INTEGRAL satellite has provided high quality spectroscopic data which has placed more constraints on the possible environments in which Galactic positrons annihilate. With these new insights it has become increasingly necessary to use more rigorous models of propagation and annihilation.

In this chapter, we summarise the results of 511 keV observations, detail some processes responsible for positron production, estimate the production and distribution of some stellar sources and compare observed stellar populations responsible for positron nucleosynthesis to 511 keV observations.
3.1 511 keV Observations

Positrons and electrons form a short-lived atom called Positronium (Ps) before they eventually annihilate together, producing γ-rays. Due to invariance under charge conjugation, a single atom of Ps will produce either three (orth-Ps) photons or two (para-Ps) photons as it decays. The former case occurs 75% of the time producing continuum radiation and the latter, occurring 25% of the time, produces 511 keV γ-rays.

The first confirmed report of 511 keV γ-rays coming from electron (e−) - positron (e+) annihilation in astrophysical environments was from the Solar Maximum Mission aboard the OSO-7 satellite (Chupp et al., 1973). Concurrent extrasolar observations of γ-rays at similar energies were also made by several balloon-borne experiments focusing on the Galactic Centre (GC) region (Johnson et al. 1972; Johnson and Haymes 1973; Haymes et al. 1975). After several years, 511 keV from e− - e+ annihilation within 15 deg FWHM of the GC was confirmed as the source region (Leventhal et al., 1978).

Today, the INTEGRAL satellite observes the 511 keV sky and, using the spectrometer for INTEGRAL (SPI), it has the highest angular (∼ 3 deg FWHM) and spectral (2.1 keV FWHM at 0.5 MeV) resolution of any instrument at these wavelengths (Vedrenne et al., 2003). Using the 511 keV photon flux, \( F_{511} = 1.71 \times 10^{-3} \) ph cm\(^{-2}\) s\(^{-1}\) (Prantzos et al., 2011), and the Positronium (Ps) fraction, \( f_{Ps} = 96.7 \pm 2.2\% \) (Jean et al., 2006), we can calculate the positron annihilation rate \( \dot{N}_{e^+} \) in the Galaxy via the relation (Purcell et al., 1997):

\[
\dot{N}_{e^+} \simeq \frac{4\pi R_\odot^2 F_{511}}{2 - 1.5 f_{Ps}} = 2.4 \pm 0.1 \times 10^{43} e^+ s^{-1},
\]  

where the distance to the Galactic centre is \( R_\odot = 8 \) kpc.

Imaging of the annihilation flux shown in Figure 3.1(a) is best modelled by a narrow ∼ 3 deg and a broad ∼ 11 deg bright bulge component along with a weaker flux thick disc with a vertical extent of ∼ 7 deg and a horizontal extent of ∼ 35 deg producing a bulge/disc flux ratio of ∼ 1.4 (Prantzos et al., 2011).

Spectral results of the 511 keV flux consist of a narrow line FWHM =1.3 ± 0.4 keV and a broad line FWHM = 5.4 ± 1.2 keV in a ratio of two to one thirds, respectively, where the broad line is in good agreement with that expected from positron annihilation from charge exchange with hydrogen atoms (Martin et al., 2012). Figure 3.1(b) shows the aforementioned components along with the ortho-Ps continuum, indicating that positrons are indeed annihilating through the formation of Ps, and specifically showing a Ps fraction of 96.7 ± 2.2%. Finally, there is a power source which accounts for the Galactic diffuse continuum emission, where the MeV continuum shown has been attributed to cosmic ray electrons and positrons (Prantzos et al., 2011).

In recent times there has been interest in a new aspect of the 511 keV morphology, whereby
the radiation flux appears to favour negative Galactic longitudes by \( \approx 1.8 \) times (Weidenspointner et al., 2008). The exact nature, or even the existence of, the asymmetry is still under dispute with a significance of \( 4\sigma \), and there have been suggestions that it is seen in either the inner disc emission (Weidenspointner et al., 2008), the central peak emission (Bouchet et al., 2010) or from flawed background treatment (Churazov et al., 2011). An inner disc asymmetry (\(|l| > 10\ \text{deg}\)) is suggested to arise from the distribution of Galactic low-mass X-ray binaries (LMXB) (Weidenspointner et al., 2008) or spiral arm densities (Higdon et al., 2009). A central asymmetry is suggested to arise from a longitudinally off-centred peak in 511 keV, modelled at \( l \approx -0.6\ \text{deg}, b \approx 0\ \text{deg} \) (Bouchet et al., 2010; Knödlseder et al., 2005), although, apart from our analysis (as detailed in Chapter 4), there have been no suggested mechanisms for this.

Theses observations can be summarised by four main features (Prantzos et al., 2011):

- The \( e^+ \) annihilation rate in the Galaxy is at least \( 2 \times 10^{43} \)\( e^+ s^{-1} \) originating predominantly from the bulge.

- The bulge to disc ratio of the annihilation rate is \( B/D \sim 1.4 \), but this would decrease if there was an, as yet, undetected low surface brightness component in the disc.

- The ratio of the 511 keV line to the \(< 511\ \text{keV}\) continuum indicates a high Positronium fraction of \( \sim 97\% \). The observed \( \sim \) MeV continuum can be mostly explained by inverse Compton emission by cosmic ray electrons, although a small fraction from Cosmic ray positrons cannot be ruled out. The amplitude of the MeV continuum can constrain the energy of the injected electrons, once cosmic rays are considered there is little room for considerable contribution of high energy \( e^+ \) sources.
3.2 Production mechanisms

Positrons can be produced by several different Galactic processes and associated phenomena. Many of these can be eliminated as likely candidate sources of the Galactic positron budget due to observational constraints. We first review and analyse some of the processes and sources that produce positrons and then compare them to the observed Galactic annihilation budget.

Production mechanisms can be broadly categorised into four main groups (Guessoum et al., 2005).

- $\beta^+$ decay of radioactive nuclei, e.g., explosive and/or hydrostatic nucleosynthesis environments of novæ, supernovæ, Wolf-Rayet and Asymptotic Giant Branch stars.
- Pair-production from photon-photon interactions, high energy photons in the environment of luminous compact objects, e.g., black hole candidates, micro-quasars, active galactic nuclei, X-ray binaries etc.
- $\pi^+$ decay to $\mu^+$, giving off $e^+$, $\pi^+$ produced in cosmic ray collisions with protons ($\gtrsim 200$ MeV).
- Pair-production of an electron in strong magnetic fields, common in the environments of pulsars/neutron stars.

As we will discuss in detail later in the chapter, observations of 511 keV spectra have put constraints on the energies of positrons contributing to the Galactic budget, limiting them to the lower energy products of radioactive decay and pair production from photons, i.e., the first two points above. Furthermore, the only sources definitely known to produce large quantities of $e^+$ are from nucleosynthesis. Without ruling out other processes, positron nucleosynthesis in stars and associated Galactic phenomena will be the main processes considered in Chapter 3.

3.2.1 Nucleosynthesis

$\beta^+$ decay of radioactive elements produced in stars and their environments is expected to produce a Galactically significant amount of positrons. The primary decay species include, $^{26}$Al, $^{44}$Ti, $^{56}$Ni, and $^{22}$Na. The mean kinetic energy ($KE$) of the ejected positrons are low enough ($\lesssim 1$ MeV) to satisfy the MeV continuum constraint.

$$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+ + \gamma \ [1809 \text{ keV} \ (1)]$$

Produced in stars, predominantly by proton capture on $^{25}$Mg, $^{26}$Al is unstable with a mean lifetime of $\tau_{26} = 1.04 \times 10^6$ years and decays to $^{26}$Mg plus positron emission (mean $KE \approx 445.7$ MeV).
An environment rich in protons, at sufficiently high temperatures can potentially produce large amounts of \(^{26}\text{Al}\). Proton-rich environments include: \textit{hydrostatic} hydrogen burning in the cores of high mass stars \((\geq 11M_\odot, T > 4 \times 10^7 \text{ K})\), the hydrogen shell of low and intermediate mass stars \((\leq 9M_\odot, T \sim 5 - 9 \times 10^7 \text{ K})\); \textit{explosive} hydrogen burning in high mass stars, and on the surfaces of white dwarfs in novae explosions. The O-Ne-Mg rich subclass of white dwarfs are rich in Mg as well as protons. Other Mg-rich environments are in \textit{hydrostatic} \((T \sim 1 \times 10^9 \text{ K})\) or \textit{explosive} \((T \sim 2 - 2.5 \times 10^9 \text{ K})\) carbon and neon burning shells of massive stars. After production, \(^{26}\text{Al}\) is ejected in part by strong winds \(\text{i.e. Wolf-Rayet and asymptotic giant branch stars}\) and in full by explosions \(\text{core collapse supernovae and novae, Diehl and Timmes, 1998; Prantzos and Diehl, 1996}\).

After decaying to \(^{26}\text{Mg}\), the first excited state of \(^{26}\text{Mg}\) de-excites by producing a 1.809 MeV photon. The detection of these photons by the HEAO-3 satellite in 1982 was the first ever detection of radioactivity in \(\gamma\)-rays \(\text{Mahoney et al., 1982}\). Observations made by its successor COMPTEL aboard the Compton Gamma Ray Observatory \(\text{CGRO}\) reveal a Galactic flux of \(3.2 \times 10^{-4}\text{ ph cm}^{-2}\text{ s}^{-1}\text{ MeV}^{-1}\), distributed predominantly in the plane of the Galaxy shown in Figure 3.2 from Diehl and Timmes \(\text{1998}\). In a steady-state this implies a total Galactic \(^{26}\text{Al}\) mass of \(M_{^{26}\text{Al}} \sim 3M_\odot\) however this value does not take into account the contributions from local hotspots of activity, \text{i.e. nearby star clusters} \(\text{Diehl et al., 1995}\). Recently, more accurate spectroscopic and photometric observations of 1.809 MeV have been taken by SPI aboard Integral. Models including this dependence on Galactic distribution have suggested Galactic mass yields of \(M_{^{26}\text{Al}} = 2.8 \pm 0.8 M_\odot\) \(\text{Diehl et al., 2006}\) and \(M_{^{26}\text{Al}} = 2.7 \pm 0.7 M_\odot\) \(\text{Wang et al., 2009}\), where the error range reflects the dependence. In addition to Galactic distribution there has been some development in modelling massive star clusters such as the Cygnus and Sco-Cen complexes, which adjusts the stationary Galactic \(^{26}\text{Al}\) mass yield to \(M_{^{26}\text{Al}} = 1.7 - 2.0 \pm 0.2 M_\odot\) \(\text{Martin et al., 2009}\).

Figure 3.2 shows the all-sky distribution of 1.809 MeV due to \(^{26}\text{Al}\) from COMPTEL. This was the first map of 1.809 MeV along the plane of the Galaxy. From these data, it was concluded that massive stars dominate \(^{26}\text{Al}\) production \(\text{Diehl et al., 1995}\). Bright regions such as Cygnus suggest that even before the core collapse substantial \(^{26}\text{Al}\) is ejected in the Wolf-Rayet phase of massive stars \(\text{Knödlseder et al., 2004}\). In comparison, novae and AGB stars, which are also candidate sources for \(^{26}\text{Al}\) production, probably provide only a small contribution of the 23 \(M_\odot\) of \(^{26}\text{Al}\) in the Galaxy \(\text{Diehl, 2007}\).

These observations, both photometric and spectral, have been modelled with Galactic stellar distributions and used to constrain the mass yields and hence the possible sources of \(^{26}\text{Al}\) mentioned above. Specifically, these sources are low- and high-mass Asymptotic Giant Branch stars \(\text{lAGBs and hAGBs}\), Novae, Core-Collapse Supernovae \(\text{CCSNe}\) and Wolf Rayet stars \(\text{WRs}\). The \(^{26}\text{Al}\) and \(e^+\) production rates of these various sources will be discussed in detail in Section 3.3. We assert that each of them individually \(\text{except lAGBs}\) has the theoretical potential to pro-
produce the total expected Galactic $^{26}$Al yield and discuss how the spatial distribution of the 1.809 MeV signature, as shown in Figure 3.2, has been used to discriminate between these sources. Naturally, this method requires that $^{26}$Al travels only a few hundred parsecs in its $\sim 10^6$ year lifetime, such that the radioactive species can be traced back to its origin. The distribution is mostly planar ($b \lesssim 10$ deg) and does not especially favour the Galactic bulge regions and the flux distribution appears to have several discrete or clumpy sources as opposed to being smooth or continuous. The planar nature and lack of a bright bulge rules out any classes of old populations and the lack of smoothness rules out any class with a high number of low individual yield sources, i.e. IAGBs and novae (Prantzos and Diehl, 1996). Of the remaining sources there are high uncertainties associated with $^{26}$Al production, particularly in hAGBs and WRs, suffice to say that explosive yields (i.e. CCSNe) are thought to dominate hydrostatic yields (i.e. massive stars before CCSNe, hAGBs and WRs, Chieffi and Limongi, 2006), although this may only be in the low-metallicity outer regions of the Galaxy (Tur et al., 2010).

The mass yields of $^{26}$Al as well as the decay fraction to $^{26}$Mg can also be used to calculate the expected positron yield from the decay. Its $e^+$ annihilation rate ($\dot{N}_{26}$) is found via:

$$\dot{N}_{26} = 0.82 \times \frac{M_{26} N_A \lambda}{A_{26}} = 1.7 - 4.0 \times 10^{42} \text{e}^+ \text{s}^{-1},$$  \hspace{1cm} (3.2)

where the decay rate $\lambda = 1/\tau$, the atomic number $A_{26} = 26$ g mol$^{-1}$, $N_A$ is Avagadro’s number and we use a stationary mass (mass per unit decay time) of $M_{26} = 1.5 - 3.5 M_{\odot}$ Myr$^{-1}$.

Similar to the above arguments on constraining $^{26}$Al sources, we can use what we know of 511 keV to constrain $^{26}$Al as a positron source. From Equation 3.2, we see that the Galactic $^{26}$Al yield produces an $e^+$ production rate that is 5 - 10 times too low to be the only Galactic source.
3. POSITRONS IN THE GALAXY AND 511 KEV

Furthermore, the observed 511 keV distribution appears to be smooth with a bright bulge and the only $^{26}$Al sources that meet that requirement are the old, low-yield IAGBs and novae, both of which are considered as unlikely sources of the 1.809 MeV decay line because of these two properties. Undoubtedly, $^{26}$Al decay must contribute to the Galactic $e^+$ budget, but this can only be significant in the case of their young disc sources which may contribute to the entire observed 511 keV disc emission. Interestingly though, an old population of many low yield $e^+$ sources might be an appropriate candidate source for the observed 511 keV.

$^{44}$Ti → $^{44}$Sc$^* + \gamma [68 \text{ keV (0.94)}, 78 \text{ keV (0.96)}]$

$^{44}$Sc → $^{44}$Ca$^* + \gamma [1157 \text{ keV (1)}] + e^+$

$^{44}$Ti has a mean lifetime of 89 years, its daughter $^{44}$Sc decays almost immediately to $^{44}$Ca plus a positron with a mean $KE = 597.2$ keV. The positron is thus released into the envelope of the exploded star and, unless accelerated to $\gtrsim 100$ MeV by supernovæ shocks (Martin et al., 2012), propagates with a relatively unchanged energy into the ISM. $^{44}$Ti was first observed in $\gamma$-rays coming from Cassiopeia A, initially via the decay of its daughter nuclei $^{44}$Sc producing 1157 keV photons (COMPTEL, Iyudin et al., 1994) and subsequently by the 68 and 78 keV lines as well (OSSE, The et al., 1996). Approximately 300 years old, it is most likely a type Ib supernovæ remnant producing $\approx 1.6 \times 10^{-4} \text{ M}_\odot$ (SPI, Diehl, 2013). It has also been detected in the late light curve of SN1987A, at a steady-state mass of $0.520 \times 10^4 \text{ M}_\odot$ (Fransson and Kozma, 2002).

In massive stars, $^{44}$Ti is most probably produced in the “$\alpha$-rich freeze-out” in high temperature burning near Nuclear Statistical Equilibrium (NES) occurring in CCSNe (Woosley et al., 1973). The production yield of these events have many uncertainties including the reaction rates (The et al., 1996), the explosion mechanism (Timmes et al., 1996) and asymmetries in the explosion (Nagataki et al., 1998). The latter of these has increased the theoretical production of $^{44}$Ti in Cas A from the predicted $\sim 10^{-9} \text{ M}_\odot$ in the symmetric model to the actual observed value above.

The low yield dependence on asymmetry and relatively low frequency of events leaves room for sources with much larger yields. The foremost of these are sub-Chandrasekhar limit SNIa events which, through He explosions on the surface of the white dwarf involved, predict 10-20 times the yield of $^{44}$Ti than CCSNe although the frequency of these events are unknown.

Taking into account Galactic chemical evolution of the $^{44}$Ca/$^{40}$Ca ratio, the rate of $^{44}$Ti production in the Galaxy is somewhere between $1.2 - 12 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1}$ (The et al., 2006). Using Equation 3.2 for a steady state mass yield and a mean decay time $\tau_{44} = 89$ years we find the Galactic positron yield $\dot{N}_{44} = 0.1 - 1 \times 10^{43} e^+ \text{ s}^{-1}$.
 Much like $^{44}\text{Ti}$, $^{56}\text{Ni}$ is produced in the interiors of CCSNe and thermonuclear supernovae explosions through explosive Si-burning. It has a mean life $\tau_{56} = 120$ days and hence a very low positron escape fraction of somewhere between 1 − 10% (Martin et al., 2012), where the $\beta^+$ decay branching ratio is 0.18 and mean value of the energy distribution is 126.1 keV.

Regardles of the well constrained observations of $\gamma$-rays arising from $^{56}\text{Ni}$ decay, the number of escaped positrons is not easy to constrain due to the fact that they are born within the explosive environment. Their escape fraction is greatly reduced by a strong, tangled or turbulent magnetic field structure, a high ionisation fraction of the ejecta, or ejecta not mixing well before decay leaving the positrons to travel outward from the innermost layers of the explosion (Martin et al., 2010). These scenarios would leave positrons mainly annihilating within the remnant before the resultant $\gamma$-rays escape into the ISM, adding to the Galactic budget.

From the analysis of SNe light curves, the $^{56}\text{Ni}$ yield per SNIa event is $\approx 0.6 \ M_\odot$ (taken from Tycho, Kepler, SN1006 and G1.9 + 0.3, Martin et al., 2010) and for SNII is $\gtrsim 0.07 \ M_\odot$ (taken from Cas A and SN1987A, Martin et al., 2010). Computing Equation 3.2 for SNII:SNIa = 0.9 : 0.1 × [2.4 − 2.7] per century, we find that for an escape fraction of 6.0 ± 0.5% we obtain a Galactic yield of $\approx 2.3 \pm 0.2 \times 10^{45} \ e^+ \ s^{-1}$ (depending on SNE rate and SNII:SNIa fraction). At 5% this becomes $\approx 85\%$ of the Galactic positron budget and at 1% this becomes $\approx 17\%$.

The 6% escape fraction result is close to the 5% obtained by Higdon et al. (2009) for an exclusive Galactic $\beta^+$ from $^{56}\text{Ni}$ model as well as the value obtained by Chan and Lingenfelter (1993) for the W7 deflagration model of Nomoto et al. (1984) (i.e. no ejecta mixing and a radial magnetic field). Furthermore, it is also consistent with the 5.5% obtained by Milne et al. (1999) for the W7 model (i.e. a radial or weak magnetic field and a 1% ionisation of the ejecta).

$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + \gamma [1275 \text{keV}(1)] + e^+$

$^{22}\text{Na}$ is expected predominantly from novae. It has a mean lifetime $\tau_{22} = 3.75$ years and 90% of the time has a decay branch to $\beta^+$ with a mean energy 215.9 keV. Observations from COMPTEL limit the mass ejected by any ONe novae to $3.7 \times 10^{-8} \ M_\odot$ (Iyudin et al., 1995). It has a short lifetime and an expected $e^+$ production rate of $\sim 1.5 \times 10^{41} \ e^+ \ s^{-1}$ at a mean energy of 215.9 keV (Martin et al., 2012; Prantzos et al., 2011).

### 3.3 Possible sources

Positrons produced by other radioactive processes not discussed above are not considered to significantly contribute to the Galactic budget. Furthermore, we have excluded some of the more
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exotic processes that may occur, e.g. dark matter annihilation, from this analysis, see Prantzos et al. (2011) for detailed study of possible sources. As will be explored further in Section 3.4, higher energy processes are not thought to contribute to the Galactic budget and either do not occur largely in the Galaxy or the positrons produced escape the Galaxy before they annihilate (Guessoum et al., 2005; Jean et al., 2009).

This section describes the classes of sources, which may involve one or more of the above processes, and compares the positron production from the source to positron observations. We have broadly categorised these sources into binary and accretion phenomena, high-mass high-energy stars, low-mass low-energy stars and non-stellar. When considering stellar sources, it is important to understand that many of these phenomena are connected and may produce substantial numbers of positrons at different stages of their stellar evolution. This becomes important in Chapter 4, where we explore large scale stellar models of the Galaxy involving considerations which include the age and structure of the Milky Way.

3.3.1 Binary phenomena

Thermonuclear supernovæ type Ia (SNIa)

The likely process involved in $e^+$ production in SNIa are from nucleosynthesis of $^{44}$Ti and $^{56}$Ni occurring from silicon burning deep within the explosions.

Using a $^{44}$Ti abundances of SN Ia = $0.87 - 2.7 \times 10^{-5} \, M_\odot$ per star and taking into account an SNe fraction of SN Ia:IIb/c:II = 0.1 : 0.15 : 0.75 for 2.4 - 2.7 SNe per century and including an extra factor of 3 on model predictions due to the chemical evolution predicted from $^{44}$Ca/$^{56}$Ca abundances (The et al., 2006), we can estimate the steady state $^{44}$Ti yield for SN Ia:

$$M_{44}^{SN Ia} = 3 \times 10^{-5} \, M_\odot \times \left( \text{events per century} \right) \times \frac{\text{mean life}}{\text{century}}$$

where all of the $^{44}$Ti is expected to escape in its 89 year decay time. The positron production rate is then calculated by Equation 3.2, $\dot{N}_{44}^{SN Ia} = 0.1 - 0.2 \times 10^{42} \, e^+ \, s^{-1}$, i.e. $\sim 1\%$ Galactic $e^+$. However, an alternative method using the Solar abundance of the more reliable $^{56}$Fe, where $^{44}$Ca/$^{56}$Fe = $1.2 \times 10^{-3}$ (Prantzos et al., 2011) and noting that SN Ia produce $^{56}$Fe $\approx 0.6 \, M_\odot$ per event (Chan and Lingenfelter, 1993), we can calculate a steady state mass of $^{44}$Ti $\approx 4 \times 10^{-4} \, M_\odot$ and a Galactic annihilation yield of $\dot{N}_{44}^{SN Ia} \approx 4 \times 10^{42} \, e^+ \, s^{-1}$, i.e. $\sim 20\%$ Galactic $e^+$. Thus, we see that $^{44}$Ti in SNIa could produce a very significant fraction of Galactic $e^+$.

As per Equation 3.3, we can similarly calculate the steady state mass of $^{56}$Ni and the positron ejection rate. Using the SN Ia abundance for $^{56}$Fe mentioned above, the steady state mass is $M_{56}^{SN Ia} = [0.6] \times [0.1 \times 2.4 - 2.7] \times 120 \, \text{days/century} = 5.0 \pm 0.3 \times 10^{-4} \, M_\odot$ and given an escape fraction of 6%, $\dot{N}_{56}^{SN Ia} = 1.2 \pm 0.1 \times 10^{43} \, e^+ \, s^{-1}$, i.e. 50% of the Galactic budget. Where,
3.3 Possible sources

Figure 3.3: a) Aitoff projection of SNRs, b) Histograms in Galactic longitude of SNRs (data obtained from Green, 2009).

for this escape fraction, the other 50% would originate from $^{56}$Ni nucleosynthesis in CCSNe. At an escape fraction of 1%, this drops to 10% of the Galactic annihilation rate but there have been several suggestions that the higher escape fraction is more reasonable (see Section 3.2.1).

The Galactic morphology of SNIa, taken from the catalogue of known supernovae remnants from Green (2009), is shown in Figure 3.3(a). The SNIa population is expected to be spread throughout the central Galactic bulge/bar and the thin and thick discs producing infrequent discrete bursts of positrons. Comparing this distribution to that of the 511 keV morphology, the positrons produced must propagate far enough from their origin and live long enough such that they can fill the entire bulge/bar volume in a relatively smooth distribution before annihilating. Higdon et al. (2009) produced a model where SNIa positrons achieve both of these conditions by escaping into the HII and HI envelopes of molecular clouds that lie within 1.5 kpc of the Galactic centre before they slow down and annihilate producing the observed 511 keV bulge to disc luminosity ratio.

Novae

Novae are the third most energetic explosions in the Galaxy, after GRBs and SNIa, but are far more common. Nucleosynthesis occurring in white dwarf accretion prior and during novae outbursts should result in many specific $\gamma$-ray line signatures and often associated $\beta^+$ decay. The importance of $\gamma$-rays from radioactive decay in novae was first pointed out by Clayton and Hoyle (1974), but as yet, none of the predicted lines have been observed because they are either too faint or too short lived. The extremely bright short-lived signals from $^{13}$N ($\tau_{13} = 862$ s) and $^{18}$F ($\tau_{18} = 158$ min) are the result of positrons annihilating with electrons in the opaque stellar environment. They are difficult to detect because the 511 keV and continuum signal arrive much sooner than the associated optical wavelengths and are diminished by the time the optical signature gives it away. Both CO ($\lesssim M_\odot$ progenitor) and ONe ($\gtrsim M_\odot$ progenitor) novae are expected to produce this signature (José and Hernanz, 2007). Occurring more commonly but
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![Image](image.png)

**Figure 3.4:** a) Aitoff projection of LMXBs, b) Histograms in Galactic longitude of LMXBs.

not limited to ONe is $^{22}\text{Na} \quad (\tau_{22} = 3.75 \text{ years})$ and $^{26}\text{Al} \quad (\tau_{26} = 1.04 \times 10^6 \text{ years})$ which decay to their own associated $\gamma$-ray lines, 1.275 MeV and 1.809 MeV respectively, where the resultant $e^+$ pass relatively unperturbed into the ISM.

An upper limit of $M_{22}^{\text{ONe}} = 3.7 \times 10^{-8} \text{ M}_\odot \text{ per ONe}$ and $M_{22}^{\text{CO}} = 3.749 \times 10^{-8} \text{ M}_\odot \text{ per CO}$ in the Galactic disc was observed by COMPTEL (Iyudin et al., 1995). Where the ratio of ONe:CO is $0.3 - 0.5 : 0.5 - 0.7$ of all novae which occur $35 \pm 11 \text{ per year}$ (Shafter, 1997).

**X-ray binaries (LMXBs, HMXBs)**

These binary systems involve a neutron star or black hole accreting matter from either a low-mass star ($< 4M_\odot$) producing a low-mass X-ray binary (LMXB) or a high-mass star ($> 4M_\odot$) producing a high-mass X-ray binary (HMXB), through an accretion disc. The Galactic distribution of known LMXBs is shown in Figure 3.4(a), where the data are taken from Bird et al. (2010). About 300 have been catalogued but their luminosity function suggests there may be closer to 3000 in the Galaxy. Shown in Figure 3.5(a), HMXBs are less populous in the catalogue and furthermore are also $\lesssim 10$ times as bright as LMXBs. Their distribution follows more closely the scale height of the thin disc as opposed to their low-mass companions, which follow the thick disc (Grimm et al., 2002; Prantzos et al., 2011).

Some XRBs exhibit radio emission, which is usually attributed to synchrotron radiation emitted by leptons (electrons, and perhaps positrons), which are launched along diametrically opposite jets fuelled by the accretion energy. If the jets are confirmed by imaging, the system is called a Microquasar ($\mu$Q), which we discuss further in the following section.

Pair production occurs in the vicinity of these compact objects, either in the hot inner accretion disc, in the X-ray corona surrounding the disc, or at the base of the jets (where some may escape the system). An alternative production mechanism can occur though secondary pair production of a relatively cold plasma jet at the termination shock with the ISM. Heinz and Sunyaev (2002)
noticed that the total kinetic luminosity of micro-quasar jets in the Galaxy, evaluated at $3 \times 10^{38}$ ergs $s^{-1}$, can produce up to $4 \times 10^{33} e^+ s^{-1}$ (using a 5% conversion efficiency of kinetic power), well above what is required from observations. In a similar study, Bandyopadhyay et al. (2009) considered hadronic jets (also containing lepton pairs) launched by all LMXRBs and estimated that a bulge population of $\approx 300 - 3000$ LMXRBs could produce the expected $e^+$ annihilation rate, $N_{LMXB} \approx 2 \times 10^{43} e^+ s^{-1}$, if there were $\sim 40 - 400$ electron-positron pairs per proton (Prantzos et al., 2011).

While these are promising signs for finding a Galactic $e^+$ source, apart from the uncertainties in yield, the issue of Galactic distribution is another hurdle. It was pointed out that the strongest XRB sources (accounting for 80% of the flux) are evenly distributed in the Galactic plane, whereas 511 keV is most concentrated in the bulge (Grimm et al., 2002; Prantzos, 2004). This can be explained by either the possibility of a non-steady state distribution or the positrons produced annihilate far from their birthplaces in the bulge/bar (Prantzos et al., 2011). Despite this, Weidenspointner et al. (2008) peaked interest in LMXBs more recently when they pointed out the similarity between the morphological asymmetry in 511 keV data and an asymmetry in the distribution of LMXBs observed at hard X-ray energies.

We have produced and modelled the all-sky distribution in Figure 3.4(b), where the data are taken from Bird et al. (2007). It can be seen that the significance of the asymmetry in LMXB population and brightness is much less than that of the asymmetry in the 511 keV radiation (Skinner, 2010) and may be coincidental (Bandyopadhyay et al., 2009). Furthermore, Figure 3.4(b) shows that the known LMXB asymmetry lies well into the Galactic disc; in the nearby annihilation case, it may not account for the 511 keV asymmetry if confined to the Galactic centre as suggested by Bouchet et al. (2010), or the result may simply be a red herring if the 511 keV morphological asymmetry is simply due to a modelling error (Churazov et al., 2011, see Section 3.1 and Chapter 4 for a more detailed analysis of the asymmetry.)
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Microquasars ($\mu$Qs)

Microquasars ($\mu$Qs) are XRBs that exhibit jets frequently, but not continuously. These jets may contribute significant numbers of lepton pairs. However, the physics of $\mu$Qs is extremely complex and there is no generally accepted model at present. For example, the content of the jets, leptonic or baryonic (i.e. electron-positron pairs, electron-ions or pions-protons), is unknown at present. Even if positrons are largely present, it is not known whether they may be ejected at ultra-relativistic velocities. If so, there are obvious implications for in-flight annihilation and the limits placed on production of $>1$ MeV $\gamma$-ray continuum. Finally, calculations of positron yield that depend on the correlation between the power of the jet, the X-ray luminosity of the compact object, and the ratio between the two (often assumed to be small), is highly uncertain (Guessoum et al., 2006; Prantzos et al., 2011).

Guessoum et al. (2006) explored various scenarios and estimated $e^+$ production for existing theoretical models; they estimate an average value of up to $N_{\mu Qs} \approx 10^{41} e^+ s^{-1}$ for a jet. If 100 $\mu$Qs exist in the Milky Way, a reasonable extrapolation from Bird et al. (2010), then these objects may contribute substantially to the observed 511 keV emission. Their Galactic morphology is shown in Figures 3.6(a) and 3.6(b); there is some clustering toward the inner galaxy, but the data are insufficient for statistically significant conclusions.

Interestingly, the presence of an annihilation line signature in misaligned $\mu$Qs (where the jet impinges on the companion star) could produce an interesting observational signature in the characteristic light curve that could be obtained from close enough and/or strongly active sources with more sensitive $\gamma$-ray observations (Guessoum et al., 2006).
3.3 Possible sources

3.3.2 High-mass (or young) stars

Pulsars (and Magnetars)

After the high-mass progenitor star suffers thermonuclear detonation in a supernovæ explosion, these objects produce high-energy radiation and/or strong magnetic fields which are associated with intense $e^- - e^+$ pair creation. The pairs are further accelerated in parallel electric fields in the polar caps or in the outer gaps close to the light cylinder. The interaction of secondary photons produced by the primary particles yields a pair cascade, which can eventually escape into the pulsar wind (Prantzos et al., 2011).

The main problem with compact magnetised objects being candidate $e^+$ sources, is the expected high energy of the produced positrons $> 30$ MeV which violates the constraint from the continuum MeV emission observed in the inner Galaxy (Prantzos et al., 2011). This does not exclude the possibility that they may produce significant numbers of positrons that contribute to the thick disc emission in some way (see Figure 3.7(a) and 3.7(b)). However, those positrons do not annihilate significantly within the Galaxy and must instead escape into the intergalactic medium.

Core Collapse supernovæ (CCSNe)

The likely process involved in $e^+$ production in CCSNe are from nucleosynthesis of $^{26}\text{Al}$, $^{44}\text{Ti}$ and $^{56}\text{Ni}$. Using a $^{44}\text{Ti}$ abundance of SN IIb = $3 - 9 \times 10^{-5}$ M$_\odot$ and SN II = $1.5 - 4 \times 10^{-5}$ M$_\odot$ per star and taking into account an SNe fraction of SN Ia:IIb/c:II = 0.1 : 0.15 : 0.75 for 2.4–2.7 SNe per century and including an extra factor of 3 on model predictions due to the chemical evolution predicted from $^{44}\text{Ca}/^{40}\text{Ca}$ abundances (The et al., 2006), the estimated steady state $^{44}\text{Ti}$ yield for CCSNe is $\approx 1 - 3.5 \times 10^{-4}$ M$_\odot$, producing $\dot{N}_{^{44}\text{CCSNe}} \approx 1 - 3 \times 10^{42}$ e$^+$ s$^{-1}$, i.e., $\approx 10\%$ of the galactic budget.
3. POSITRONS IN THE GALAXY AND 511 KEV

We can also calculate the steady state mass of $^{56}$Ni and the positron ejection rate. Using a CC-SNe abundance for $^{56}$Fe of 0.07 per star (Prantzos, 2011), the steady state mass is $M^{CCSNe}_{^{56}Ni} = [0.07] \times [0.75 \times 2.4 - 2.7] \times 120$ days /century = $4.7 \pm 0.3 \times 10^{-4}$ M$_\odot$ and given an escape fraction of 6%, $\dot{N}^{CCSNe}_{^{56}Ni} = 1.0 \pm 0.1 \times 10^{13}$ e$^+$ s$^{-1}$, i.e. $\approx 50\%$ of the Galactic budget. For this escape fraction, the other 50% would originate from $^{56}$Ni nucleosynthesis in SN Ia. Thus, although the errors are not well constrained, using this escape fraction, positron nucleosynthesis from $^{56}$Ni in both SNIa and CCSNe could easily account for the total Galactic budget of annihilated positrons. At an escape fraction of 1% this drops to 10% of the Galactic annihilation rate but there have been several suggestions that the higher escape fraction is more reasonable (see Section 3.2.1).

The relatively young age of the progenitor stars mean that CCSNe lie in the disc of the Galaxy (see Figures 3.3(a) and 3.3(b)). Without providing a transport mechanism, another contributing bulge/bar source or a non-steady state 511 keV scenario, CCSNe cannot account for total Galactic e$^+$ budget.

3.3.3 Low-mass (or old) stars

Giant branch stars (RGBs, lAGBs, hAGBs)

As low-mass star evolve off the main sequence into Red Giant Branch stars (RGBs) and Asymptotic Giant Branch stars (AGB) so too do their positron yields.

Low-mass AGBs (lAGBs) evolve from progenitor mass stars between $\sim 1 - 4$ M$_\odot$, i.e. $\sim$ 0.09 of all stars, at a Galactic rate of $f_{lAGBs} \sim 5 \times 10^5$ stars Myr$^{-1}$. Their positron contribution is expected mainly from $^{26}$Al decay where a single $\sim 3$ M$_\odot$ IAGB produces $\sim 10^{-8}$ M$_\odot$ of $^{26}$Al. Roughly translated this equates to total Galactic $^{26}$Al production rate of $\dot{M}_{lAGBs} \sim 5 \times 10^{-3}$ M$_\odot$ Myr$^{-1}$ and a positron production rate of $\dot{N}_{lAGBs} \sim 6 \times 10^{39}$ e$^+$ s$^{-1}$, i.e. a factor of $\sim 3 \times 10^3$ lower that the Galactic yield (Forestini et al., 1991; Prantzos and Diehl, 1996).

High-mass AGBs (hAGBs) evolve from progenitor mass stars between $\sim 4 - 9$ M$_\odot$, i.e. $\sim$ 0.005 of all stars, at a Galactic rate of $f_{hAGBs} \sim 3 \times 10^4$ stars Myr$^{-1}$. Their positron contribution is expected mainly from $^{26}$Al decay through convective envelope burning of the hydrogen shell where on average a single hAGB produces $\sim 10^{-5}$ M$_\odot$ of $^{26}$Al. This is significantly larger than their low mass counterparts but occurs less frequently. Roughly translated this equates to total Galactic $^{26}$Al production rate of $\dot{M}_{hAGBs} \sim 1$ M$_\odot$ Myr$^{-1}$ and a positron production rate of $\dot{N}_{hAGBs} \sim 1 \times 10^{41}$ e$^+$ s$^{-1}$, i.e. a factor of $\sim 20$ lower that the Galactic yield (Bazan et al., 1993; Prantzos and Diehl, 1996).

hAgbs alone could account for a non-negligible portion of the Galactic e$^+$ yield. However the estimate given represents the best-case scenario, and there are considerable uncertainties associated with convective mixing which could reduce hAGB yield to IAGB amounts. Furthermore, the younger hAGBs would occur almost exclusively in the disc whereas the 511 keV dominates
the bulge, so their contribution to the Galactic $e^+$ budget is expected to be seen only in the disc emission. This leaves IAGBs, which could possibly be a very low yield bulge source. However in studying their $^{26}$Al source potential, their low-yield smooth distribution does not seem to follow the 1.809 meV line and morphology, which is very clumpy in the disc and seems to favour young stars in star-forming regions (Martin et al., 2009; Prantzos and Diehl, 1996).

### 3.3.3.1 Other Sources

There are still a number of non-stellar sources that could be responsible for positron annihilation in the Galaxy, but we do not consider more than a few here as there are many possibilities with significant uncertainties.

An interesting possible source is the Galactic Super-Massive Black Hole (SMBH), which became popular when 511 keV was discovered. The emission originating from the Galactic centre was thought to originate from the so called ‘Great Annihilator’. Its relatively low X-ray luminosity compared to LMXBs saw it lose credibility as a likely source and later the MeV continuum condition seemed to be the final nail in the coffin for the SMBH. However, after SPI/Integral data, it drew interest again because of the failure of any other source to meet the Bulge/Disc luminosity ratio (Prantzos et al., 2011). With a non-steady state model of Galactic 511 keV, a past higher activity, coupled with a long $e^+$ life, could explain the observed 511 keV emission (Goldwurm, 2007; Totani, 2006). This past higher activity is supported by the suggestion that the Fermi bubbles may be a result of the Milky Way producing a Seyfert flare 1-3 Myr ago (Bland-Hawthorn et al., 2013). The main issue with this, and many other intriguing sources, is with constraining the large uncertainties.

### 3.4 Constraints on sources

Positrons can be produced by several different Galactic processes and associated Galactic phenomena, but many such sources have since been eliminated as likely candidate sources of the Galactic positron budget due to the aforementioned constraints. $\beta^+$ decay of $^{26}$Al and $^{44}$Ti are the only well established and constrained sources of $e^+$ in large amounts but there are also contributions expected from other radioactive nuclei including $^{56}$Ni and $^{22}$Na (Prantzos et al., 2011). $^{26}$Al occurring in massive stars is propagated by stellar winds and core collapse supernovæ explosions (CCSNe). It decays to $^{26}$Mg in the interstellar medium (ISM) at a rate of $\sim 0.4 \times 10^{45} e^+ s^{-1}$ at a mean energy of 400 keV. $^{44}$Ti occurring in CCSNe and thermonuclear supernovæ explosions (SN Ia) is released into the envelope of the exploded star at a rate of $0.34 \pm 0.17 \times 10^{43} e^+ s^{-1}$ at a mean energy of $\sim 600$ keV, although it is possible that the positrons are accelerated to $\gtrsim 100$ MeV by supernovæ shocks. $^{56}$Ni is produced in CCSNe and SN Ia, its short lifetime means that the number and energy of positrons produced will be heavily influenced by propagation from the stellar ejecta and is therefore not well constrained with $\sim 0.31 - 3.1 \times 10^{43} e^+ s^{-1}$ at a mean energy $\lesssim 300$ keV after escape. $^{22}$Na produced by ONe novæ also has a short lifetime and an expected $e^+$ production rate of $\sim 1.5 \times 10^{41} e^+ s^{-1}$
3. POSITRONS IN THE GALAXY AND 511 KEV

at a mean energy of 215.9 keV (Martin et al., 2012; Prantzos et al., 2011). At these relatively low injection energies, all of these nucleosynthesis positrons fulfil the continuum constraint of $\gamma$-rays produced by in-flight annihilation.

Pair-production from photons in the accretion disc or at the base of the jets of low-mass X-ray binaries (LMXBs), $\mu$Qs and the SMBH at the Galactic centre (GC) also produce positrons of sufficiently low energy to meet the in-flight annihilation continuum constraint and can theoretically contribute to Galactic $e^+$ annihilation rate. Although there are uncertainties with the number of $e^+$ produced, their energy as well as specific propagation conditions for each prospective source, any of which could rule them out as significant producers of $e^+$. Nonetheless, any of these sources may provide the entire Galactic $e^+$ budget alone including the SMBH. To achieve this, the SMBH requires a non-steady state production versus annihilation situation, whereby the SMBH produced significantly more $e^+$ in its earlier life filling the entire bulge volume with $e^+$; the present annihilation rate is a reflection of this (Prantzos et al., 2011).

Candidate sources producing $\gtrsim 30$ MeV $e^+$ from pair-production of high energy photons in compact objects, such as black holes (BHs), micro-quasars ($\mu$Qs) and X-ray binaries (XRBs), or by electrons in strong magnetic fields in pulsars and magnetars, do not meet the in-flight annihilation continuum constraint and are thus considered unlikely to contribute to the Galactic $e^+$ budget. The same constraint puts limits on the mass of putative decaying or annihilating dark matter (DM) particles to $< 10$ MeV, but not on de-exciting DM particles (Prantzos et al., 2011).

3.4.1 Propagation and annihilation

Positrons born in dense, highly ionised or strong turbulent magnetic environments, suffer significant energy losses until they thermalise and annihilate. This will be the case for positron nucleosynthesis of short-lived species. The ones that escape lose energy through collisions with gas particles; $\sim 50\%$ (narrow 511 keV peak) through coulomb collisions with ionised gas and $\sim 50\%$ through collisional ionisation and excitation of neutral atoms (broad 511 keV peak). Once they have thermalised ($KE \lesssim 100$ eV), they annihilate with electrons by either direct annihilation with electrons, radiative recombination with free electrons or charge exchange with atoms. Depending on the local ISM properties, positrons can live from $\sim 10^4 - 10^8$ years. This can send positrons tens of kpc from their origin making them difficult to trace (Guessoum et al., 2005; Prantzos et al., 2011).

3.4.2 Energy loss and Annihilation sites in the Galaxy

Energy losses and annihilation of $e^+$ occurs with electrons, ions, atoms, molecules, solid dust grains, photons, and magnetic fields (Prantzos et al., 2011). Some of these have been directly imaged and can be compared to the 511 keV annihilation. Figure 3.8 shows the galactic distribution of molecular clouds, indicative of star forming regions, data are taken from Dame et al. (2001); Figures 3.9(a) and 3.9(b) shows the distribution of dust at different wavelengths (24, 70
3.5 Discussion and model development

![Figure 3.8](image1.png)

**Figure 3.8:** Carbon Monoxide histogram and map of relative flux seen by Dame et al. (2001).

![Figure 3.9](image2.png)

**Figure 3.9:** Histogram and maps of relative flux for Galactic plane dust surveys, (a) Mipsgal, 24 µm and 70 µm (b) Atlasgal, 870 µm.

and 870 µm imaged from the Multiband Infrared Photometer for Spitzer Galactic Plane Survey (MIPSGAL) and The APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) data. Histograms show relative flux data compressed in latitude in order to better visualise any longitudinal asymmetry that exists in the Galactic distribution. Although, there appears to be no correlation between 511 keV at this stage, it has been suggested that $e^+$ annihilation in dust grains may be significant (Guessoum et al., 2005, 2010).

### 3.5 Discussion and model development

There are many sources of positrons that have the potential to account for the Galactic budget. Using existing data, we have produced maps, histograms and in some cases projected flux of many of these sources and possible annihilation sites. We have calculated the expected $e^+$ annihilation flux contribution from the $\beta^+$ decay of various elements in the Galaxy as well as
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specifically in stars. Our analysis shows that several of these sources can potentially produce enough \(e^+\) to account for the entire budget alone (i.e. SNIa, LMXBs SMBH etc). However, due to large uncertainties in their distributions and also in \(e^+\) propagation, results remain inconclusive.

In observing 511 keV morphology we draw inspiration from the only other successful low energy \(\gamma\)-ray source finding mission, namely the 1.809 MeV signal from the radioactive decay of \(^{26}\text{Al}\) (Diehl et al., 2006). Observations of their discrete morphology lead to a connection to fewer high powered nucleosynthesis sources. Although, 511 keV observations have less angular resolution than the 1.809 MeV observations, there is still a noticeably indiscrete morphology of Galactic 511 keV. The corollary of the \(^{26}\text{Al}\) case may imply that the relatively smooth 511 keV morphology is more likely due to many sources in a smooth distribution in the Galaxy.

In the next chapter we explore the possibility of many sources of positron nucleosynthesis in the Galaxy and through modelling stellar distributions of the bulge/bar and disc and introducing positron propagation, we compare our results to 511 keV morphology and make some observable predictions.
The influence of Galactic stellar structures on the positron annihilation morphology

"Nothing is impossible if you can imagine it; that’s what being is a scientist is all about." - Professor Hubert J. Farnsworth

Abstract

The source of Galactic positron \( (e^+) \) annihilation emission remains elusive despite many years of investigation. We use synthetic models of the Galaxy to generate models of the Galactic positron source distribution from stars and make predictions about their observational consequences. We find unique signatures that stars in Galactic bulge/bar should have on the positron annihilation morphology, for example asymmetries in flux distribution, and make comparisons to observations. Our results apply to many \( e^+ \) sources in an extended bulge/bar population or fewer sources with diffusion into the bulge/bar volume. When including disc components, a \( \chi^2 \) analysis between the 511 keV data and our models, including both age and diffusion, yields a best-fit for a model composed of a bulge/bar, a thin disc older than 8 Gyr, a thick disc and stellar halo, and an overall diffusion of \( 1.5 \pm 0.7 \) kpc. We find limits that along with old bulge/bar sources, old disc sources may be responsible for a substantial portion of Galactic annihilation. Using this, we find limits for the initial \( e^+ \) injection energy of \( \approx 100 - 200 \) keV and suggest that \( e^+ \) of greater energies than this escape the thick disc and have a negligible contribution to Galactic annihilation.

4.1 Introduction

The first confirmed report of 511 keV \( \gamma \)-rays generated by electron - positron \( (e^- - e^+) \) annihilation in astrophysical environments was from the Solar Maximum Mission aboard the OSO-7 satellite (Chupp et al., 1973). Concurrent extrasolar observations of \( \gamma \)-rays at similar energies were made by several balloon borne experiments focusing on the Galactic Centre (GC) region (Johnson et al. 1972; Johnson and Haymes 1973; Haymes et al. 1975). After several years of
4.1 Introduction

experiments, 511 keV from $e^- - e^+$ annihilation originating from the GC was confirmed as the source (Leventhal et al., 1978).

Today, the INTEGRAL satellite observes the 511 keV sky and, using the spectrometer for INTEGRAL (SPI), it has the highest angular resolution ($\sim 3$ deg FWHM) of any instrument at these wavelengths, and measures a Galactic $e^+$ annihilation rate of $2 \times 10^{13} e^+ s^{-1}$ (Prantzos et al., 2011; Vedrenne et al., 2003). The radiation originates from the Galactic centre with a strong inner peak ($\lesssim 2 - 3$ deg), a weaker outer peak ($\lesssim 8 - 10$ deg) and almost insignificant disc (Martin et al., 2012). Through modelling the radiation, attempts have been made to ascertain a bulge (central peaks) to disc flux ratio and there have also been claims of a longitudinal asymmetry in flux favouring negative Galactic longitudes (Bouchet et al., 2010; Weidenspointner et al., 2008).

Until recently, imaging 511 keV from $e^+ - e^-$ annihilation was considered the only way to identify sources of Galactic $e^+$. This was based on the assumption that the spatial morphology of 511 keV followed the spatial distribution of $e^+$ sources, i.e. positrons annihilate near their production sites. Whilst there are many plausible candidates that may emit many $e^+$, reproducing the bulge/disc luminosity ratio for source distribution is far more difficult. A newer method involved analysing 511 keV spectra which showed that the positrons were annihilating at low energies (Prantzos et al., 2011). Many of the candidate sources produce high energy positrons; this could either mean that high energy positrons propagate significantly, lose energy and eventually annihilate generating 511 keV $\gamma$-rays or that these high energy positrons propagate far enough (Jean et al., 2009) that they escape the Milky Way and positrons produced at low energies are responsible for 511 keV.

Low energy $e^+$ are produced radioactively within stars and their explosions, i.e. $\beta^+$ decay of unstable nuclei in supernovae type Ia (SNIa), $^{56}$Ni; novae, $^{22}$Na; supernovae type II (SNII), $^{44}$Ti; massive stars, $^{26}$Al; etc. High energy $e^+$ are produced in processes occurring within strong magnetic fields, jets of accreting binary phenomena or from cosmic ray interactions (Bandopadhyay et al., 2009) i.e. pulsars, low and high-mass X-ray binaries (LMXBs and HMXBs, Weidenspointner et al., 2008), microquasars ($\mu$Qs, Guessoum et al., 2006) and the Galactic super-massive black hole (Totani, 2006). However, other more exotic sources such as dark matter annihilation (Bœhm, 2009) have not been ruled out as candidate sources (See Prantzos et al., 2011, for a comprehensive discussion of positron production processes).

Apart from SNII, the above mentioned stellar sources of $e^+$ are considered to be part of the old stellar population ($\gtrsim 10$ Gyr) and thus occupy the Galactic bulge/bar, thick disc and stellar halo regions of the Galaxy. The stars within these regions of the Galaxy or Galactic structures are modelled in several different configurations, including age constraints, and maps of stellar density within the Galaxy are produced. In each case, by applying the condition that each star within a region produces the same amount of $e^+$; this study examines the effects on Galactic $e^+$ production due to these structures. When $e^+$ annihilates nearby, a map of $e^+$ production due to stars will follow closely a map of their annihilation. After some modelling to find observational
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNIHILATION MORPHOLOGY

equivalence, this should predict the Galactic \( e^+ \) annihilation distribution including the 511 keV from those stars. This is the method followed in this chapter, both with and without diffusion, using best-fit Gaussian modelling and through direct \( \chi^2 \) analysis with data.

Motivation for this research comes in part from the relatively poor angular resolution of experiments at these \( \gamma \)–ray wavelengths compared to those in say the optical and near infrared. At these wavelengths, large volumes of the Milky Way are being sampled with high precision data of stars, for example the Hipparcos and 2MASS wide area surveys. Theoretically, a detailed enough knowledge of stars and their Galactic distribution allows for the formation of models predicting stellar \( e^+ \) production and their Galactic distribution. Already, surveys such as these allow theoreticians to produce self consistent models of Galactic structure, including the tilted central bulge/bar (López-Corredoira et al., 2005), the long thin bar (López-Corredoira et al., 2007) or tufts on the bulge/bar (Martinez-Valpuesta and Gerhard, 2011), the thin disc (now with only two major spiral arms, Churchwell et al., 2009), the thick disc and the stellar halo. Many of these structures have been combined into single self-consistent synthetic models of the Milky Way such as the model presented in Robin et al. (2003).

4.2 Methodology

Recently, Sharma et al. (2011) developed a code named \textsc{GALAXIA} to implement density and stellar parameter models of the large surveys, and allows one to generate smooth, wide area synthetic surveys in a fast and efficient manner. This study uses \textsc{GALAXIA} as a tool to efficiently sample large volumes of the Milky Way, generate a smooth distribution of stars, isolate different Galactic structures (e.g. the bulge/bar, thin disc, thick disc etc.) and find stellar properties such as age and metallicity.

Using the generated stellar distributions, we model various populations as “standard candle” of \( e^+ \) production, i.e. stars of the same population generate the same number of positrons, calculating the relative \( e^+ \) flux from stars along a particular line of sight. After considering positron propagation, we produce models that correlate the \( e^+ \) stellar source distribution to \( e^+ \) annihilation flux in the Galaxy.

Propagation of high energy positrons (\( \sim \) GeV) from cosmic rays is well understood (Strong et al., 2007), but due to the processes and large distances involved, any observational consequences to their morphology caused by the density distribution of their sources are difficult to observe. On the other hand, propagation of low energy positrons (\( \sim \) MeV) in a turbulent, magnetised interstellar medium (ISM) is very poorly understood (Prantzos et al., 2011), but possible effects on \( e^+ \) annihilation morphology from the density distribution of their sources may be seen. In the simplest case where positrons propagate \( \sim 0 \) kpc (Jean et al., 2006), they annihilate near their sources and our \( e^+ \) source flux map qualitatively becomes a map of \( e^+ \) annihilation due to stars. However, it is also possible that they travel large distances (\( > 1 \) kpc).
4.3 Modelling stars in Galaxy

Before annihilating (Higdon et al., 2009; Jean et al., 2009; Martin et al., 2012) making direct comparison to source flux impossible without considering diffusion.

Firstly, we use \textsc{galaxia} to sample Milky way stars using several configurations of age-bound Galactic structures and then use our algorithms to generate a map of positron production density. The structures we use include the bulge/bar and its longitudinal tilt, the thin disc, thick disc and stellar halo. Using the standard candle approach, we calculate flux from number density, distance to stars and apply approximations for $e^+$ propagations and annihilation. These are converted to comparable flux maps for 511 keV observations by SPI and are fitted for peaks, full-width at half maxima and bulge/disc ratio. We compare these to published studies of the 511 keV morphology, both for model fit parameters and least $\chi^2$ analysis, to 511 keV data provided by Bouchet et al. (2010). Finally, we predict positron diffusion length, energy of positron emission and ultimately the Galactic stellar populations responsible for positron emission.

4.3 Modelling stars in Galaxy

\textsc{galaxia} uses the same density functions as that of the Besançon model (Robin et al., 2003) and Padova Isochrones (Marigo et al., 2008) for generating stellar properties, a summary of these properties is shown in Figure 4.1. (see Sharma et al., 2011, for a detailed description of parameters).

4.3.1 The bulge/bar

A stellar density model for the Galactic bulge/bar is generated first and since Galactic stellar density peaks most strongly towards the GC, correct treatment of the bulge is crucial. Figure 4.2 is a rough sketch of the Galactic bulge/bar and its tilt with respect to the Sun-GC line. The distance to the GC is 8 kpc, the latitudinal tilt of the bulge/bar is close to zero but is set to $\beta = 3.5$ deg as defined in Robin et al. (2003). The longitudinal tilt of the bulge/bar, $\alpha$, is still a matter of conjecture (López-Corredoira et al., 2005, 2007; Martinez-Valpuesta and Gerhard, 2011; Robin et al., 2003) but for this paper we use the values prescribed in Robin et al. (2003), namely $\alpha = 21.1$ deg.

4.3.2 The disc

Along with the bulge/bar we have modelled several configurations of stars in the Galactic disc. Stellar classes are broken up into age-bound regions within the Galactic disc which loosely correspond to a disc with: a) the same old stars as in the bulge (bulge + thick disc stellar halo), b) different young stars than in the bulge (bulge + 0-7 Gyr thin disc) and c) all stars (bulge + thin disc + thick disc + stellar halo). These three regions allow us to make a distinction between the types of sources in the bulge/bar versus the Galactic disc. To apply these conditions to our model, we use the density functions described in Figure 4.1; defined herein as: the Bulge (10
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNihilation MORPHOLOGY

Geometry of Stellar Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Age (Gyr)</th>
<th>Density Law $\rho(r, z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin disk</td>
<td>$\leq 0.15$</td>
<td>$\frac{\rho_{\text{thin}}}{\rho_{\text{thin}}}$ \left(\exp\left(-\frac{(a/h_G)^2}{2}\right) - \exp\left(-\frac{(a/h_G)^2}{2}\right)\right)$</td>
</tr>
<tr>
<td>Thin disk</td>
<td>0.15–10</td>
<td>$\frac{\rho_{\text{thin}}}{\rho_{\text{thin}}}$ \left(\exp\left(-\frac{(0.5^2 + \frac{z^2}{h_G^2})}{2}\right) - \exp\left(-\frac{(0.5^2 + \frac{z^2}{h_G^2})}{2}\right)\right)$</td>
</tr>
<tr>
<td>Thick disk</td>
<td>11</td>
<td>$\frac{\rho_{\text{thick}}}{\rho_{\text{thick}}}$ \left(\exp\left(-\frac{(R_R^2)}{R_{\text{thick}}^2}\right) - \exp\left(-\frac{(R_R^2)}{R_{\text{thick}}^2}\right)\right)$</td>
</tr>
<tr>
<td>Spheroid</td>
<td>14</td>
<td>$\rho_{\text{sph}}(\tau = 14) \left(\frac{M_{\text{total}}}{M_\odot}\right)^{1/4}$</td>
</tr>
<tr>
<td>Bulge</td>
<td>10</td>
<td>$\rho_{\text{bulge}}(\tau = 10) \exp\left(-\frac{0.5r_e^2}{R_e^2}\right)$</td>
</tr>
<tr>
<td>ISM</td>
<td></td>
<td>$\rho_{\text{ISM}} \exp\left(-\frac{R}{R_{\text{ISM}}\times R_h}\right)$</td>
</tr>
<tr>
<td>Dark halo</td>
<td></td>
<td>$\rho_{\text{dark}} \frac{1}{\left(1 + (a/R_e)^2\right)}$</td>
</tr>
</tbody>
</table>

*Notes. The formulas used are from Robin et al. (2003). Note: $(R, \theta, z)$ are the coordinates in the galactocentric cylindrical coordinate system and $a^2 = R^2 + \frac{z^2}{h_G^2}$ (for the thin disk).

**Figure 4.1:** Properties of stellar components in the Galaxy from Robin et al. (2003) as used in GALAXIA. For the purposes of this thesis, the regions of the Galaxy used are defined as: the Bulge (10 - 14 Gyr), the Thin disc (0 - 10 Gyr), the Thick disc (11 - 14 Gyr) and the Stellar Halo (0 - 14 Gyr).
- 14 Gyr), the Thin disc (0 - 10 Gyr), the Thick disc (11 - 14 Gyr) and the Stellar Halo (0 - 14 Gyr) and together are used in modelling the entire Milky Way.

4.3.3 Morphology

Having established a working model of the stars in the Galaxy, we can identify the distribution of any particular class of stars based on its age. It is then possible to calculate the relative flux-density, or relative surface-brightness of the class for Galactic longitude and latitude. Before considering a full positron propagation scenario, this morphology would represent the case of nearby annihilation (as in the nucleosynthesis of $^{13}\text{N}$ ($\tau_{13} = 862$ s) and $^{18}\text{F}$ ($\tau_{18} = 158$ min) in novæ) multiplied by some normalisation factor.

4.3.3.1 Relative flux calculation

The data are computed as a histogram in $(l, b)$ space for a range of longitudinal bulge/bar tilt, $\alpha$, and a range of disc ages. By making the assumption that stars of the same class have the same luminosity, we can convert the number density histogram, $\rho_i(l, b)$, into a flux histogram, $\phi_i(l, b)$, by introducing the $1/r^2$ drop in flux for each star in the model. For each pixel $(i)$, the flux per unit solid angle ($F_i$) is calculated by computing the flux integral along the line of sight for a fixed solid angle ($\Delta\Omega$);

$$F_i(l, b) = \frac{\phi_i(l, b)}{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_0^\infty \frac{\rho(l, b, r)}{r^2} \Delta\Omega \, r^2 \, dr,$$

$$= \frac{1}{\Delta\Omega} \int \frac{1}{r^2} \rho(l, b, r) \, dV,$$

which can be reduced to a summation of each star $(j)$ in the cone divided by the solid angle of the cone:

$$F_i(l, b) = \frac{1}{\Delta\Omega} \sum_j \frac{1}{r_j^2},$$

(4.2)

where $\Delta\Omega = \Delta l \int_{b_{\min}}^{b_{\max}} \cos b \, db$ for each bin.

Thus, $F_i$ is a measure of the relative flux density observed at Earth for all the stars in the model, where the constant of proportionality corresponds to the number of photons produced by each star within a pixel and is assumed to be same for each population in question.

4.3.3.2 Gaussian fits and longitude profiles

Two Gaussian fitting algorithms are employed for both a bulge and a disc component, and longitude profiles are used to observe the effects of the bulge/bar tilt on flux. These models are used to produce a measure of the Galactic flux morphology.
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Figure 4.2: A sketch of the geometry of the Galactic bulge/bar as viewed from the Earth. The labels “l” and “b” indicate the direction of positive Galactic longitude and latitude respectively.
4.4 Results

A tilted bulge/bar has two noticeable features in projection (see Figure 4.2); the near-side produces a higher flux per particle/stars than the far-side because it is closer to us on the near side, and an enclosed volume for a light of sight will have more particles/stars on the far-side than the near-side because they appear more spread out on the near side. These effects produce two noticeable outcomes on the Galactic longitude flux profiles; the near-side of the bulge/bar appearing at positive longitudes has a low-flux tail that stretches out further than the far side at negative longitudes, and the peak in flux will occur slightly towards negative longitudes due to a greater density of stars than at positive longitudes. The measurable asymmetry caused by the two effects can be measured by taking the total positive vs negative flux of the distribution. In fitting to the bulge, we use a two-Gaussian model to account for the low-flux tail at positive longitudes and accurately find the position of the longitudinally off-zero shifted peak in flux.

Along with longitude profiles, we generate a 2D flux map of the surface brightness of the bulge/bar contribution and fit its morphology using this expression:

\[
f_{\text{bulge}}(l, b) = G_{B1} \times \exp \left[ -\frac{(l - l_{0B})^2 + b^2}{2\sigma_{B1}^2} \right] + G_{B2} \times \exp \left[ -\frac{(l - l_{0B})^2 + b^2}{2\sigma_{B2}^2} \right],
\]

where \( b_0 = 0 \) deg because the tilt in latitude of the bulge/bar \( \beta \approx 0 \) deg. We approximate the FWHM of the bulge/bar to be axisymmetric as there is minimal difference between height and width of FWHM.

Similarly, we find fits to the flux morphology of the disc contribution, where both \( l_0 = b_0 = 0 \), as the disc model is symmetric about the GC and we include the height and width, \( \sigma_{Dl} \) and \( \sigma_{Db} \), to encapsulate the flux morphology produced by the scale height of the disc and its planar extent, i.e.

\[
f_{\text{disc}}(l, b) = G_{D} \times \exp \left[ -\left( \frac{l^2}{2\sigma_{Dl}^2} + \frac{b^2}{2\sigma_{Db}^2} \right) \right].
\]

We then make a fit to the total Galactic flux using simply, \( f_{\text{tot}}(l, b) = f_{\text{bulge}}(l, b) + f_{\text{disc}}(l, b) \), and re-fitting for the amplitudes. Thus we can examine the relative flux contributions from stars of different classes, namely young vs old and bulge/bar vs disc stars.

4.4 Results

A synthetic model of the Galactic bulge/bar was generated using GALAXIA and applied for the different \( \alpha \) tilt angles. The flux of each pixel is calculated by taking into account the distance to each star from Equation 4.2 and the overall flux morphology and longitude profiles for \( b < |10| \) deg are shown in Figure 4.3; these represent positron flux from stellar sources. As we expect analytically, the longitude profiles show that the flux peaks are all offset from the Galactic ori-
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNIHILATION MORPHOLOGY

Figure 4.3: Positron flux generated from GALAXIA bulge/bar model data for varying longitudinal tilt, \( \alpha \).

Above: Longitude profile of the relative flux per unit solid angle for \(|b| < 10\) deg, longitudinal bin size is 0.1 deg and flux is normalised to \(F/F_{\text{max}}\) for \(\alpha = 11.1\) deg. The blue line represents model data, the red line represents the best-fit two gaussian model and the green lines are the individual gaussian profiles. \(l_0\) is the Galactic longitude at which the model’s peak flux occurs and the FWHM of the best-fit gaussian is displayed.

Below: The expanded version, a 2D histogram of flux where pixel size is 0.1 deg.

gin tending towards negative longitudes, \(l_0 = -0.35, -0.65, -2.25\) deg, increasing in negativity with an increase in bulge tilt, \(\alpha = 11.1, 20.0, 40.0\) deg. Additionally, the longitude profile shows the expected low-amplitude tail at positive longitudes again increasing with \(\alpha\). The combination of these two effects leads to a negative to positive longitude flux ratio of \(1.1 - 1.3\).

Our bulge/bar model is then fitted with the disc components described in Section 4.3.2. These have three components for bulge tilt, \(\alpha = 11.1, 20.0, 40.0\) deg, and three for disc age: old \(10 - 14\) Gyr, young \(0 - 7\) Gyr and all-ages \(0 - 14\) Gyr. Figure 4.4 shows the resultant positron flux maps, longitude profiles and some relevant fit parameters. The longitude profiles are normalised to the case with the brightest peak in flux, \(\alpha = 11.1\) deg and a \(10 - 14\) Gyr disc. Scale heights and widths of the disc components are listed in terms of their FWHM and relative flux brightness between the bulge/bar and the disc is denoted by the bulge:disc (B:D) value. Disc brightness depends on both the scale height/width and stellar density; an old disc has a greater scale height and lesser density than a young disc. The brighter the bulge/bar is with respect to the disc, the more confined the total positron flux will appear about the Galactic centre. For a bright bulge/bar (B:D \(\sim 10\)) this will be almost circular within \(\sim 8\) deg of the Galactic centre; for a dim bulge (B:D \(\sim 1\)) this will be elliptical and extend to within \(\sim 15\) deg in Galactic longitude. In either case we still see a shift in peak flux toward negative longitudes due to the bulge/bar, shown by the negative to positive (neg:pos) flux ratio.

Classes of these old bulge/bar stars are evenly distributed within the parameters of our model;
Figure 4.4: Model data generated using GALAXIA showing the relative positron flux per unit solid angle of the Galaxy due to stellar density. Rows show variation in bulge tilt angle; $\alpha = 11.1, 20.0$ and 40.0 deg. Columns show variation in disc component with age; an old disc: $10 - 14$ Gyr (thick disc + stellar halo), a young disc: $0 - 7$ Gyr (g thin disc) and the entire disc: $0 - 14$ Gyr (thin disc + thick disc + stellar halo). Pixel size is 0.1 deg and flux is normalised to peak flux of these figure which occurs for $\alpha = 11$ deg and the entire disc ($0 - 14$ Gyr). Best-fit parameters for the FWHM of the disc is displayed along with the bulge/disc flux ratio and negative:positive longitudinal flux computed within $|b| < 10$ deg and $|l| < 50$ deg. The longitude profiles are normalised to the case with the brightest peak in flux, $\alpha = 11.1$ deg and a $10 - 14$ Gyr disc.
thus, any class or combination of classes of stars produces the above positron flux morphology in the Galactic bulge/bar. There are two scenarios in which the Galactic structure present in our stellar density model is responsible for the Galactic positron annihilation; either many $e^+$ sources ($N_*$) in an extended semi-continuous bulge/bar population with nearby annihilation, or fewer discrete $N_*$ with diffusion into the bulge/bar volume where they annihilate.

### 4.5 Discussion

In the case of nearby or symmetric positron propagation our results show an asymmetry between negative and positive flux, generated from the shape and tilt of the Galactic bulge/bar. There have also been reports of asymmetries found in 511 keV annihilation data, these are not confirmed (Churazov et al., 2011), we compared our results to 511 keV data which shows similar asymmetry. Our models predict an excess flux at negative longitudes compared to positive ones of between neg:pos = 1.1 $-$ 1.3 for $|l| < 50$ deg. These values are within acceptable limits for those expected in Bouchet et al. (2010) ($1.1^{+0.4}_{-0.3}$) but less than in Weidenspointner et al. (2008) (1.8) times greater than positive. When $|l| > 50$ deg, our predicted flux is symmetric about longitude in agreement with Bouchet et al. (2010); Churazov et al. (2011). Along with excess negative flux, our model predicts a shift in the peak of the distribution away from $l = 0$ deg towards negative longitudes, $l_0 = -0.35, -0.65, -2.25$ deg for bulge tilt $\alpha = 11.1, 20.0, 40.0$ deg. Interestingly, one study of 511 keV data has claimed a shift in peak to $l_0 = -0.64^{+0.20}_{-0.19}$ although no mechanism has been suggested until now (Bouchet et al., 2010).

The FWHM of positron source flux is 6 deg, for the standard bulge/bar tilt of $\alpha = 11.1$, and the corresponding morphology expected from 511 keV positron annihilation in the Galactic centre is very similar (Martin et al., 2012). The model shows the relative $e^+$ flux generated from the number density distribution of Milky Way stars, however we must consider their transport when connecting the source distribution to the $e^+$ annihilation distribution. Understanding positron propagation in the MeV scale is a formidable challenge (Prantzos et al., 2011) with models predicting scenarios from $\sim 0$ to 30 kpc diffusion (Jean et al., 2009; Jean et al., 2006). In the simplest case where positrons propagate $\sim 0$ kpc, and our $e^+$ source flux map becomes a representative map of $e^+$ annihilation due to stars; all of our results thus far can describe the nearby annihilation of stellar positrons in the Galaxy. However, it is also possible that they travel large distances ($> 1$ kpc) before annihilating (Higdon et al., 2009; Jean et al., 2009; Martin et al., 2012) making direct comparison to source flux impossible without considering significant diffusion.

Without a single picture of positron diffusion in the Galaxy, for completeness we nevertheless wish to make some comparisons of our results with $e^+$ annihilation observations. We compute an approximation of diffusion and compare it to 511 keV positron annihilation data. The approximation of diffusion displaces a positron from its original stellar source position $(x, y, z)$ to an annihilation position $(x + \Delta x, y + \Delta y, z + \Delta z)$, where $\Delta x = \Delta y = \Delta z$, a random Gaussian.
number defined by a distance $\sigma$. Our treatment of the diffusion is a simple prescription that aims only at giving an average diffusion length for the entire Galaxy. In reality, of course, positrons injected in dense regions like the molecular ring will have a shorter range than those injected in the tenuous halo. We use this symmetric density-dependent model to directly compare 511 keV data to our models preserving the effects of Galactic structure on positron annihilation flux.

The 511 keV flux data along with errors provided by Bouchet et al. (2010) is used to perform a least $\chi^2$ analysis to our generated Galaxy models. In making comparisons, the flux data is converted to flux sr$^{-1}$ and the models are normalised to the maximum flux sr$^{-1}$ of the data. A value of $\chi^2$ is then calculated for each model. The data are shown in Figure 4.5a, the central peak of the data spans 9 pixels, corresponding to a dimension of 15 deg $\times$ 15 deg, each of which is at least twice as bright as any other pixel. Taking into account the dimensions and poor resolution of the data, we apply our approximations for average Galactic diffusion and disc age, both of which influence the morphology of the annihilation flux distribution, and map the least $\chi^2$. The results are shown in Figure 4.6, where the number of degrees of freedom is equal to the number of pixels. In the figure, a cumulative disc age of $0 - 14$ to $10 - 14$ Gyr corresponds to (from left to right) progressively older thin disc stars along with the thick disc and stellar halo. Beyond $11 - 14$ Gyr corresponds to thick disc stars and stellar halo stars. In all three cases, the Galactic Bulge/bar is present. The minimum reduced $\chi^2$ is 3.149 and occurs for a diffusion of $1.5 \pm 0.7$ kpc, where the error in diffusion is calculated from half maximum, and a disc age of between about $5 - 14$ Gyr to $11 - 14$ Gyr. The average $8 - 14$ Gyr model as well as a difference map between model and data is shown in Figures 4.5b and 4.5c. The separate trends in diffusion and cumulative age of this model, along with error calculation are shown in Figure 4.7, where diffusion tends to $1.5 \pm 0.7$ kpc distance as well as suggesting a preferentially better fit for older stars in the thin disc (and thick disc and stellar halo stars) over younger stars in the thin disc. The suggestion that positrons propagate this far is plausible (Higdon et al., 2009; Jean et al., 2009); indeed, using finer descriptions of the ISM, Alexis et al. (2010) suggested that the average positron propagation in the disc, from $^{26}$Al, was 1.5 kpc as well.

The trend in disc age is more difficult to quantify as the low density disc produces a much lower flux than the bulge/bar which dominates the overall fit. Nonetheless, Table 4.1 shows the $\chi^2$ trend indicating that there is a better fit when including a disc of old thin disc stars, thick disc stars and stellar halo stars and a worse fit when including young thin disc stars ($\leq 5$ Gyr) or only stellar halo stars ($> 11$ Gyr). Thus, our data suggest young thin disc stars and old stellar halo stars may not be major contributors to Galactic 511 keV annihilation. Coupled with our bulge/bar data, this suggests that the same ancient stellar sources of positrons in the bulge may be responsible for the positrons in the disc too.

This may appear unsurprising because many of the stars thought to produce significant quantities of positrons are old and thus occupy the bulge/bar, thick disc and stellar halo. Figures 4.8 and 4.9 show two classes of old population stars; known pulsars (Manchester et al., 2005) and LMXBs (Bird et al., 2010) along with the FWHM of their number density and a summary of
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNIHILATION MORPHOLOGY

Figure 4.5: Top: 511 keV flux per unit solid angle from Bouchet et al. (2010). Middle: Best-fit GALAXIA model flux per unit solid angle, normalised to 511 keV data. Diffusion is $1.5 \pm 0.7$ kpc and Galactic Age is 10-14 Gyr. Bottom: Difference map where each pixel is $(\text{data flux} - \text{model flux})^2/\text{error}^2$. All data is in the region $|l| < 100$ deg and $|b| < 50$ deg.
4.5 Discussion

Figure 4.6: The least $\chi^2$ fitting between 511 keV flux and GALAXIA model flux for Gaussian diffusion (kpc) and cumulative Galactic disc age (Gyr). 0-10 Gyr corresponds to a progressively older thin disc with the thick disc and stellar halo, after 10 Gyr the thin disc is turned off and after 11 Gyr the thick disc is turned off. In all cases the bulge is present and is shown on the right without a disc component. GALAXIA flux is normalised to the maximum 511 keV flux and computed for a 5 deg pixel size and in a range of $|l| < 100$ deg, $|b| < 50$ deg. The least $\chi^2$ values occur for a diffusion of $1.5 \pm 0.7$ kpc and for a disc age of 8 - 14 Gyr (see Table 4.1).

The findings. They both likely produce considerable quantities of positrons and their FWHM resembles that of the thick disc. Although observations show a larger scale height than the thick disc, it is likely due to the observations favouring brighter nearby sources, and as such is to be expected.

Furthermore, $1.5 \pm 0.7$ kpc corresponds to an initial injection energy for magnetic-field aligned positrons of $\approx 100 - 200$ keV for a hydrogen density of $1 \text{ cm}^{-3}$, from the cold to hot phases of the interstellar medium in a uniform magnetic field (see Fig. 4 Jean et al., 2009). This corresponds to the $e^+$ energy produced by the radioactive decay of $^{22}\text{Na}$, predominantly in novae, and $^{26}\text{Al}$, from massive stars, as well as $^{56}\text{Ni}$ and $^{44}\text{Ti}$, if positrons partially lose momentum when escaping their supernovae sources. Initially, this injection energy may appear strange because it suggests many candidates which produce $e^+$ with higher energies might not be as important to Galactic annihilation as expected. However, when considering that the vertical extent of the warm ionised medium (WIM) is $\approx 1.8$ kpc (Gaensler et al., 2008) and that $e^+$ annihilation occurs primarily within this boundary in the warm and possibly cold phases of the ISM rather than in the hot ionised medium (HIM) (Churazov et al., 2005; Harris et al., 1998; Higdon et al., 2009; Jean et al., 2009; Jean et al., 2006), it is feasible that $e^+$ with higher initial kinetic energies than these simply diffuse beyond the WIM into the low-density HIM where they annihilate infrequently and potentially diffuse far enough such that their contribution to Galactic annihilation is negligible. This may also explain why the Galactic $e^+$ annihilation rate is much less than the predicted $e^+$ production rate (Prantzos et al., 2011).

Our model shows that the relative $e^+$ flux due to the density of stars in the bulge/bar produces a $\approx 6$ deg FWHM annihilation morphology without diffusion. Similarly, 511 keV has been modelled with a central 2-3 deg inner peak and an 8-10 deg outer peak (Prantzos et al., 2011). If 511 keV is produced by $e^+$ generated by stars in the bulge/bar, our results are indicative of a continuous distribution of annihilation sites in an extended bulge/bar population. However, our results
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNIHILATION MORPHOLOGY

Figure 4.7: The relative $e^{-\chi^2}$ of the best-fit model, diffusion is 1.5 ± 0.7 kpc, the bulge is present and the disc age is 8-10 Gyr. The quoted errors are at half maximum of the $e^{-\chi^2}$.

<table>
<thead>
<tr>
<th>Component</th>
<th>Age (Gyr)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge</td>
<td>10</td>
<td>3.165</td>
</tr>
<tr>
<td>All</td>
<td>0 - 14</td>
<td>3.304</td>
</tr>
<tr>
<td>Bulge + Thin + Thick + SH</td>
<td>8 - 14</td>
<td>3.149</td>
</tr>
<tr>
<td>Bulge + Thick + SH</td>
<td>10 - 14</td>
<td>3.151</td>
</tr>
<tr>
<td>Bulge + SH</td>
<td>10 + 14</td>
<td>3.174</td>
</tr>
</tbody>
</table>

Table 4.1: The least $\chi^2$ between 511 keV data and Galactic models for a diffusion scale length of 1.5 kpc where age and structure are defined in GALAXIA.

Figure 4.8: Summary figure including the best-fit parameters for the $\alpha = 20$ deg Galactic bulge/bar model, a 10-14 Gyr disc with 1.5 ± 0.7 kpc diffusion, stellar candidate number density morphology and some 511 keV flux model fit parameters.
4.5 Discussion

Figure 4.9: Number density of two well known stellar $e^+$ source candidates, LMXBs (Bird et al., 2010) and pulsars (Manchester et al., 2005). http://www.atnf.csiro.au/research/pulsar/psrcat

are consistent with either: many $N_*$ in the bulge/bar, with $e^+$ annihilating nearby; or few $N_*$, diffusing and annihilating continuously within the bulge/bar volume. For the many $N_*$ case, this is unsurprising as many (theoretical) $e^+$ producing stars are old and thus occupy the bulge/bar, thick disc and stellar halo. For example, after producing many $e^+$ in SN Ia explosions, pulsars accreting in binary systems can produce millisecond pulsars, LMXBs, HMXBs and $\mu$Qs, all of which are old and considered to produce significant quantities of positrons. Moreover, because observed binarity increases with stellar density and age, the bulge/bar is likely to contain many of these classes of stars. Finally, it is also possible that this inner peak arises from a central engine e.g., Sgr A* and the bulge/bar itself, where diffusion is responsible for the outer peak. While we have used simple approximations of diffusion, a more rigorous treatment of diffusion (e.g., Martin et al. (2012); Strong and Moskalenko (1998)) will allow us to probe the stellar contribution of positrons much more effectively and remains a very important consideration for future work.

We cannot exclude the possibility that the $e^+$ sources derive from a single population distributed in a bulge and a disc, or a nuclear star cluster and a disc. Recent work has shown how nuclear bars and/or spiral perturbations can cause stars to migrate outwards, particularly those confined to the same plane as the perturber (Minchev et al., 2012, I. Minchev, personal communication). The process is very slow (> 1 Gyr) for long-lived perturbations but can be an order of magnitude faster if an inner bar dissolves and then reforms shedding most of its angular momentum.
4. THE INFLUENCE OF GALACTIC STELLAR STRUCTURES ON THE POSITRON ANNIHILATION MORPHOLOGY

to the outer disc. Whether bars and spiral arms are long-lived or reform in this way is a highly contentious issue (Quillen et al., 2009). If bar or spiral arm reformation is rare, this may provide further evidence of an ancient population that first formed at the nucleus. The imminent Gaia astrometric survey (Perryman et al., 2001) is needed to determine the timescales of such events.

4.6 Conclusions

Our investigation of the positron contribution from stellar sources in the Galaxy has revealed many observable consequences to Galactic positron annihilation from the natural stellar density structure. For the bulge/bar, when considering minimal or density dependent diffusion, these include a shift in peak flux to $l_0 = -0.35$ for a bulge/bar tilt angle of 11.1, a negative to positive flux ratio of 1.1 and a FWHM of 6 deg. Similar values have been reported for 511 keV annihilation; thus we cannot exclude the possibility that central $e^+$ annihilation sources derive from either single or multiple populations distributed in the bulge. Furthermore, an average propagation distance in the disc of 1.5 kpc of the same old stellar population in the disc (8-14 Gyr) provides the best fit of our models to 511 keV data. Although, this trend in age has a low statistical significance and could suggest a combination of young and old sources cannot be ruled out. Finally, given a diffusion length of 1.5 kpc, the initial $e^+$ kinetic energy is between $\approx 100 - 200$ keV and we suggest that at energies much higher than this, $e^+$ may escape the WIM and into the HIM where they continue to diffuse out of observational significance.
Conclusions

Professor. Morris Katz: “The committee will now vote yea or nay. Nay.”
Dr. Ogden Wernstrom: “Nay.”
Dr. Ethan ‘Bubblegum’ Tate: “Hell nay.”
Professor. Fisherprice Shpeekenshpell: “The horse says, doctorate denied.”

There are many theoretical sources of positrons that can potentially account for the annihilation rate observed in the Milky Way. We have modelled the population of various candidate classes of stars and their theoretical $e^+$ yield and directly compared them to the 511 keV morphology. Finding no obvious connection, we have explored the large-scale distribution of stars within the Galaxy, focusing on the Galactic distribution with the age, and therefore class, of star.

Drawing inspiration from the only successful low energy gamma-ray source finding mission, namely the 1.809 MeV line produced from the radioactive decay of $^{26}$Al, we have attempted to compare observed 511 keV positron annihilation morphology to these sources. Unlike the former, 511 keV has a indiscrete distribution and is strongly peaked towards the Galactic centre.

While considering negligible $e^+$ diffusion in the bulge/bar, we find that the natural peak in luminosity flux to be at $l_0 = -0.35$ for a bulge/bar tilt angle of 11.1 deg. This produces a negative to positive flux ratio of 1.1 at a FWHM of $\approx 6$ deg. Allowing for symmetric diffusion in the bulge/bar, this result would remain the same, but the FWHM of the resultant morphology would increase. This result provides a mechanism for a central 511 keV flux asymmetry, first suggested by Bouchet et al. (2010). Although this asymmetry is unconfirmed, our results suggest that a smooth distribution of $e^+$ annihilation sources in an extended population can be attributed to the natural distribution of stars in the Galaxy without requiring any asymmetric sources.

When introducing the Galactic disc, we compute a fit to 511 keV data obtained from Bouchet et al. (2010) for both age and diffusion. We find a best-fit for a disc age of 8-14 Gyr, i.e., the same stars as in the bulge/bar model and a propagation distance of 1.5 kpc. Given a diffusion of 1.5 kpc, the initial $e^+$ kinetic energy is between $\approx 100 - 200$ keV. For positron nucleosynthesis, this energy corresponds most closely to the radioactive decay of $^{22}$Na, which occurs
predominantly in novae and $^{26}$Al, from massive stars. Furthermore, if positrons partially lose momentum when escaping their supernovae sources, there may also be contributions from $^{56}$Ni and $^{44}$Ti. Moreover, we suggest that at energies much higher than this, $e^+$ may escape from the warm into the hot ionised medium and eventually diffuse out of observational significance. It is important to note that these results are suggestive as it has a low statistical significance and could suggest a combination of young and old $e^+$ sources cannot be ruled out. They do however suggest that either the $e^+$ sources derive from a single population distributed in a bulge and a thick disc, or a nuclear star cluster and a thin disc. Similarly, they cannot differentiate between many $e^+$ sources with minimal propagation or few $e^+$ sources with significant propagation.

Observations of positron annihilation and its counterparts have a low resolution due to the intrinsically high $\gamma$-ray background of experiments at these wavelengths. This makes it extremely difficult to resolve point sources or reach meaningful conclusions about the environments they are in. In the future, through higher resolution observations of positrons, such as the proposed DUAL experiment (Boggs et al., 2010), or novel approaches, such as infra-red experiments observing the nuclear transitions of positronium (Ps) above or below the atmosphere using atmospheric OH-suppression (Ellis and Bland-Hawthorn, 2008, 2009), we will gain further insight into the environments positrons live in. Although many of the breakthroughs in observations at these wavelengths are mostly iterative, future experiments have the potential to image with arc minute resolution. Eventually, through creative experimentation and careful modelling we will be able to probe these highly energetic environments accurately enough to finally resolve primary sources and annihilation sites of the elusive Galactic positrons.
References


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The inspiration for the establishment of γ-ray astronomy came from theoretical calculations by Morrison (1958). He suggested that interactions between cosmic rays and the interstellar medium should produce easily detectable γ-rays. His research led to a flood of balloon borne experiments which unfortunately, due to unexpectedly low γ-ray fluxes and high backgrounds, failed to conclusively detect any γ-rays. This led to the first launch of a γ-ray satellite in 1962, Explorer-XI.

1962, Explorer-XI Satellite. [Mission: $E > 50$ MeV detection. Construction: Stacked CsI/Nal Scintillator, Lucite Čerenkov detector, plastic anti-coincidence scintillator.] Explorer-XI was decommissioned after only four months due to some deterioration connected with the power supply, and no γ-rays were conclusively detected. The unexpected result indicated that Morrison’s calculations for γ-ray fluxes were too high and the expected background of the instruments were too low (Kraushaar and Clark, 1962).


1969, Balloon. [Mission: $E = 511 \pm 9\%$ keV. Construction: 4 inch diameter, 2 inch thick NaI(Tl) crystal viewed by a RC8054 phototube, collimation by a large well scintillator viewed by six RC8054 phototubes, plastic anti-coincidence scintillator (Haymes et al., 1968).] Hint of 511 keV at the Galactic centre (Haymes et al., 1969).

1972, Balloon. [Mission: $E = 511 \pm 9\%$ keV. Construction: 4 inch diameter, 2 inch thick NaI(Tl) crystal viewed by a RC8054 phototube, collimation by a large well scintillator viewed by six RC8054 phototubes, plastic anti-coincidence scintillator (Haymes et al., 1968).] Much clearer detection of 511 keV at the Galactic centre, though not yet unambiguous (Johnson
et al., 1972).

1973, Vela Satellites. [Mission: Soviet nuclear tests, $E = 0.2 - 1.5 \pm 9\%$ MeV. CsI(Ti) scintillators, no anti-coincidence shield and minimal passive shielding.]
Serendipitously picked up 16 gamma ray bursts of extra-solar origin, whilst looking back at data from 1969 to 1972. A positive detection despite the spacecraft’s primitive design indicated very large intensity spikes at the time of the bursts (Klebesadel et al., 1973).

Confirmed $\gamma$-ray detection during Solar flare, most likely from the 511 keV positron annihilation line (Chupp et al., 1973).

Designed to observe energies above 20 MeV and succeeding at above 30 MeV (Kniffen et al., 1973), SAS-2 confirmed the diffuse $\gamma$-ray background in the Galactic plane and made its own discovery of the pulsar that would later be known as Geminga, a relatively quiet radio pulsar but incredibly bright in gamma wavelengths (Fichtel et al., 1975).

COS-B discovered another 25 $\gamma$-ray sources, some turn out to be pulsars, confirms Geminga. Another one of the objects is the first extragalactic gamma-ray source: 3C 273, which is a relatively nearby quasar. It also detected diffuse galactic emission (Bignami et al., 1981; Buccheri et al., 1983; Mayer-Hasselwander et al., 1982).

1978, Balloon. [Mission: $E = 476 \pm 24$ keV. Construction: NaI(Ti) scintillator.]
The first evidence of 511 keV continuum radiation (Leventhal et al., 1978).

COS-B discovered another 25 $\gamma$-ray sources, some turn out to be pulsars, confirms Geminga. Another one of the objects is the first extragalactic gamma-ray source: 3C 273, which is a relatively nearby quasar. It also detects diffuse galactic emission (Bignami et al., 1981; Buccheri et al., 1983; Mayer-Hasselwander et al., 1982). Discovers low-energy (soft) gamma rays coming from the Galactic centre from the annihilation of electrons and positrons. (This is the 511 keV line, which some scientists consider to be hard X rays.) Some still-unknown process must be producing antimatter in the region around the galactic centre. These results are confirmed by balloon instruments.

A. HISTORICAL SUMMARY OF $\gamma$-RAY OBSERVATIONS

Detects 511 keV form positron annihilation, 2.22 MeV from neutron capture and other soft $\gamma$-rays in solar flares (Murphy et al., 1987).

In the late 1980s, the second generation of ACTs becomes operational, led by the 10-meter Whipple Telescope in Arizona. Whipple indirectly detects hard gamma rays from the direction of the Crab Nebula, but not the pulsar at the centre of the nebula. In the early 1990s, Ground-based ACTs discover hard gamma rays from several blazars. To the amazement of astronomers, this emission varies on a timescale of just minutes to hours.

1991 - 2000, CGRO (Compton Gamma-ray Observatory). [Mission: COMPTEL, All-sky imaging of low-energy $\gamma$-rays producing during radioactive decay; OSSE, All-sky 511 keV; BATSE, $\gamma$-ray bursts]. Construction: See Section 2.5.4, designed for two years of operation, CGRO returns data for nine years and is de-orbited because of a gyro-hardware failure.

COMPTEL, $^{26}$Al emission has been mapped all along the plane of the Galaxy (see Figure 3.2). From these measurements it was concluded that massive stars dominate $^{26}$Al production (Diehl et al., 1995). OSSE produced the data uses in the first 511 keV line emission map of the central Galactic ridge (Cheng et al., 1997; Purcell et al., 1997, 1994) and finds gamma-ray emission from X-ray binaries and Seyfert galaxies. BATSE detects more than 2,700 GRBs and shows that they come from all over the sky, strongly suggesting they are explosions occurring in distant galaxies. It also shows that GRBs seem to occur in two types: long (greater than two seconds) and short (less than two seconds).


EGRET found 271 point sources, two-thirds remain unidentified but seventy blazars and six pulsars were conclusively confirmed (Gehrels et al., 2000); 4 spin-down pulsars in high energy $\gamma$-rays; In conjunction with ROSAT (Halpern and Holt, 1992) found that the Geminga is a GRB with little or no radio emission (Bertsch et al., 1992); long lasting high energy emission from both GRBs (Hurley et al., 1994) an solar flares (Kamae et al., 2000).

1997 - 2003, BeppoSAX satellite. [Mission: 0.1 – 10 keV]

Localizes several GRB positions quickly through observations of the afterglows of long GRBs. The positions are precise enough that follow-up ground-based observations, and later observations from the Hubble Space Telescope, prove that the bursts occur at great distances, a major breakthrough.

2002 - , INTEGRAL (The ESA International Gamma-Ray Astrophysics Laboratory). [Mission: X-ray and low energy $\gamma$-rays, SPI - spectrometer, IBIS - imager]

Mapping of X-ray sources, including LMXRBs, HMXRBs, $\mu$Qs, etc (Bird et al., 2010). Measures $^{26}$Al throughout our galaxy, demonstrating that the Milky Way produces, on average, about two supernovae per century. It also produced an all-sky 511 keV positron annihilation emission distribution, indicating Galactic longitudinal asymmetry mapping and imaging 511 keV and continuum (Weidenspointner et al., 2008).
2008, FGST (Fermi Gamma-ray Space Telescope). [Mission: LAT, $E = 30$ MeV - 300 GeV. All-Sky. GBM, 8 keV - 1 MeV 150 keV - 30 MeV. Gamma-ray Burst Monitor. Construction: LAT. These electrons and positrons pass through interleaved layers of silicon microstrip detectors, causing ionisation and producing charge. By combining information from the layers it is possible to determine the trajectory of the particles. The particles then enter the calorimeter, consisting of a stack of CsI scintillators, which measures the total energy of the particles. GBM, Modelled on the retired BATSE (CGRO) and coupled with LAT, they have a spectral coverage of six orders of magnitude on GRBs, never before achieved from space. It has an all-sky view that is not occluded by the Earth. It detects sudden flares of $\gamma$-rays produced by $\gamma$-ray bursts and solar flares and immediately moves to its location with a sensitivity to within 15°, once there it achieves a final resolution of 3°. There is a 15 $\mu$s dead time before another event can be recorded. It consists of 14 scintillation detectors (twelve NaI crystals for the 8 keV - 1MeV range and two bismuth germanate crystals.) The first major discovery was a pulsar in the CTA 1 supernova remnant that appeared to emit radiation in the gamma ray bands only, a first of its kind. In September 2008, the gamma-ray burst GRB 080916C in the constellation Carina was recorded by the Fermi telescope. This burst had the largest apparent energy release yet measured (Ackermann et al., 2010). The discovery of $\gamma$-ray bubbles extending outward from the Milky Way has been suggested to have arisen from a Seyfert flare, 1-3 Myr ago (Bland-Hawthorn et al., 2013).
B.1 Modelling Galactic nucleosynthesis positron propagation and annihilation

Chapter 1 discussed the limitations of $\gamma$-ray astronomy at these wavelengths, particularly in observing a low $\gamma$-ray flux or in observing with a high spatial resolution. Apart from future $\gamma$-ray observatories, such as the DUAL experiment (Boggs et al., 2010), it may be possible to observe positron annihilation with much better spatial resolution via the recombination spectrum at near infrared wavelengths. None-the-less with the recent observations described in Chapter 2, it was possible to constrain sources via the annihilation energy spectra. The most notable result was that positrons were being produced at an energy no higher that a few MeV, ruling out substantial Galactic contribution from high energy sources, unless of course their $e^+$ escape the Galaxy. The only realistic candidates left are from; nucleosynthesis products from stars and their explosions, accretion disc and jet phenomena i.e. XRBs and $\mu$Qs, the Galactic SMBH in a non steady state scenario and theorised DM annihilation, although the latter three have a high degree of uncertainty. This work focuses on stellar nucleosynthesis products, considering source yields, distributions and positron propagation, resulting in comparisons to the annihilation morphology and other associated observational consequences.

The only similar all-sky $\gamma$-ray morphological observations are of the 1.809 MeV line of $^{26}$Al decay, which itself produces a positron and the signature is strong evidence for this process to be responsible for most if not all of the disc emission in the Galaxy. The signal has been attributed to CCSNe, because of both the high theoretical yield of the nuclei in each event and the signal’s connection to various star forming regions where CCSNe are known to occur. The highly discrete bright signals, mainly in the plane of disc, not preferring the bulge and associated with nearby star forming complexes, ruled out other popular sources which had low individual yields, or were associated with old populations. Interestingly, the mean lifetime of $^{26}$Al is $10^6$ years, which is above the a positron’s lifetime in the cold and warm phases of the ISM $\sim 10^4 - 10^6$ years (Guessoum et al., 1991, the hot phases are $\sim 10^8$ years). As such, with a proper treatment of positron propagation it will be possible to apply a similar treatment to the 511 keV signal,
B.1 Modelling Galactic nucleosynthesis positron propagation and annihilation

which conversely is very smooth and seems to favour the old population toward the Galactic centre.

The inception of this research comes in part from large volumes of the Milky Way which are being sampled with high precision data of stars, for example the Hipparcos and 2MASS wide area surveys. Theoretically, a detailed enough knowledge of stars and their Galactic distribution allows for the formation of models predicting stellar \( e^+ \) production and their Galactic distribution. Already, surveys such as these allow theoreticians to produce self consistent models of Galactic structure, including the tilted central bulge/bar (López-Corredoira et al., 2005), the long thin bar (López-Corredoira et al., 2007) or tufts on the bulge/bar (Martinez-Valpuesta and Gerhard, 2011), the thin disc (now with only two major spiral arms, Churchwell et al., 2009), the thick disc and the stellar halo. Many of these structures have been combined into single self-consistent synthetic models of the Milky Way such as the model presented in Robin et al. (2003).

Once positrons have escaped their stellar environments, they enter into the ISM where they lose the bulk of their energy through coulomb collisions with ionised gas (mainly \( e^- \) and \( H^+ \)), but also through excitation and ionisation of neutral atoms. Energy losses due to turbulent magnetic fields cannot be ignored, but are beyond the scope of this research. After the positrons have slowed to a few hundred eV, they reach the imminent-thermalisation regime, whereby they will annihilate through charge exchange with atoms or molecules, radiative recombination or direct annihilation with electrons. The final phase corresponds to the shortest period of the journey and will not greatly effect the final resting place of the positron, which is what we are interested in. Several studies have explored positron propagation and annihilation in detail (Bussard et al., 1979; Guessoum et al., 2005; Guessoum et al., 1991; Higdon et al., 2009; Jean et al., 2009; Martin et al., 2012), utilising these previous results we create an original prescription for collisional energy loss and scattering in the ISM.

Firstly, we utilise high precision data of stars to model the distribution of various populations and connect it to their \( e^+ \) yield. Secondly, we model ISM propagation scenarios for the positrons. Lastly, we calculate the resultant morphology and compare to the 511 keV morphology for best-fit gaussian fits and bulge to disc ratio.

B.1.1 Positron source model

B.1.2 Propagation and energy loss in the ISM

In a fully ionised plasma, Coulomb collisions represent the dominant loss process for positrons with \( E \lesssim 100 \text{ MeV} \). In modelling positron propagation in an ionised medium, we have produced a working model of energy loss and pitch angle scattering along with a using a complete description of the ionised medium from literature. A program was written to simulate the transport of \( e^+ \) through the ionised components (\( e^- \) and \( H^+/\text{HII} \)) of the interstellar medium (ISM).

In modelling the ionised gas in the ISM, we include \( e^- \) and \( H^+ \) in the completely ionised phases
B. GALACTIC POSITRON PROPAGATION MODEL DEVELOPMENT

<table>
<thead>
<tr>
<th>Phase</th>
<th>T (K)</th>
<th>$n_{H1}$ (cm$^{-3}$)</th>
<th>$X_{\text{ion}}$</th>
<th>$n_{e0}$ (cm$^{-3}$)</th>
<th>$z_0$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIM</td>
<td>$\sim 8000$</td>
<td>-</td>
<td>-</td>
<td>0.0125 - 0.035</td>
<td>430 - 1830</td>
</tr>
<tr>
<td>HII</td>
<td>$10^5 - 10^6$</td>
<td>-</td>
<td>-</td>
<td>$\sim 0.15$</td>
<td>70 - 140</td>
</tr>
<tr>
<td>WNM</td>
<td>$\sim 8000$</td>
<td>0.1 - 0.5</td>
<td>0.007 - 0.05</td>
<td>$[0.7 \times 10^{-3} - 25 \times 10^{-3}] / 2$</td>
<td>$\sim 400$</td>
</tr>
<tr>
<td>CNM</td>
<td>$\sim 100$</td>
<td>0.19 - 50</td>
<td>$4 \times 10^{-4} - 10^{-3}$</td>
<td>$[1.9 \times 10^{-3} - 50 \times 10^{-3}] / 2$</td>
<td>$\sim 150$</td>
</tr>
</tbody>
</table>

Table B.1: Properties of the different phases of the ISM including; the temperature, the mid-plane number density of hydrogen (and ionisation fraction) or electrons, and scale height. Bracketed values are obtained from $n_{H1} \times X_{\text{ion}}$ contributions come from Cordes and Lazio (2002); Ferrière (2001); Gaensler et al. (2008); Kalberla (2003); Kalberla and Dedes (2008); Kalberla and Kerp (2009); Prantzos et al. (2011)

as well as the ionised fractions of the neutral phases of the ISM. For neutral media we have calculated the relevant cross sections of energy loss (there is no pitch angle scatter) and applied them to our propagation model.

B.1.2.1 ISM models

Ionised regions

Most of the ionised gas in the interstellar medium (ISM) is found in dense HII regions around massive stars at low latitudes in the plane of the Galaxy as well as in the warm ionised phase of the Galaxy (WIM), a widespread diffuse component stretching far above the plane (Gaensler et al., 2008). The variation of the species number density $n$ with scale height $z$ of the Galaxy is usually modelled using an exponential of the form $n = n_0 \exp (-z/z_0)$, where $n_0$ is the mid-plane number density and $z_0$ is the scale height, the point at which $n = 1/e \times n_0$. Observations of H$\alpha$ and pulsar dispersion are the most common measurements used to constrain the parameters of the WIM, values for the relevant parameters to our study for different phases of the ISM are shown in Table B.1. Using some of these parameters, we can calculate the number density of electrons in any phase of the ISM via:

$$n_e = n_{e0} \exp \left(-\frac{z}{z_0}\right).$$  \hspace{1cm} (B.1)

For the WIM we use $n_{e0} = 0.0125$ cm$^{-3}$ and $z_0 = 950$ pc (Cordes and Lazio, 2002) and for HII we use $n_{e0} = 0.015$ cm$^{-3}$ and $z_0 = 70$ pc (Ferrière, 2001). Note that the electron density is equivalent to the H$^+$ density in these regions.

Ionised fraction of neutral regions

Many all-sky surveys have probed the global picture of HI in the Milky Way via the interstellar 21 cm line revealing, amongst other things, the parameters important to our study; hydrogen density $n_{H1}$, ionisation fraction $X_{\text{ion}}$ and scale height of both the warm (WNM) and cold (CNM) neutral phases of the ISM (Ferrière, 2001). By multiplying the hydrogen density by the ionisa-
Figure B.1: Rutherford scattering of 100 $e^+$ in an $e^-$ medium, where $KE_i = 1 \times 10^4$ eV, electron density is varied from $n_e = 0.001 - 0.030$ cm$^{-3}$ (number of targets per cylinder is $N = 1000$, width $x = 1 \times 10^{-10}$ m) and the maximum impact parameter before collision can occur $b_{max} = 1 \times 10^{-10}$ m.

Addition fraction we obtain the ion density, roughly composed of half $e^-$ and half $H^+$, the electron density in the Galactic plane is shown as $n_{e0}$ in Table B.1. In calculating the electron density as a function of scale height in Equation B.1, we use the value of $n_{HI}$ from Kalberla and Kerp (2009) and select a value for $X_{ion}$ presented in the range given in Ferrière (2001). In the CNM we use, $n_{HI} = 5.4$cm$^{-3}$ and $X_{ion} \approx 5 \times 10^{-4}$, in the WNM we use, $n_{HI} = 0.1$cm$^{-3}$ and $X_{ion} \approx 0.01$. Using the relation, $n_{e0} = n_{HI} \times X_{ion}/2$, we find that for the CNM $n_{e0} = 0.0029$cm$^{-3}$ and for the WNM $n_{e0} = 0.001$cm$^{-3}$.

Results

Adding together of the exponential functions, we obtain the ionised population of the ISM shown in Figure B.1.

B.1.2.2 Collisional scattering model

The medium

Given an appropriate value for $n_{e-}$, $N$ electrons are randomly distributed in a cylinder of area, $A = \pi r^2$, where $r = b_{max} = 1 \times 10^{-10}$ m is the maximum impact parameter before a collision is said to occur, and thus length is calculated from:

$$l = \frac{N}{n_{e^-}A} \quad (B.2)$$

such that,

$$\tau = n_{e^-}l\sigma = N \quad (B.3)$$
B. GALACTIC POSITRON PROPAGATION MODEL DEVELOPMENT

where the cross section of collision $\sigma = \pi b^2$.

The projectile

In each cylinder an incident positron particle is propagated from $l = 0$ and $r = 0$ until it undergoes a collision with the first electron in the cylinder. There, the distance to the electron, the impact parameter, the resultant scattering angle $\theta$ and energy loss $\Delta KE$ is recorded. The relevant scattering angle formulæ are:

\[ c = \frac{Z_1 Z_2 e^2}{2KE} \]  \hspace{1cm} (B.4)

and,

\[ \theta = \pm \cos^{-1} \left( \frac{b^2 - c^2}{b^2 + c^2} \right) \]  \hspace{1cm} (B.5)

where $Z_1$ and $Z_2$ are the atomic numbers of the projectile species and the target species, $k = 1.44$ (in units of MeV), $e = 1$ (in units of eV) and $KE$ is the kinetic energy of the projectile in eV.

Relativistic energy loss is calculated from:

\[ \Delta E \approx \frac{(\Delta p)^2}{2\gamma m_2} = \frac{q_1^2 q_2^2}{8\pi^2 c_0^2 \gamma b^2 v^2 \gamma m_2} \]  \hspace{1cm} (B.6)

where $v$ and $b$ vary in each collision.

After a collision occurs, the process is repeated for a new cylinder of electrons and the new $e^+$ kinetic energy, $KE_f = KE - \Delta KE$ until the positron has lost sufficient energy that it may radiatively recombine, i.e. $E < 6.8$ eV. The overall particle trajectory is then reconstructed from each step.

Initial parameters of the projectile

$KE_i = 1 \times 10^4$ eV, the initial kinetic energy must be low enough that relativistic effects on collisions can be ignored.

$r_c = 1 \text{ m}^{-10}$, the minimum collision radius corresponding to a scattering angle $\theta \approx 0.0015$ radians.

B.1.3 Annihilation

After positrons have slowed to a a few 100 eV, they are in the imminent-thermalisation regime. Here they can annihilate in-flight, by picking off electrons from atoms and molecules, once thermalised, through charge exchange with atoms and molecules, through radioactive combinations with free electrons and through direct annihilation with free or bound electrons. There is also suggestions that annihilation in dust grains may be important(Guessoum et al., 2010). In this regime, the distance travelled by positrons is negligible compared to the distance travelled in their slowing down period. The relative cross sections of formation may effect the 511 keV
Figure B.2: Coulomb scattering of 500 $e^+$ in an $e^-$ medium, where $KE_i = 1 \times 10^4$ eV, electron density is $n_e = 0.014$ cm$^{-3}$ (number of targets per cylinder is $N = 1000$, width $x = 1 \times 10^{-10}$ m) and maximum impact parameter before collision can occur $b_{\text{max}} = 1 \times 10^{-10}$ m. The mean free path is $\lambda \approx 0.0073$ pc and the mean total displacement from the origin is $d \approx 23.9$ pc.

Figure B.3: Total $e^+$ displacement before thermalisation ($KE < 6.8$ eV) in an ionised medium of half $e^-$ and half $H^+$ where ion density is varied from $n_e = 0.001 - 0.060$ cm$^{-3}$ and $KE_i = 1 \times 10^4$ eV. Fitting function is a double exponential: $f(n_e) = a \times \exp(b \times n_e) + c \times \exp(d \times n_e)$, where $a = 475$, $b = -449.4$, $c = 61.63$ and $d = -40.11$ such that $R^2 = 0.997$.

spectra, but not so much the 511 keV morphology, for that reason as we are only interested in the morphology we consider propagation and energy loss via coulomb collisions and charge exchange down to 6.8 eV to encompass the extra distance travelled in the imminent-thermalisation regime. The relevant information about annihilation cross sections and energy thresholds can be found in Bussard et al. (1979); Guessoum et al. (2005), and shown in Figure B.6
B. GALACTIC POSITRON PROPAGATION MODEL DEVELOPMENT

**Figure B.4:** Total $e^+$ displacement before thermalisation at different Galactic scale heights, ion density is calculated from Figure B.1.

**Figure B.5:** Coulomb scattering of 100 $e^+$ in an $e^-$ and $HII$ medium, where $n_{ion} = 0.028$ cm$^{-3}$ and the initial kinetic energy of the positrons is varies from $KE_i = 1 \times 10^3 - 1 \times 10^6$ eV.
B.1 Modelling Galactic nucleosynthesis positron propagation and annihilation

(a) Cross sections for annihilation

(b) Thresholds for annihilation processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Threshold (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ + H \rightarrow \text{Ps + H}^+$</td>
<td>6.8</td>
</tr>
<tr>
<td>$e^+ + H \rightarrow e^+ + e^- + H^+$</td>
<td>13.6</td>
</tr>
<tr>
<td>$e^+ + H \rightarrow e^+ + H^*$</td>
<td>10.2</td>
</tr>
<tr>
<td>$e^+ + \text{He} \rightarrow \text{Ps + He}^+$</td>
<td>12.1</td>
</tr>
<tr>
<td>$e^+ + \text{He} \rightarrow e^+ + e^- + \text{He}^+$</td>
<td>17.8</td>
</tr>
<tr>
<td>$e^+ + \text{He} \rightarrow e^+ + \text{He}^*$</td>
<td>24.6</td>
</tr>
<tr>
<td>$e^+ + \text{He} \rightarrow e^+ + \text{He}^*$</td>
<td>21.2</td>
</tr>
<tr>
<td>$e^+ + \text{H}_2 \rightarrow \text{Ps + H}_2^+$</td>
<td>8.6</td>
</tr>
<tr>
<td>$e^+ + \text{H}_2 \rightarrow e^+ + e^- + \text{H}_2^+$</td>
<td>15.4</td>
</tr>
<tr>
<td>$e^+ + \text{H}_2 \rightarrow e^+ + \text{H}_2^*$</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Figure B.6: Cross sections for annihilation (Bussard et al., 1979) and annihilation thresholds Guessoum et al. (2005).
The influence of Galactic structures on positron annihilation and propagation

The influence of Galactic structures on positron annihilation and propagation

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ABSTRACT

The source of Galactic positron \((e^+)\) annihilation emission remains elusive despite many years of searching. What is known is that photons produced in electron-positron annihilation are highly concentrated towards the Galactic centre and in all-sky observations the associated 511 keV \(\gamma\)-rays have a bulge/disc flux ratio of \(\approx 1 - 3\) and are suggested to have greater flux at negative Galactic longitude compared to positive. Using synthetic models of the Galaxy, we find possible connections between age-bound stellar structures in the Milky Way and the 511 keV annihilation morphology. The projected flux of the old tilted stellar bulge/bar can reproduce the best fit models of the 511 keV radiation, including the asymmetry. This suggests either a large number of \(e^+\) sources in an extended bulge/bar population or fewer sources with diffusion into the bulge/bar volume. When looking at the same stars in the disc we were not able to reproduce the bulge to disc ratio in flux, indicating either a separate class of \(e^+\) sources to the bulge or the same sources with significant diffusion. A \(\chi^2\) analysis between the 511 keV data and our models, including both age and diffusion, yields a best-fit for a bulge/bar, a thin disc older than 8 Gyr, along with the thick disc and stellar halo, and an overall diffusion of \(1.5 \pm 0.7\) kpc. Using this, we find limits for the initial \(e^+\) kinetic energy for annihilation in the various phases of the interstellar medium and conclude that \(e^+\) of greater energies than \(\approx 200\) keV can potentially escape the thick disc and have a negligible contribution to Galactic annihilation.

Key words: Galaxy: bulge - elementary particles - gamma rays: theory.

1 INTRODUCTION

The first confirmed report of 511 keV \(\gamma\)-rays generated by electron \((e^-)\) - positron \((e^+)\) annihilation in astrophysical environments was from the Solar Maximum Mission aboard the OSO-7 satellite (Chupp et al. 1973). Concurrent extrasolar observations of \(\gamma\)-rays at similar energies were made by several balloon borne experiments focusing on the Galactic Centre (GC) region (Johnson, Harraden, & Haymes 1972; Johnson & Haymes 1973; Haymes et al. 1975). After several years, 511 keV from \(e^- - e^+\) annihilation within 15 deg FWHM of the GC was confirmed as the source (Leventhal, MacCallum, & Stang 1978).

Today, the INTEGRAL satellite observes the 511 keV sky and, using the spectrometer for INTEGRAL (SPI), it has the highest angular resolution \((\approx 3\) deg FWHM) of any instrument at these wavelengths, and measure a Galactic \(e^+\) annihilation rate of \(2 \times 10^{43}\) \(e^+\) s\(^{-1}\) (Vedrenne et al. 2003; Prantzos et al. 2011). The radiation is centred within \(\approx 6\) deg – 8 deg of the GC and has a bulge/disc flux ratio of \(\approx 1 - 3\) (Bouchet, Roques, & Jourdain 2010). In recent times there has been interest in a new aspect of the 511 keV morphology, whereby the radiation flux appears to favour negative Galactic longitudes over positive ones of \(\approx 1.8\) (Weidenspointner et al. 2008a). The exact nature or even the existence of the asymmetry is still under dispute with suggestions that it is seen in the inner disc emission (Weidenspointner et al. 2008a), the central peak emission (Bouchet et al. 2010) or from flawed background treatment (Churazov et al. 2011). A possible inner disc asymmetry \((l > 10\) deg) is suggested to arise from the distribution of Galactic low-mass X-ray binaries (LMXB) (Weidenspointner et al. 2008a) or spiral arm densities (Higdon, Lingenfelter, & Rothschild 2009). A possible central asymmetry is suggested to arise from a longitudinally off-centred peak in 511 keV, modelled at \(l \approx -0.6\) deg, \(b \approx 0\) deg (Knödlseder et al. 2005; Bouchet et al. 2010), although there are no suggested mechanisms for this.

While attempts have been made to unify candidate sources to \(e^+\) annihilation observations, apart from the Sun,
there have been no confirmed detections of discrete extraterrestrial sources of the radiation (de Cesare 2011). Theoretical contributions to the Galactic positron budget are expected primarily from stars through radioactive processes within them (and within their explosions) and in high energy processes outside them within strong magnetic fields and jets of accreting binary phenomena (Bandyopadhyay et al. 2009). However, dark matter annihilation (Boehm 2009), the Galactic super-massive black hole (Totani 2006) and other more exotic sources have not been ruled out as candidates. In terms of individual stellar phenomena supernovae type Ia (SNIa) (Higdon et al. 2009), LMXBs (Weidenspointner et al. 2008a) and microquasars (μQs, Guessoum, Jean, & Prantzos 2006) are expected to produce the bulk of Galactic positrons while lesser contributions are expected from pulsars, millisecond pulsars (MSPs), supernovae type II (SNII), novae and high-mass X-ray binaries (HMXBs, Prantzos et al. 2011).

These phenomena can all be connected by their evolutionary phases. For example, white dwarf progenitors in binary systems can accrete matter in such a way that they are observed as novae or HMXBs and under the right conditions can suffer thermonuclear explosions as an SNIa. Similarly, neutron stars, conceived in SNI explosions, go on to further produce positrons in highly magnetised pulsar jets and in accreting binary systems, appearing as a MSPs, LMXBs, HMXBs or μQs. Apart from SNIa, all of these phenomena predict that positrons are produced in old stellar populations, some in excess of 10 Gyr, which occupy the Galactic bulge/bar, thick disc and stellar halo. Since most of the $e^+$ sources are in old stellar populations, the density distribution of these stars is tested as a tracer of the 511 keV data, both in terms of comparing best-fit Gaussian models and through direct $\chi^2$ comparison with data.

Motivation for this research comes in part from the relatively poor angular resolution of experiments at these wavelengths (e.g. 511 keV) compared to those in the optical and near infrared. Hipparcos and 2MASS are two such wide area surveys sampling large volumes of the Milky Way and providing high precision data of stars. Surveys such as these allow theoreticians to produce self consistent models of Galactic structure, including the tilted central bulge/bar (López-Corredoira, Cabrera-Lavers, & Gerhard 2005), the long thin bar (López-Corredoira et al. 2007) or tufts on the bulge/bar (Martinez-Valpuesta & Gerhard 2011), the thin disc (now with only two major spiral arms, Churchwell et al. 2009), the thick disc and the stellar halo. Robin et al. (2003) has combined many of these into a self-consistent synthetic model of the Milky Way. Recently a code named galaxia has been developed (Sharma et al. 2011) which implements the above model and allows one to generate wide area synthetic surveys in a fast and efficient manner and this is what we use in this paper. Using Galaxia we can generate a smooth distribution of stars over any given volume of the Galaxy and isolate different Galactic components (e.g. the bulge/bar, thin disc, thick disc etc.) and also get information about the age and metallicity of the stars.

Firstly, we use Galaxia to test if the 511 keV emission arises from a statistically large number of sources in an extended population or a few discrete sources. Next, several Milky Way configurations are explored, including the tilt of the bulge/bar axis and the age of the disc. Their expected flux (due to number density) is calculated including best-fit parameters for position, FWHM and their bulge to disc ratios. These are then compared with results of previous studies of the 511 keV morphology. Secondly, using the 511 keV INTEGRAL data provided by Bouchet et al. (2010), we perform a least $\chi^2$ analysis between the data and the Milky Way models and try to identify the galactic populations responsible for positron emission and put constraints on the diffusion length of the positrons.

2 MODEL

In Section 2.1 we describe the Milky Way models created using Galaxia and then explain the methods used to compare this model with 511 keV data. Then in Section 2.2.1, we perform a simple Gaussian fit, finding the centres, FWHM, bulge/disc flux ratio and a measure of asymmetry of our Milky Way models. These parameters have been found for...
The influence of Galactic structures on positron annihilation and propagation

<table>
<thead>
<tr>
<th>Component</th>
<th>Age (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge</td>
<td>10</td>
</tr>
<tr>
<td>Thin disc</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Thick disc</td>
<td>11</td>
</tr>
<tr>
<td>Stellar Halo</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 1. The age of Galactic structures as defined in GALAXIA and used herein.

511 keV data in earlier studies and, instead of a direct multi-component fit, we try to follow similar fitting procedures so as to make a meaningful comparisons with earlier studies. Gaussians are not an ideal way to describe either the disc components or the bulge/bar, and our aim is to test the assumption that the 511 keV can be reproduced by a simple selection in stellar ages. In doing so, the age of Galactic structures as defined in Robin et al. (2003) and Padova Isochrones (Marigo et al. 2008) for generating stellar properties (see Sharma et al. 2011, for a detailed description of parameters).

A flux density model for the Galactic bulge/bar was generated first. Since the 511 keV flux peaks most strongly towards the GC, correct treatment of the bulge is crucial to the comparison. Figure 1 shows a sketch of the bulge/bar along with the distance to the GC is 8 kpc, the latitudinal tilt of the bulge/bar $\beta = 3.5$ deg and the FWHM is defined in Robin et al. (2003). As the longitudinal tilt of the bulge/bar, $\alpha$, is still a matter of conjecture (López-Corredoira et al. 2005, 2007; Martínez-Valpuesta & Gerhard 2011; Robin et al. 2003), it has been allowed to vary through 11.1 deg, 20.0 deg and 40.0 deg to account for common tilt angles.

Aside from the central 511 keV peak, there is a large diffuse component corresponding to a disc emission, although its exact spatial dimensions are not well understood due to its comparatively low flux. Thus, we have included in a disc component to our bulge/bar models (see Table 1). Loosely, these correspond to a disc with: a) the same stars as the bulge (bulge + thick disc stellar halo), b) different stars to the bulge (bulge + 0.7 Gyr thin disc) and c) all stars (bulge + thin disc + thick disc + stellar halo). These are the three configurations used in modelling the entire Milky Way.

Our aim is to test the assumption that the 511 keV can be reproduced by a simple selection in stellar ages. In doing so, by modelling the number density distribution of stellar populations, we can also model the density distribution of $e^+$ annihilation. Specifically, models of the stellar distribution of the Milky Way are generated for a range of longitudinal bulge tilt, $\alpha$, and disc ages. The flux $\phi_i$ of each pixel $i$ is taken to be proportional to the number of stars $N_i$ within it, after correcting for the distance $r_i$ to each star $j$, i.e.

$$\phi_i(l, b) = \frac{1}{\gamma_i^2} ,$$

where the flux per unit solid angle is given by:

$$F_i(l, b) = \phi_i(l, b) / \Omega = \phi_i(l, b) / \left( \Delta l \int_{b_{min}}^{b_{max}} \cos b \, db \right) .$$

This is a measure of the relative flux density observed at Earth for all the stars in the model, where the constant of proportionality corresponds to the number of positrons produced by all the stars within a pixel and is assumed to be constant for the populations in question. In order to directly compare this to the 511 keV asymmetry, flux is computed in the region $-10 \deg < b < 10 \deg$ (from Weidenspointner et al. 2008a; Bouchet et al. 2010).

2.2 Comparing models to observations

2.2.1 Multi-component Gaussian fits

From 511 keV analysis, a single Gaussian is inadequate at explaining the 511 keV bulge morphology (Knödlseder et al. 2005). Thus, 2D Gaussian fitting algorithms are employed for the bulge flux in $l$ and $b$ and another one is used for the disc. Equation 3 is the most general form of the Gaussians used for the fit (including the disc):

$$f(l, b) = G_1 \exp \left[ -\frac{(l - l_{01})^2 + (b - b_{01})^2}{2\sigma_{11}^2} \right] + G_2 \exp \left[ -\frac{(l - l_{02})^2 + (b - b_{02})^2}{2\sigma_{22}^2} \right] + G_3 \exp \left[ -\frac{(l - l_{03})^2 + (b - b_{03})^2}{2\sigma_{33}^2} \right] ,$$

where $G_1$ and $G_2$ define the amplitude of the bulge and $G_3$ defines the amplitude of the disc. Instead of all the parameters, we have followed a step-by-step fitting routine similar to the one used in Bouchet et al. (2010) for the sake of comparison. A non-linear least squares algorithm was employed for the fitting routine in two steps:

(i) Fit two Gaussians for the bulge: fix $l_{01}, b_{01} = 0$ and find six free parameters ($G_1, \sigma_{11}, \sigma_{1b}, G_2, \sigma_{21}, \sigma_{2b}$). Leave $\sigma_{11}, \sigma_{1b}, \sigma_{21}$ and $\sigma_{2b}$ constant and find four free parameters ($G_1, l_{02}, G_2, b_{02}$).

(ii) Fit a third Gaussian for the disc: find five free parameters ($G_3, \sigma_{31}, \sigma_{3b}, l_{0d}, b_{0d}$). Leave $\sigma_{31}$ and $\sigma_{3b},$ constant and find three free parameters ($G_1, G_2, G_3$).

Apart from the amplitude constants, which only have relative significance, these parameters can be compared to their established counterparts in the annihilation morphology including the bulge centres and dimensions, the bulge/disc ratio and the longitudinal asymmetry (Knödlseder et al. 2005; Weidenspointner et al. 2008a; Bouchet et al. 2010; Churazov et al. 2011). The bulge/disc ratio was found by calculating the total flux per unit solid angle in the corresponding regions along $l$ and $b$ via the surface integral:

$$F_{tot}(l, b) = \int_{b_{min}}^{b_{max}} \left( \int_{l_{min}}^{l_{max}} \cos b \, F(l, b) \, dldb \right) ,$$

where the bulge flux corresponds to $G_1$ and $G_2$ and the disc flux $G_3$. The longitudinal asymmetry is found from the same equation in the limit $|b| < 10 \deg$ for $-50 \deg < l < 0 \deg$ vs. $0 \deg < l < 50 \deg$ and $-180 \deg < l < -50 \deg vs. 50 \deg < l < 180 \deg$ (as in Weidenspointner et al. 2008a and Bouchet et al. 2010).
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<table>
<thead>
<tr>
<th>“Bulge model” (step i)</th>
<th>$l_{OB}$</th>
<th>$b_{OB}$</th>
<th>FWHM$_{11,1b}$ deg</th>
<th>FWHM$_{21,2b}$ deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 11.1$ deg</td>
<td>$-0.30$</td>
<td>$0.00$</td>
<td>$5.0, 4.7$</td>
<td>$7.3, 6.1$</td>
</tr>
<tr>
<td>$\alpha = 20.0$ deg</td>
<td>$-0.51$</td>
<td>$0.02$</td>
<td>$8.5, 5.9$</td>
<td>$5.3, 5.0$</td>
</tr>
<tr>
<td>$\alpha = 40.0$ deg</td>
<td>$-1.00$</td>
<td>$0.01$</td>
<td>$13.3, 5.8$</td>
<td></td>
</tr>
</tbody>
</table>

511 keV data models

| Authors (2005)         | $-0.6^{+0.3}_{-0.2}$ | $0.1^{+0.3}_{-0.3}$ | $7.2^{+0.9}_{-0.9}$ | $8.1^{+0.9}_{-0.9}$ |
| Bouchet et al. (2010)  | $-0.64^{+0.20}_{-0.19}$ | $0.06^{+0.19}_{-0.20}$ | $3.2^{+1.0}_{-1.0}$ | $11.8^{+1.9}_{-1.5}$ |

Table 2. Model fit parameters of the Galactic Bulge/Bar from Step (i) generated using GALAXIA for varying tilt angle, $\alpha$, as shown in Figure 2. Equivalent fit parameters for 511 keV observations are also listed. Note, we use a pixel size of 0.1 degree while observations have a larger pixel size.

2.2.2 Comparing models to observations - $\chi^2$ analysis to constrain model parameters

The model thus far compares the number density distribution of Milky Way stars with the 511 keV morphology, restricting the analysis to the case where positrons are annihilating near their stellar sources. However, it is also possible that they travel large distances (>1 kpc) before annihilating (Jean et al. 2009; Higdon et al. 2009), necessitating the addition of diffusion to the model.

A simple model of diffusion is used whereby the position of a star in the model $(x, y, z)$ is displaced to $(x + \Delta x, y + \Delta y, z + \Delta z)$, where $\Delta x = \Delta y = \Delta z$ is a random Gaussian number defined by a distance $\sigma$. As this is a symmetric process and is still defined by two Gaussians for the bulge and one for the disc, the bulge centres, the bulge/disc ratio and the longitudinal asymmetry should vary little with relatively short diffusion but the FWHM of all the Gaussians will change.

Next, the 511 keV flux data along with errors provided by Bouchet et al. (2010) is used to perform a least $\chi^2$ analysis between this data and the generated Galaxy models. In making comparisons, the flux data is converted to flux sr$^{-1}$ and the models are normalised to the maximum flux sr$^{-1}$ of the data. A value of $\chi^2$ is then calculated for each model.

3 RESULTS

The first section of the analysis concerns the morphology of the Galactic bulge/bar where the longitudinal tilt of the bulge/bar is varied from the given value in Robin et al. (2003), $\alpha = 11.1$ deg, to 20.0 and 40.0 deg to account for variations in the literature. In projection from the Earth, the Galactic bulge/bar is further away and, due to azimuthal tilt, $\beta$, however as this is much smaller than $\alpha$, it is not noticeable at this resolution. Using Step (i), several best-fit Gaussian models were generated for the bulge/bar flux and varying $\alpha$, these are shown in Figure 2 and Table 2. The centre of the best fit Gaussians, and hence the peak flux, are all offset from the Galactic origin, tending towards negative longitudes ($l = -0.3$ to $-1.0$ deg) for all $\alpha$ tilt angles in good agreement with 511 keV observations in Knödlseder et al. (2005); Bouchet et al. (2010). Furthermore, the bulge/bar FWHM are confined to within <15 deg of the Galactic centre and have greater flux at negative longitudes than positive ones, both of which are features of 511 keV observations (Weidenspointner et al. 2008a). As a semi-continuous stellar density model was used, these results support either a large number of $e^+$ sources ($N_e$) in an extended bulge/bar population with nearby annihilation or fewer $N_e$ with diffusion into the bulge/bar volume where they annihilate.

As mentioned earlier, the bulge/bar models are then fitted with a disc such that the resultant Galaxy model correspond to: a) the same stars as the bulge (bulge + thick disc stellar halo), b) different stars to the bulge (bulge + O7 T Gry thin disc) and c) all stars (bulge + thin disc + thick disc + stellar halo). The bulge + disc configurations are shown in Figure 3 and the best-fit Gaussian parameters calculated from Step (ii) are shown in Table 3 along with the corresponding literature values from 511 keV modelling. In terms of the asymmetry, within $|l| = 50$ deg there is an excess in flux toward negative longitudes than positive ones of between 1.1 and 1.3 times, depending primarily on $\alpha$ but also on disc age, in accordance with expected values for 511 keV in Bouchet et al. (2010) but less than in Weidenspointner et al. (2008a) which has negative flux 1.8 times greater than positive. However, above $|l| = 50$ deg the flux is symmetric about longitude, supporting the position that an off-centred peak flux (where $l < 0$ deg) and a symmetric disc flux produces the observed 511 keV morphology (Bouchet et al. 2010) as opposed to a centred peak flux ($l = 0$ deg) with an asymmetric disc flux (Weidenspointner et al. 2008a). The bulge/disc flux ratio also falls within the range of those expected by 511 keV for model b and c, however it is slightly higher than the accepted values for the older stars in model a. This is due in part to the morphology, but mainly due to model a having much less disc stars than the others. Therefore, from the bulge/disc flux when considering nearby annihilation, the old source/s responsible for the bulge flux do not account for the total disc flux as well; there must be at least one other distinct class of sources responsible for the rest of the annihilation.
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Figure 2. Model data generated using GALAXIA showing the relative flux per unit solid angle of the bulge/bar for varying tilt angle, \( \alpha \). The pixel size is 0.1 deg and flux is normalised to \( F/F_{\text{max}} \). Solid lines indicate the FWHM of the larger amplitude Gaussian of the fitting function in Step (i), and dashed lines indicate smaller amplitude Gaussian. Best-fit parameters listed in Table 2.

Figure 3. Model data generated using GALAXIA showing the logarithm of the relative flux per unit solid angle of the Galaxy for varying bulge/bar tilt angle, \( \alpha \), and disc age. The pixel size is 0.1 deg and flux is normalised to \( \log(F_{\text{max}}) = 0 \). Best-fit parameters listed in Table 3.
Table 3. Model fit parameters of the Milky Way from Step (ii) are generated using GALAXIA for varying tilt angle, α, and disc age as shown in Figure 3. Equivalent fit parameters for 511 keV are also listed specifically for the bulge/disc flux ratio and longitudinal flux asymmetry, within |β| < 10 deg, for both the inner disc (|β| < 50 deg) and outer disc (|β| > 50 deg). Units of flux are 10^{-4} ph cm^{-2}s^{-1} and the total flux has been normalised to φ_{-4} = 20 ph cm^{-2}s^{-1}. In the case where there are two bulge gaussians, their fluxes and associated uncertainty has been added. Note, we use a pixel size of 0.1 degree while observations have a larger pixel size.

<table>
<thead>
<tr>
<th>bulge (step i)</th>
<th>disc</th>
<th>G1 - G2 - G3</th>
<th>bulge + disc</th>
<th>φ_{B1} + φ_{B2}, F_B</th>
<th>F_D</th>
<th>V_{ext}</th>
<th>B/D</th>
<th>F_B/F_D</th>
<th>F_D/F_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>α = 11.1</td>
<td>0 - 7</td>
<td>0.01 - 0.10</td>
<td>50.0, 2.0</td>
<td>1.00 - 0.69 - 0.22</td>
<td>13.9, 6.1</td>
<td>2.3</td>
<td>1.1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>α = 20.8</td>
<td>10 - 14</td>
<td>0.10 - 0.06</td>
<td>31.6, 7.7</td>
<td>1.00 - 0.35 - 0.04</td>
<td>17.6, 2.4</td>
<td>20.0</td>
<td>7.2</td>
<td>1.3</td>
<td></td>
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<tr>
<td>α = 40.8</td>
<td>0 - 14</td>
<td>0.01 - 0.09</td>
<td>47.7, 2.6</td>
<td>1.00 - 0.18 - 0.32</td>
<td>11.3, 8.7</td>
<td>20.0</td>
<td>1.3</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

511 keV data models

The number of degrees of freedom is equal to the number of pixels

1 The number of degrees of freedom is equal to the number of pixels.
The influence of Galactic structures on positron annihilation and propagation

Figure 4. Top: 511 keV flux per unit solid angle from Bouchet et al. (2010). Middle: Best-fit GALAXIA model flux per unit solid angle, normalised to 511 keV data. Diffusion is $1.5 \pm 0.7$ kpc and Galactic Age is 10-14 Gyr. Bottom: Difference map where each pixel is $(\text{data flux} - \text{model flux})^2/\text{error}^2$. All data is in the region $|l| < 100$ deg and $|b| < 50$ deg.
Figure 5. The least $\chi^2$ fitting between 511 keV flux and GALAXIA model flux for Gaussian diffusion (kpc) and cumulative Galactic disc age (Gyr). 0-10 Gyr corresponds to a progressively older thin disc with the thick disc and stellar halo, after 10 Gyr the thin disc is turned off and after 11 Gyr the thick disc is turned off. In all cases the bulge is present and is shown on the right without a disc component. GALAXIA flux is normalised to the maximum 511 keV flux and computed for a 5 deg pixel size and in a range of $|l| < 100$ deg, $|b| < 50$ deg. The least $\chi^2$ values occur for a diffusion of 1.5$\pm$0.7 kpc and for a disc age of 8 - 14 Gyr (see Table 4).

Figure 6. The relative exp($-\chi^2$) of the best-fit model, diffusion is 1.5$\pm$0.7 kpc, the bulge is present and the disc age is 8-10 Gyr. The quoted errors are at half maximum of the $\exp(-\chi^2)$.

Table 4. The least $\chi^2$ between 511 keV data and Galactic models for a diffusion scale length of 1.5 kpc where age and structure are defined in GALAXIA.

<table>
<thead>
<tr>
<th>Component</th>
<th>Age (Gyr)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulge</td>
<td>10</td>
<td>3.165</td>
</tr>
<tr>
<td>Bulge + Thin + Thick + SH</td>
<td>0 - 14</td>
<td>3.304</td>
</tr>
<tr>
<td>Bulge + Thick + SH</td>
<td>8 - 14</td>
<td>3.149</td>
</tr>
<tr>
<td>Bulge + SH</td>
<td>10 + 14</td>
<td>3.174</td>
</tr>
</tbody>
</table>

and considered to produce significant quantities of positrons. Furthermore, as observed binarity increases with stellar density and age, the bulge/bar is likely to contain many of these classes of stars. A distribution in the disc of the same old sources does not provide the flux required for the observed bulge to disc ratio in 511 keV, suggesting that there may be a separate distinct class of disc sources that dominate the annihilation flux in these regions.

In a separate analysis, the minimum $\chi^2$ is found between 511 keV data from Bouchet et al. (2010) and the Galactic models for an overall diffusion of 1.5$\pm$0.7 kpc and a Galactic age of between about 5 - 14 Gyr to 11 - 14 Gyr, corresponding to a bulge/bar, an old thin disc, a thick disc and a stellar halo. Although, the bulge clearly dominates with only a minor contribution from the disc making it difficult to properly constrain the disc with the low angular and energy resolution of the data. Nevertheless, old stars in the bulge, thin disc, thick disc and stellar halo are found as the major producers of positrons in the Galaxy and significant diffusion of positrons from their birthplaces of the order seen in Galactic positron diffusion modelling Jean et al. (2009); Higdon et al. (2009).

In terms of best-fit diffusion, 1.5$\pm$0.7 kpc corresponds to an initial kinetic energy for magnetic-field aligned positrons of $\approx 100 - 200$ keV, from the cold to hot phases of the interstellar medium in a uniform magnetic field (see Fig. 4 Jean et al. 2009). Considering that this diffusion is well confined to within 1.5$\pm$0.7 kpc, these results suggest that $e^+$ injected at these energies are responsible for most of the Galactic annihilation. Most notable about this energy is that it corresponds to the $e^+$ energy produced by the radioactive decay of $^{22}$Na that occurs predominantly in Novæ. Initially, this appears strange as it rules out many $N_e$ of higher energies. However, when considering that the vertical extent of the warm ionised medium (WIM) is $\approx 1.8$ kpc (Gaensler et al. 2008) and that $e^+$ annihilation occurs primarily within this boundary in the warm and possibly cold phases of the ISM rather than in the hot ionised medium (HIM) (Harris et al. 1998; Churazov et al. 2005; Jean et al. 2006; Higdon et al. 2009; Jean et al. 2009), it is feasible that $e^+$ with higher initial kinetic energies than these simply diffuse beyond the WIM into the low-density HIM where they annihilate infrequently and potentially diffuse far enough such that their contribution to Galactic annihilation is negligible. This may also explain why the Galactic $e^+$ annihilation rate is much less than the predicted $e^+$ production rate (Prantzos et al. 2011).

The results obtained for the bulge/bar remain unchanged under diffusion except for the FWHM of the bulge which increase to $\approx 12$ deg, higher than that of 511 keV. A more rigorous treatment of diffusion in the bulge and disc regions will be important for future consideration.

We cannot rule out the possibility that the $e^+$ sources derive from a single population distributed in a bulge and...
The influence of Galactic structures on positron annihilation and propagation

Figure 7. Summary figure including the best-fit parameters for the $\alpha = 20$ deg Galactic bulge/bar model, a 10-14 Gyr disc with $1.5 \pm 0.7$ kpc diffusion, stellar candidate number density morphology and some 511 keV flux model fit parameters.

Figure 8. Number density of two well known stellar $e^+$ source candidates, LMXBs (Bird et al., 2010) and pulsars (Manchester et al., 2006).

Observations of positron annihilation and its counterparts have a low resolution due to the intrinsically high $\gamma$-ray background of experiments at these wavelengths. This makes it extremely difficult to resolve point sources or reach

Figure 8. Number density of two well known stellar $e^+$ source candidates, LMXBs (Bird et al., 2010) and pulsars (Manchester et al., 2005).

http://www.atnf.csiro.au/research/pulsar/psrcat
meaningful conclusions about the environments they are in. In the future there will be higher resolution observations of positron annihilation, such as the proposed DUAL experiment (Boggs et al. 2010), and recent developments in the capabilities of infra-red experiments will make it possible to observe the nuclear transitions of positronium (Ps), both above the atmosphere (i.e. JWST), and ground-based through atmospheric OH-suppression (Ellis & Bland-Hawthorn 2008, 2009). With potentially arc minute resolution these future experiments will make it possible to probe these highly energetic environments much more accurately and may allow us to resolve annihilation sites and perhaps primary sources of Galactic positrons.

5 CONCLUSIONS
In conclusion, we have reproduced the 511 keV morphology, including Gaussian fit parameters, the bulge/disc ratio and the apparent asymmetry, based on the models of the structure present in the Galactic stellar density. Including a mean $e^+$ propagation of 1.5 kpc from these same stars in the disc produces a close fit to the 511 keV flux data in Bouchet et al. (2010) and thus find a possible link between one or more classes of stars in the old spheroid population and the 511 keV annihilation radiation. Given this diffusion length, the initial $e^+$ kinetic energy is between $\approx 100$ – $200$ keV and we propose that at energies much higher than this, $e^+$ escape the WIM and into the HIM where they continue to diffuse out of observational significance.

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