Extragalactic Positrons

Answer to the 511 keV Peak?

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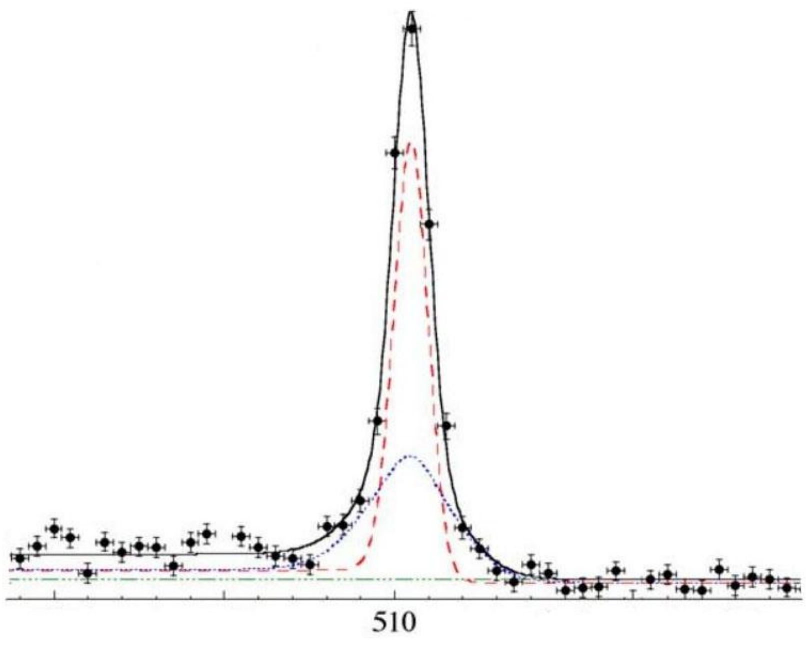
Summary

The 511 keV peak in the gamma-ray spectrum emitted by the Milky Way is caused by the annihilation of positrons and electrons, especially near the Galactic bulge. The annihilation takes place almost exclusively as a result of the forming of positronium. However, the sources providing the positrons are still subject of debate due in part to discrepancies in the morphology of the 511 keV radiation. In an effort to determine whether an extragalactic object, like another galaxy, could theoretically provide the Milky Way with positrons it is found that this possibility does certainly exist. Even the farthest known galaxy can theoretically function as a source. The biggest obstacle for extragalactic particles making it to the Milky Way is the InterGalactic Medium. This huge space separating galaxies considerably reduces the overall energy of any particle beam passing through it over large enough distances. Nevertheless it does not form an insurmountable hurdle.



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2. Introduction

In 2002 the INTEGRAL/SPI instrument (Winkler et.al. 2011 & Figure 1) was sent into space aboard a satellite. One of its main goals: to detect, with greater than before accuracy, the brightest gamma-ray line in the galaxy (Churazov et. al. 2010) and hopefully shed more light on its existence. This line, or rather peak, is known as the 511 keV peak (Figure 2) and it indicates that our galaxy is emitting a disproportionate amount of electromagnetic radiation with an energy of 511 keV compared to radiation intensities at other energies (the eV being a measure of energy, like the Joule). In the many years since its discovery we have come to understand the mechanics causing this radiation. It involves particle annihilation between an electron and its anti-particle, the positron. While our galaxy has plenty of electrons, the exact origins of the positrons needed for annihilation, and thus the creation of 511 keV radiation, is still subject of debate among scientists.

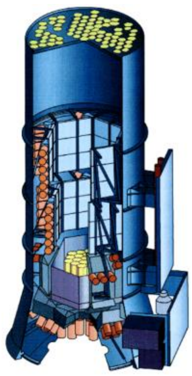


Figure 1: The INTEGRAL satellite with the SPI spectrometer, Source: http://sci.esa.int

In astrophysics circles the story of the 511 keV peak is a well-known one, as it's been more than four decades since Johnson et. al. (1972) made its discovery. While in that timespan much research has been conducted on the subject, resulting in a better grasp of the physics involved, there is still one important point of contention. Namely, the main source (or sources) responsible for the large number of positrons that form half of the interaction responsible for 511 keV radiation.

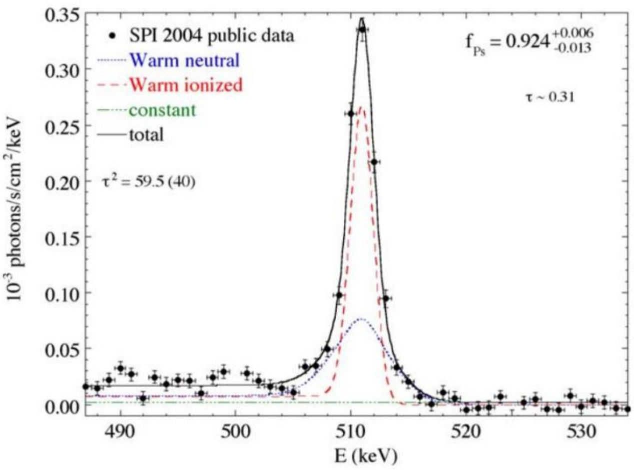


Figure 2: The gamma-ray spectrum for a narrow range around 511 keV showing the peak as measured by SPI, Source: Jean et. al. 2005, via Prantzos et. Al. 2010

Most of the discussion is centred on familiar objects within our galaxy. Numerous papers have been published evaluating supernovae, Low Mass X-ray Binaries (LMXB), the Super Massive Black Hole(SMBH) at the centre of our galaxy and dark matter as possible sources of positrons (as a search for '511 keV line' on arxiv.org will show). Papers evaluating extragalactic sources on the other hand aren't nearly as numerous, which is unfortunate. After all, irrespective of the tangible plausibility of particles from other galaxies being able to reach our own, it is in line with the general physicist's modus operandi to scrutinize all possible sources. What is established though is the disproportionate amount of 511 radiation emitted from the galactic bulge compared to the disk (Bouchet et.al. 2010, Weidenspointner et. al. 2008 & Figure 3). The bulge is the central region of the Milky Way, having a more voluminous, spherical shape compared to the relatively flat disk.

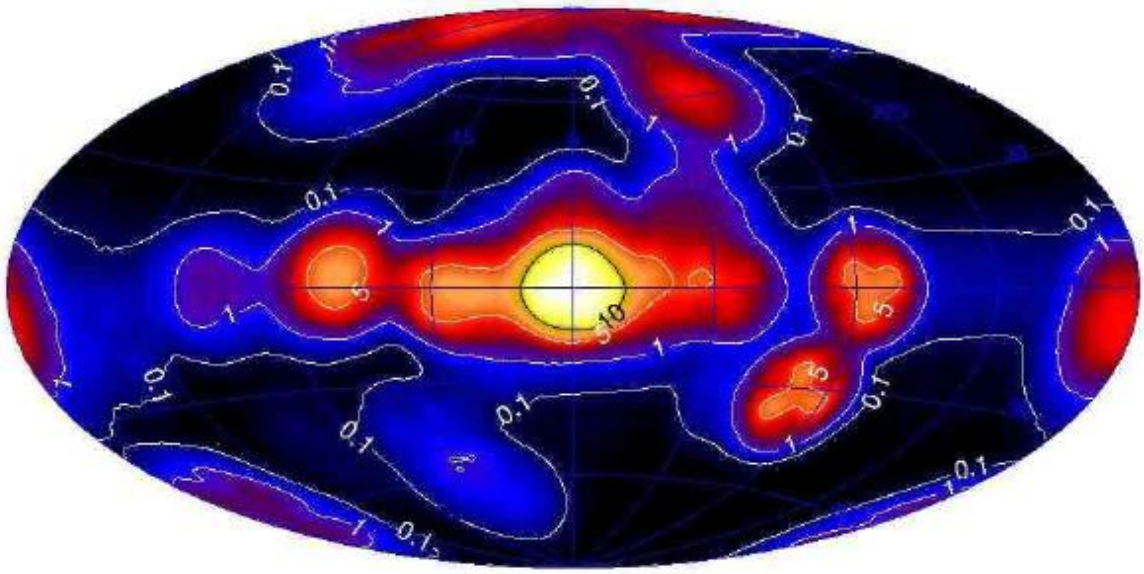


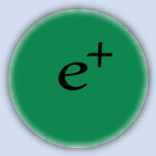
Figure 3: Full Sky Map of the Milky Way exposing the intensity distribution of 511 keV radiation (Knödlseder et.al. 2005)

It is in light of these circumstances that this article will examine exactly such a possibility and attempt to determine whether enough positrons can be salvaged by the Milky Way from such extragalactic sources to provide a noteworthy contribution to the observed 511 keV line.

3. The Positron and Annihilation physics

The 511 keV peak is the direct consequence of electron-positron annihilation. Much is known about the electron. In its most recognised shape this negatively charged particle provides the counterbalance to positively charged nuclei, customarily made up of protons and neutrons, to form stable atoms. Its role herein is confined to a range of set movement patterns revolving around the nucleus, each one determined by the particular distribution of electrons along the quantum energy levels of an atom, known as the electronic configuration.

As the standard model of physics prescribes, the electron, just as every other charged particle, has an antiparticle. This anti-electron is identical to the electron but for an opposite charge, a positive one, and has been named the positron. Peculiarly, while both the electron and the positron would have existed in equal numbers at the germination of the universe, it is the electron that enjoys the quantitative upper hand and is generally prevalent, as far as we know, throughout the universe. Nevertheless, positrons are copiously produced by a host of sources throughout the universe and in our own galaxy. It is due to the characteristics of the relation between particles and their anti-particles that most positrons do not stand much chance of survival in areas dominated by electrons.

	Electron	Positron
		
Particle class	Fermion	Fermion
Mass	$9.109x10^{-31}$ kg	$9.109x10^{-31}$ kg
Mass in eV	511 keV	511 keV
Electric charge in *e*	$-1e$	$+1e$
Quantum spin	½ (up or down)	½ (up or down)
	Source:	**Wikipedia.org**

Positronium and Annihilation

The most poignant result of this relation is a process called particle annihilation. Particles and their anti-particles, upon meeting, consume each other and all their mass is converted into energy, which is emitted in the form of radiation. Annihilation can come about in two different ways. It can occur either by a direct, head on collision between the two particles, conveniently called direct or in-flight annihilation, or it can result from a bond between the two particles.

For the subject matter, direct annihilation is inconsequential. This is because the measured 511 radiation has been determined to almost completely be the product of annihilation through the bound state of the two particles (Kinzer et. al. 1996). That bound state will be the focus of attention of this article.

The name for this bond between a positron and an electron is positronium (Ps) (Figure 4 left) and this 'atom' only sees the light of day provided that the energies of the two particles are well in non-relativistic regions as may be deduced from Heitler (1954, p271). It is effectively the equivalent of the hydrogen atom, with the proton replaced by a positron. This new makeup causes wildly different dynamics however, resulting from the mass difference between a positron and a proton. Because of this the two particles find themselves revolving around each other as they lose kinetic energy, by way of radiation, while stepping down the quantum energy levels (Figure 4 right). Once both particles reach their ground state their wave functions overlap and annihilation follows (Griffiths 1987, 5.6).

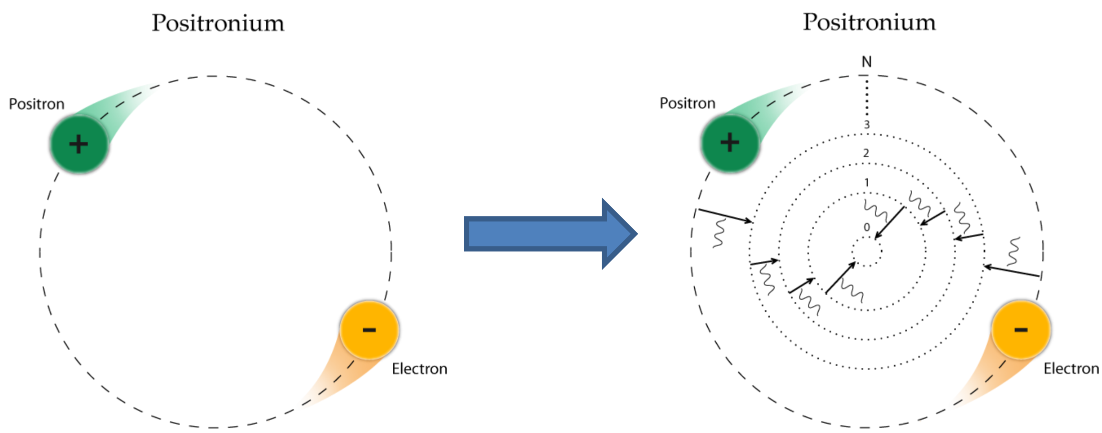


Figure 4: Left, the positronium(Ps) bond between a positron (for clarity coloured green) and an electron. Right, a schematic depiction of quantum state descent by the two particles from state N to the ground state (denoted 0). Each descent is accompanied by photon radiation (depicted is not their actual direction of emission) to facilitate the energy loss required to reside in that lower state.

Positronium's different guises

It merits mentioning the different types of Ps, arising as a consequence of the spin of the particles it consists of (Figure 5). Both the electron and the positron are leptons and have therefore a quantum spin of $^1/_2$. The bond in Ps gives rise to the addition of angular momentum (Griffiths 1987, sections 4.2-4.4). So it is that the combined spins S of the two leptons can equal either 1 ($^1/_2 + {}^1/_2$) if both have equal spin (spin up or spin down) or 0 ($^1/_2 - {}^1/_2$) if the two have opposite spins. The former arrangement is called ortho-Positronium (o-Ps) in regard to the equal spins and the latter arrangement is termed para-Positronium (p-Ps). By the rules of addition of angular momentum o-Ps has three configurations (1, 0, -1) and p-Ps has 1 (0). This results in a three to one plurality of o-Ps. These arrangements also impose restrictions on the way a Ps atom may decay. o-Ps in this case can decay in an odd number of photons and p-Ps decays into an even number of photons. This has to do with conservation of charge conjugation (Griffiths 1987, p128), a more advanced quantum physics concept. Since the eigenvalues of charge conjugation are equal to $(-1)^{l+S}$ and positronium only decays with both particles in the ground state (l = 0), p-Ps has charge conjugation equal to -1 and o-Ps to 1 (Harpen 2003). "The charge conjugation parity of photons is equal to -1 and for a system of n photons will be $(-1)^n$" (Harpen 2003). Thus *n* has to be odd to obtain -1 for o-Ps and even to obtain 1 for p-Ps. Though this would obviously allow the annihilation of positronium into more than three photons (indeed, into any number), by far the most common decay modes are those of two photons and three photons since the branching ratios, which are a measure for probability, are of the order of 10^{-6} for annihilation into 4 and 5 photons and thus the likelihood of those scenarios is practically non-existent (Harpen 2003). One photon decay doesn't conserve momentum and thus does not occur. For more information see Heitler (1954, p272).

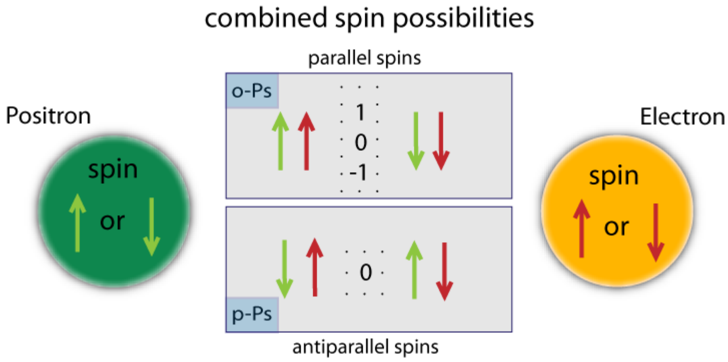


Figure 5: The combined spin possibilities of a positron and an electron. O-Ps has three variants and p-Ps has only 1, giving o-Ps a three-to-one plurality over p-Ps in nature.

For all these decay modes what is certain is that the combined rest mass energy of the two particles (the energy they have left in the ground state, according to Einstein's famous $E = mc^2$) of 1022 keV is divided amongst the photons that are radiated. This, combined with the conservation of momentum, imposes considerable restrictions on the dynamics of annihilation. In the case of p-Ps the two photons split the available energy equally and they radiate in opposite directions (Figure 7). o-Ps behaves differently. Since it radiates three photons the available energy is divided amongst the three, making sure of two things: The energy distribution directly affects the photon angles of radiation (to conserve the overall momentum of the 'static' Ps) and no photon can have exactly 511 keV in energy (Figure 8). What we have then are photons covering a broad range of energies rather than only 511 keV. The radiation spectrum for o-Ps excellently illustrates these different dynamics by its gradually rising shape, culminating in an abrupt drop (Figure 6), whereas p-Ps only emits two photons with each good for almost exactly 511 keV therefore resulting in a sharp peak at that energy.

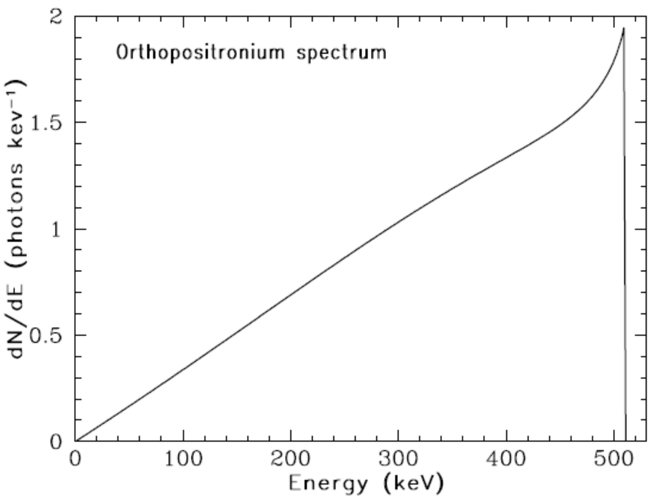


Figure 6: Three photon o-Ps theoretical annihilation spectrum (Ore & Powell 1949 via Prantzos et. al. 2010)

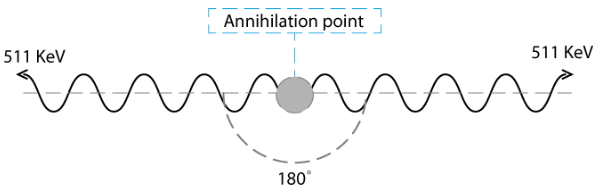


Figure 7: Two photon annihilation for para-Positronium. The combined rest mass energy of positronium (1022 keV) is split evenly between two photons which are emitted in opposite directions. Both of these restrictions are to conserve momentum.

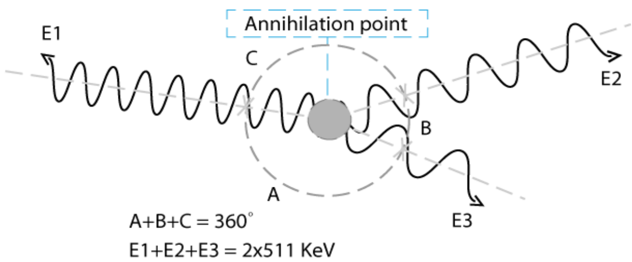


Figure 8: Three photon Annihilation for ortho-Positronium. The combined rest mass energy of positronium is split among three photons which are emitted in different directions to conserve momentum.

These emissions happen in numbers large enough to produce the spike in radiation intensity for 511 keV our satellites detect. The peak observed is an aggregation of the radiation spectra of p-Ps and o-Ps. Whereas p-Ps produces a very sharp peak at 511 keV, o-Ps produces the mentioned continuum, gradually rising in intensity right up to just below 511 keV, altogether nicely corroborating its theoretical underpinnings. It is the aggregation of these two peaks that allows scientists to confidently assert the insignificant role direct annihilation plays in its detection. Drawing such a conclusion requires the determination of the ratio between the peak of this aggregation and where the continuum of o-Ps below 511 keV takes over (Prantzos et. al. 2010). For more information on positronium one may refer to Griffiths (1987, p159).

To tread several steps back, the positron is then the particle the main source of which is contested. Considering the crucial role it plays in the 511 peak phenomenon, it is paramount to understand how and where the production of these positrons comes to pass. When deliberating an extragalactic source compared to a galactic one, it would be difficult to justify plunging into assumptions. While it is not the intention of this article to describe in painstaking detail the extragalactic sources and untangle the fundamental physics of particle production involved, the next section will briefly discuss the candidates.

Positron Sources

When trying to find the origin of the positrons causing the 511 keV line scientists mostly look within our own Galaxy for answers. That would be the obvious place to start given that we know positrons are created in galactic sources such as supernovae by means of β-decay and particle production processes (Knodlseder et.al. 2005, Prantzos et. al. 2010, Churazov et. al. 2010) There is one main problem regarding these known galactic sources however, which is morphology. Morphology relates to distribution, which is to say the arrangement of galactic objects or detected radiation within our galaxy. The problem is that there seems to be a discrepancy between the distribution of known galactic positron sources and the location of highest 511 keV radiation intensity, which is known as the galactic bulge and comprises the spherical volume making up the centre of the Milky Way (Knodlseder et.al. 2005, Vincent et. al. 2012). The bulge-to-disk ratio of radiation intensity is 1.4, higher than for any other radiation (Prantzos et. al. 2010). Supernovae most likely to produce positrons for example are generally located within the disk of the Milky Way (De Cesare 2011) and no definitive explanations exist to support the argument of positrons travelling through the crowded Milky Way to reach its core and annihilate there.

This is one reason why it's so important to study the possibility of extragalactic sources. A clear identification of which sources in the Universe are capable of producing a flux of positrons with the ability to reach the MW and cause the 511 keV line remains a source of discussion (no pun intended). The main category of candidates are active galaxies, amongst which are quasars, blazars and radio galaxies. They emit particles mainly through their core by way of relativistic jets (Giblin & Shertzer 2012) and hence these are called Active Galactic Nuclei (AGN). Exactly how these particles are produced and emitted is beyond the scope of this article. The interested reader may refer to Sol et. al. (1989), Despringre & Fraix-Burnet (1997) and Ghisellini (May 2012) for more information.

4. Positrons through the Intergalactic Medium

The InterGalactic Medium (IGM) is defined as the space separating galaxies. With most detectable matter contained within galaxies, the IGM is comparatively much less dense and thus provides, at first sight, a great medium for positrons to travel through for long distances. The IGM for a large part consists of the WHIM, or the Warm-Hot Intergalactic Medium, with temperatures extending from 10^4 K to several hundred thousand Kelvin (Bykov et. al. 2008), resulting in the Hydrogen that dominates its makeup to be ionized. This provides a cloud of protons and electrons which, combined with the CMB and magnetic fields, make up the bulk of the contents of the area this article will discuss.

The mean density of ionized hydrogen in the IGM has been determined to be (P. Madau & P. Murdin 2006)

$$n_H = (1.6 \times 10^{-7} cm^{-3})(1+z)^3 \qquad (1)$$

Which is 0.16 m^{-3}. To put that number in perspective, the density of air is of the order of 10^{19} particles per cubic centimetre (Wikipedia, Number Density). In cosmological terms, the critical density for a flat universe is approximately 5.8 hydrogen atoms per cubic metre (Perkins 2009, p120), considerably denser on a universal scale. The total baryonic part of that density however relates to about 0.24 hydrogen atoms per cubic metre (Perkins 2009, p121). Both indicate the sparse nature of the IGM. For the purpose of this article the redshift z will be taken to be 0. That is, areas in the relative vicinity of the MW. Considering the main source of electrons in the IGM is ionized hydrogen, the mean electron density and the mean proton density can be expected to equal that of the ionized hydrogen, $n_{e^-} = n_H = n_p$.

The IGM does not solely consist of particles. There are two more constituents which warrant a mention. The Cosmic Microwave Background radiation (CMB) is a radiation field consisting of low energy photons and is pervasive throughout the universe. This radiation can cause scattering effects with particles, so too positrons. Magnetic fields are also present but quite weak. It's not unlikely that they're the extremities of strong galactic magnetic fields which would also explain their random directions (Ginzburg 1979). Over long distances they may interact with particles and impact their energies. The mean energy density of the CMB is 1 eV/cm^3 (Weinberg, 2007). The strength of the magnetic field is more tricky as it can fluctuate wildly and be as low as 10^{-15} G (Tavecchio et. al. 2010), but for practical purposes a mean magnetic field strength of 1 µG, an approximation adopted based on among others Vecchio et. al. (2013) and Zweibel & Heiles (1997).

Contents of the IGM	Density/strength
Protons	1.6×10^{-7} particles/cm^3
Electrons	1.6×10^{-7} particles/cm^3
Magnetic Fields	1 µG
CMB	1 eV/cm^3

It is the interactions between positrons and the IGM which are key in determining the viability of an extragalactic source as a possible supplier to our galaxy, as interactions in physics mostly involve energy transfers and hence can result in energy losses to positrons. The goal is to determine the path-length traversed (or lifetime) of positrons of different energies through the IGM and the limits to the necessary parameters for a positron from the chosen source to reach the MW. The physics of traversing the IGM (Ginzburg 1979, Strong & Youssefi 1996) will pertain mostly to collisions (Compton Scattering, Coulomb Scattering), magnetic field interactions (Synchrotron Radiation) and Coulomb interactions (Bremsstrahlung).

Throughout this text the temperature of the intergalactic medium will be taken to equal 10^4 K. This is obviously a gross simplification but will serve our purposes well as it not only means the medium may be taken as ionised, but also that the electrons in the medium may be treated non-relativistically (Ryden). Other than that the temperature will play no direct role in coming calculations.

Interactions

The significant interactions a charged particle will undergo will each be discussed in detail in the following paragraphs.

Bremsstrahlung

Bremsstrahlung is the name given to the radiation (or the process causing it) emitted by a charged particle when it is accelerated due to the electric field of another charged particle. Laws of physics state that a charged particle, when accelerated, radiates energy. This radiation will result in an energy loss for a particle and is thus important to the study of a positron's propagation through the inhabited IGM.

This is a pervasive interaction as it involves the coulomb fields of the charged particles which, in effect, have an infinite reach. Of course to have a distinct impact such as to induce radiation from a positron, close proximity between the two particles is a proviso. The relevant interactions in this case are positron-electron interactions and positron-proton interactions (Rybicki & Lightman 2004). To determine the energy loss of a positron over time due to bremsstrahlung Ginzburg's equations will be employed (Ginzburg 1979, p386) for a completely ionised hydrogen plasma and pertaining to ultra-relativistic electrons.

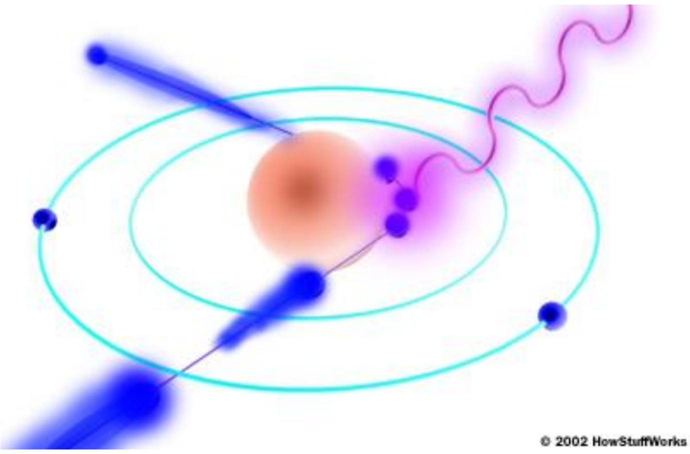


Figure 9: Bremsstrahlung, in this case involving an electron and a proton. The electric fields of two charged particles interact and the consequent acceleration taking place causes the particles to emit radiation, Source: Dr. M. K. Yip, physics.hku.hk

$$-\frac{dE}{dt}_B = 7\times 10^{-11}N \;\; ln\frac{E}{mc^2} + 0.36 \;\; \frac{E}{mc^2} \; eVs^{-1}$$

In the pertinent case the following values apply: $N = n_H = 1.6 \times 10^{-7} cm^{-3}$
Filling in the relevant values one obtains

$$-\frac{dE}{dt}_B = 2.18\times 10^{-23} \; lnE - 12.78 \; E \; eVs^{-1}$$

Inverse Compton Scattering (ICS)

Another important interaction is Inverse Compton Scattering (ICS) where high-energy positrons scatter with low-energy photons. The photon will gain energy and is likely to reach x-ray territory while the positron loses energy. The most prevalent type of photons in the universe are low-energy photons making up the CMB and are thus of low enough energy to facilitate ICS. For the energy loss due to ICS we have (Strong & Youssefi 1996)

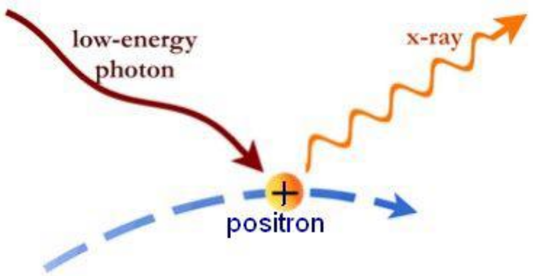


Figure 10: Inverse Compton Scattering. The low energy photon scatters off a positron and 'takes' some of its energy in the process, Source: physics.uoregon.edu

$$-\frac{dE}{dt}_{ICS} = 2.64 \times 10^{-14} \cdot W_{ph} \frac{E}{mc^2}^{2} eVs^{-1}$$

Where W_{ph} is the photon energy density which in our case is the CMB. Filling in the values pertinent to the case one obtains:

$$-\frac{dE}{dt}_{ICS} = 1 \times 10^{-25} E^2 eVs^{-1}$$

Synchrotron effect

Synchrotron radiation occurs due to the magnetic fields present in the universe. As a charged particle moves through them it will revolve around the field lines and undergo a radial acceleration (comparable to a centripetal force) as Maxwell's equations prescribe. This acceleration of a charged particle induces it to radiate. Because of their irregularity over intergalactic distances the directions of the magnetic fields will be taken as random (Ginzburg 1979, p386).

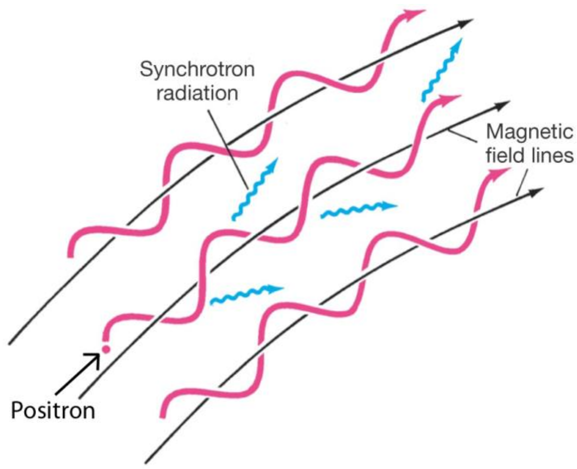


Figure 11: Synchrotron Radiation. As the positron revolves around the magnetic field lines it emits radiation, Source: A. MacKinnon & P. Mallik, sprg.ssl.berkeley.edu/

For the energy loss of an electron due to synchrotron radiation we have (Strong & Youssefi 1996)

$$-\frac{dE}{dt}_{S} = 9.8 \times 10^{-4} \cdot H_{\perp}^2 \frac{E}{mc^2}^{2} eVs^{-1}$$

Where $H_{\perp}$ is the perpendicular component of the magnetic field and $H_{\perp}^2 = \frac{2}{3}H^2$ is due to the variability of the direction of the magnetic fields (Ginzburg 1979, p386). Due to the wildly varying magnetic fields the value of 1 μG will still be maintained. Filling in the values pertinent to the case one obtains:

$$-\frac{dE}{dt}_{S} = 3.75 \times 10^{-27} \cdot E^2 eVs^{-1}$$

Ionisation

Ionisation losses occur in scattering events between positrons and electrons or protons in the plasma. This is not ionisation as is taught in secondary school. Rather here the term refers to collisions between positrons and protons and electrons. Energy losses as a result of a collision might occur by the emission of radiation, as is in the figure to the right, or by exchange of kinetic energy. For the energy loss of an electron due to ionisation in an ionized gas we have (Ginzburg 1979, p385)

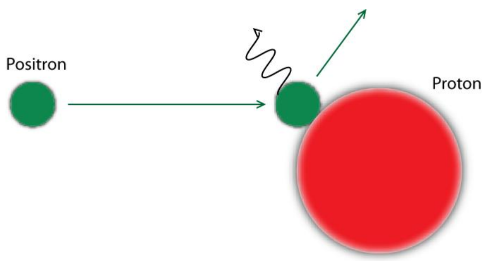


Figure 12: Ionisation, in this case involving a positron and a proton. The positron collides with a proton, thereby deflecting and losing energy either by radiating (shown here) or by transferring kinetic energy to the proton.

$$-\left(\frac{dE}{dt}\right)_I = 7.62\times 10^{-9}N\left(ln\frac{E}{mc^2} - \ln N + 73.4\right)\ eVs^{-1}$$

Filling in the values pertinent to the case one obtains

$$-\left(\frac{dE}{dt}\right)_I = 1.22\times 10^{-15}\left(ln\, E + 44.6\right)\ eVs^{-1}$$

Combined energy loss

Combining the energy losses for the different interactions one obtains the Energy Loss Equation (ELE) for relativistic positrons moving through a completely ionised gas.

$$-\left(\frac{dE}{dt}\right)_{Total} = 2.18\cdot 10^{-23}\left(lnE - 12.78\right)E + \left(1\cdot 10^{-25} + 3.75\cdot 10^{-27}\right)E^2 + 1.22\cdot 10^{-15}\left(ln\, E + 44.6\right)\ eVs^{-1}$$

It is immediately apparent that for higher energies synchrotron and ICS will be the dominant interactions for energy losses.

5. Effect on the positron source spectrum

Positron sources in the universe emit particles with a range of energies and since probabilities for annihilation tend to be energy-dependent (Heitler 1954, p271), it is worth inspecting the evolution of the source spectrum of a flux of particles covering a range of energies. Not only can an evaluation of the change of the energy spectrum show whether or not (and if so how many) positrons will be able to reach the MW from extragalactic sources, the method, owing partly to its modest flexibility, can also be used to provide an insight into the density of the region through which the positrons have travelled and, with proper models of source spectra, what source they originated from.

To achieve even moderately trustworthy and informative results a robust computer program needs to be constructed. For the purpose of this article a rather modest script will suffice. One has been written with Matlab to determine the shift in energy for particles traversing the IGM for a set period of time. Considering the troublesome differential equation a numerical approach has been taken using Euler's method (derived from Moehlis 2001). For briefness' sake further information on the program including the code itself is nested in Appendix A.

Several simplifications have been made which should be mentioned in the main text for clarity's sake. The source spectrum has been generated using the rather generic power law formula for cosmic rays, being of the form

$$Flux\left(E\right) = 10^{27}E^{-2.8}\,(m^2\cdot sr\cdot s\cdot GeV)^{-1}$$

With the flux having units of $(m^2\cdot sr\cdot s\cdot GeV)^{-1}$. Figure 13 plots this generic spectrum. Not much notion should be given to this formula. It simply states that there are more low energy positrons than there are high energy ones. More precisely, the quantity of positrons increases exponentially with decreasing energy, as it takes more energy to produce high energy ones. The factor 10^{27} is chosen so the graph will roughly follow the values of the cosmic ray spectrum detected on earth. The maximum value for initial energies has been taken to be 10^{21} eV, again in accordance with the cosmic ray spectrum. Considering the highest energy cosmic rays detected on earth have energies near 10^{21} eV one could assume this is roughly the limit for these particles, but although this is not a certainty any particles with energies of around 10^{20} eV bear an insignificant effect on final results.

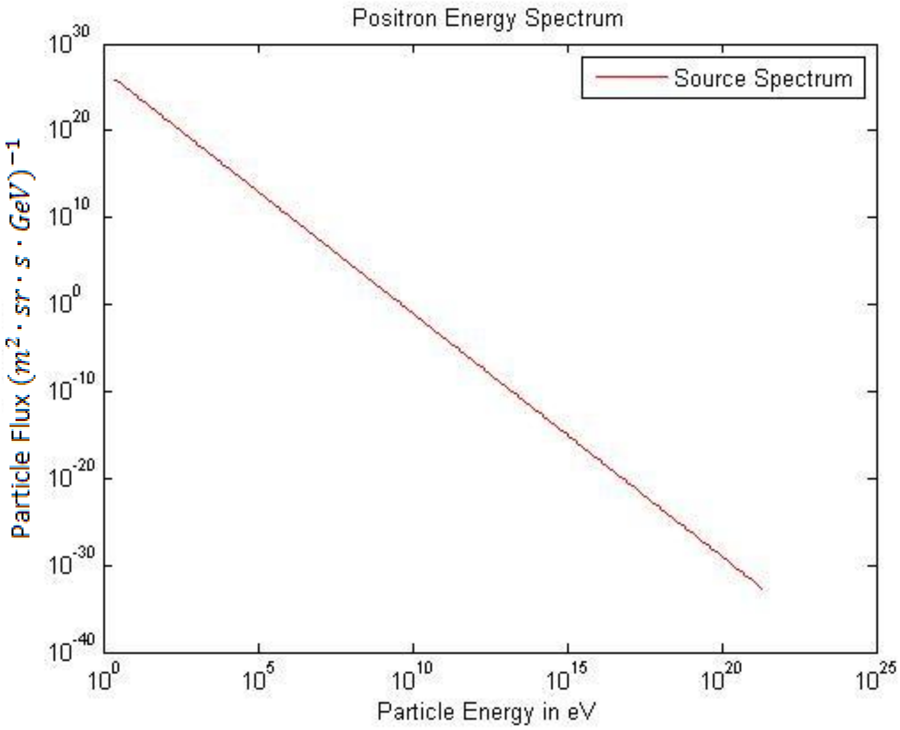


Figure 13: The source spectrum utilised. The units of the flux do not serve the purpose of the article and have been omitted for clarity. Important to note is the logarithmic scale on both axes and the steep decline of the flux as the energy rises. The plot illustrates the high number of low energy positrons compared to low numbers of high energy positrons.

Nevertheless, these remain approximations and more than a slight note should be taken regarding their simplified nature. It will however serve us well in giving an indication of the relative variance between the initial and final spectrum. Furthermore, the lower cut-off point for energies should be roughly 10^6 keV, not only as the Lorentz factor for a positron would then approach non-relativistic values and thus the equations used will lose their validity but also since the observed annihilation spectrum suggests positrons are injected in the MW with energies equalling roughly 3 MeV (De Cesare 2011), leaving as necessity only proof that a beam of positrons should be above that energy when it reaches the MW. More clearly, at energies of about 1 MeV the Lorentz factor will equal 2.

There are some important matters which require a discussion before proceeding to the results. High energy electrons (and hence positrons) do not always experience continuous energy loss. Rather, for particular interactions, like bremsstrahlung, they can lose the bulk of their energy in one “catastrophic” interaction (Ginzburg 1979, p409). The ELE does not take that into account, instead giving the average energy loss for the beam of particles. Furthermore, diffraction due to particle deflection will be neglected. While this factor can have a noticeable influence, it is particularly useful for a more advanced approach on this subject. It will be assumed that the emitted positron beam will have a sufficient quantity of particles left in the axis of its emission to facilitate the framework within which this research operates. Finally, in-flight annihilation of positrons during propagation through the IGM will be deemed as having inconsequential influence on the final results. This can be partially justified by Heitler’s statement that up to 20% of energetic positrons may annihilate in flight (Heitler 1954, via Yüksel 2007). Specifically, the cross-section equation for in-flight annihilation between an energetic positron and an electron at rest (which, relative to the fast positron, it nearly is) has a maximum for a positron with a ϒ-factor of around 1 (Heitler 1954, p271), which lies in an unimportant energy region. For a more rigorous analysis of positron propagation one should confer to the transfer equation (Ginzburg 1979, p376, Strong & Youssefi, 1996).

All in all, regarding the main goal of assessing the possibility of positrons being able to reach the Milky Way in theory, any losses of particles in a beam caused by these simplifications will be percentile based and thus have a negligible effect on a capacious beam in absolute terms. That is to say, if any particles can make it to the MW, reducing the particle beam by a percentage would still uphold the possibility.

Timescale of Energy Loss

First, to illustrate the effects of the different interactions and prove the correctness of them and the program used for this article, a timescale energy loss graph is pictured (Figure 14. For more see Appendix B). This plots, for each interaction, the general length of time it takes for a positron to lose half of its initial energy.

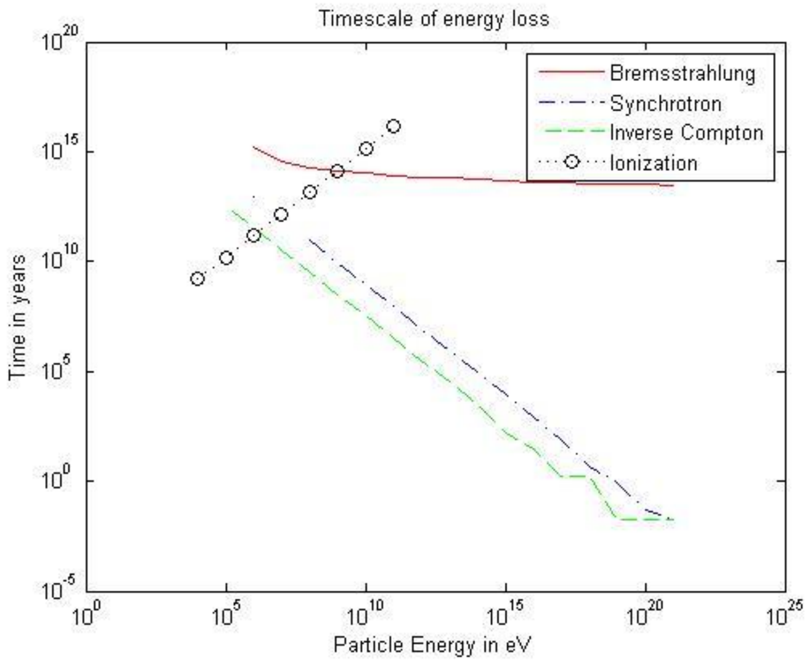


Figure 14: Timescale of energy loss. The graphs show for each interaction how long it takes for a positron to lose half its energy, depending on its initial energy.

A few notes first. The cut-off points and the wobbly tail ends of the Synchrotron and the Inverse Compton (ICS) graphs are not very trustworthy. The low cut-off point occurs in an irrelevant region. The distortion for high energies can be remedied with a more advanced program but the graphs serve their purpose well in their current form in illustrating the increasing dominance of the synchrotron effect and ICS for higher energy particles. These two graphs seem so similar because of the dependence of both interactions on E^2 and are only separated by a factor 27 as can be seen by the energy loss equations. The main region of interest is the middle region. It is then interesting to see which interactions dominate in which energy regions. Most remarkable are the effects of the Synchrotron radiation and ICS for high energy positrons. Extrapolating the graphs one can easily make the assumption that positrons beyond 10^{17} eV have, in galactic terms, barely a moment to live before conceding a very large part of their energy to the contents of the IGM. Indeed, it would seem a long journey through the IGM for positrons of such high energies would simply be unachievable.

Conversely, for low energies ionisation takes the upper hand, though not to the same degree as the former two interactions do at high energies. This simulation seems to indicate ionisation as the foremost cause of annihilation, rather than of simple energy loss at low energies. Considering the crossing point between ionisation and ICS practically signals the transition to a non-relativistic region (at which point positronium formation is increasingly likely to materialise), this would at first sight not constitute a region forming a fertile ground for a multiplicity of collisions as only one interaction would suffice to terminate the particle.

Bremsstrahlung has very little influence and can thus be disregarded considering the more general view of this article.

Spectrum Changes

Now we need to look into the effect any energy changes can have on the source spectrum. To accomplish this, a particularly well-known galaxy will be taken as a hypothetical source: the Andromeda galaxy. That is to say, we will evaluate the positron spectrum we might see on earth compared to the original spectrum (the artificial one) we assume Andromeda emits toward us. This is a hypothetical situation and merely serves to show whether Andromeda could in theory provide the Milky Way with positrons. Otherwise there is no clear evidence in the knowledge of the author that Andromeda even produces positrons. The galaxy is a relatively close-by one, lying 'only' 2.5 million light years from the MW.

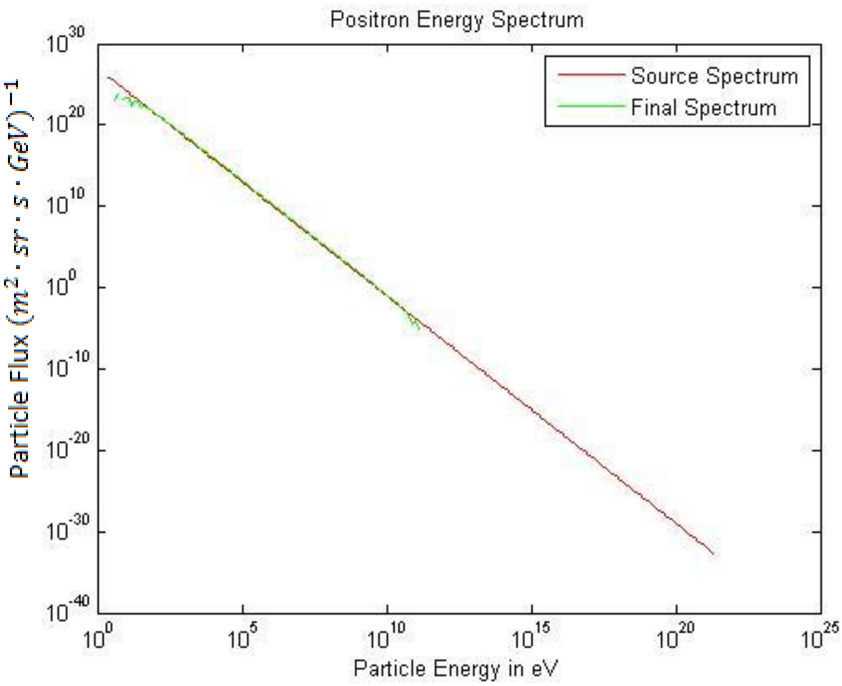


Figure 15: The expected spectrum of the positron beam upon arrival in the Milky Way (green) from Andromeda superimposed on the source spectrum (red).

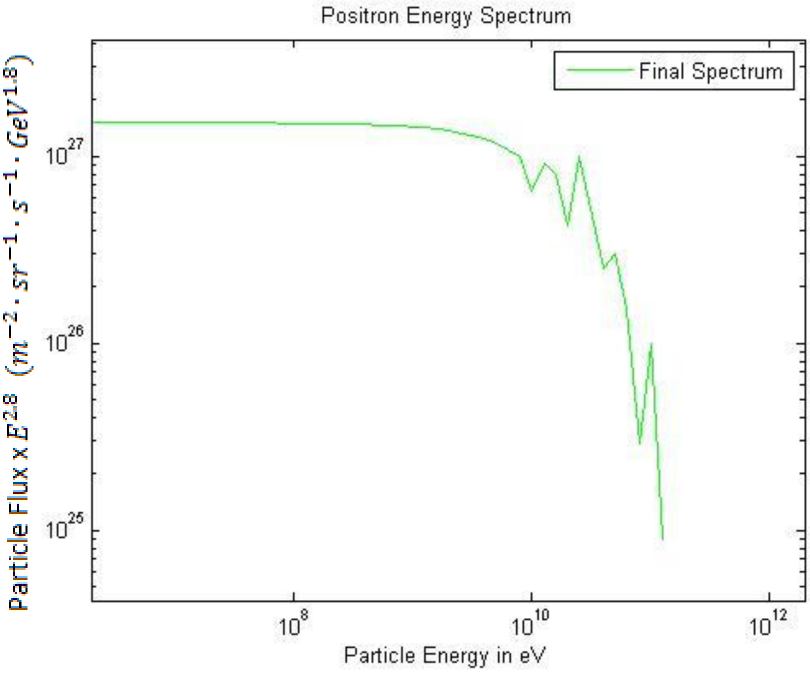


Figure 16: Close up of the highest energy part of the final spectrum. Achieved by multiplying the spectrum by $E^{2.8}$.

Figures 15 & 16 show the results obtained and they are apparent. What the plot shows (Figure 15) is a near complete absence of positrons with energies higher than about 10^{11} eV among the ones potentially reaching our Milky Way. It is important to note that in the scheme of the used equations no high-energy positrons should be assumed annihilated. Their energies have simply been reduced to such an extent that they find themselves heaped up with positrons of lower energies. One would then expect to see the final spectrum peak towards its end and when magnified (by multiplying the flux with $E^{2.8}$) the graph is definitely erratic (Figure 16), resultant from the discreteness of the code. The reason this peak isn't quite visible in figure 15 lies in the strongly logarithmic y-axis. Higher energy positrons are accumulated as their energies decrease due to the strong effect of synchrotron radiation and ICS. Positrons of energies below 10^{6} eV (1 MeV) are unimportant and that region may be disregarded. It's worth reminding the reader that in reality some positrons have already annihilated on the journey through the IGM and that these are general results pertaining to the average energy distribution in the beam.

As discussed the positrons responsible for the annihilation peak observed by our satellites are determined to be injected into the Milky Way with energies of several MeV and while these are definitely present, to claim a galaxy as a possible source we can do better and try to find a galaxy which can produce positrons which peak at just these energies and not at 10^{10} eV as is the case with Andromeda. Though fewer in number, these positrons of higher energy should have left a mark on the observed gamma-ray spectrum if annihilated in the MW. To find such a possible source we turn our attention to the farthest known galaxy we know of: UDFj-39546284, a good 13.4 billion light years away. Could this galaxy accommodate us better than Andromeda? The plots below shed light on the answer.

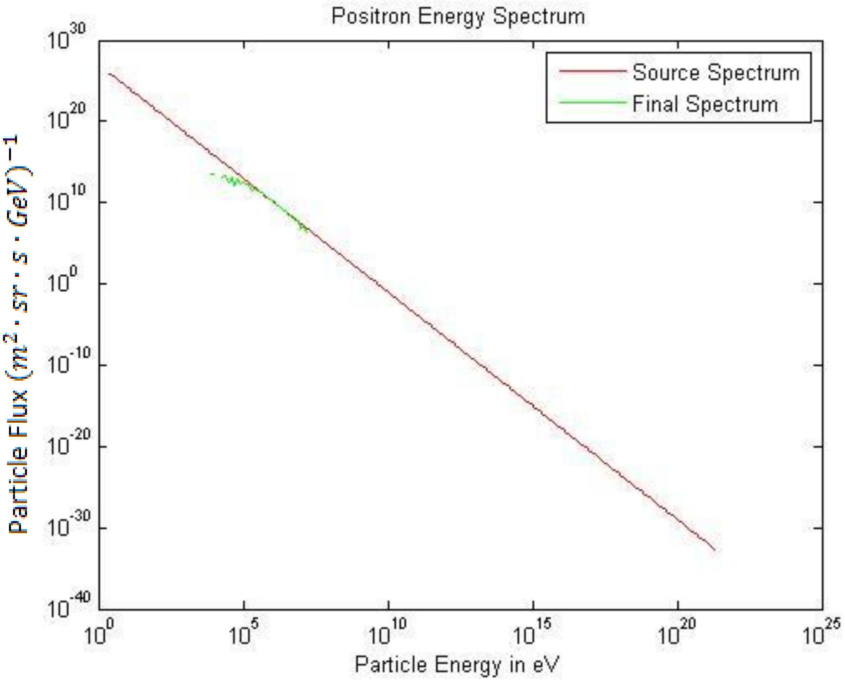


Figure 17: The expected spectrum of the positron beam upon arrival in the Milky Way (green) from UDFj superimposed on the source spectrum (red).

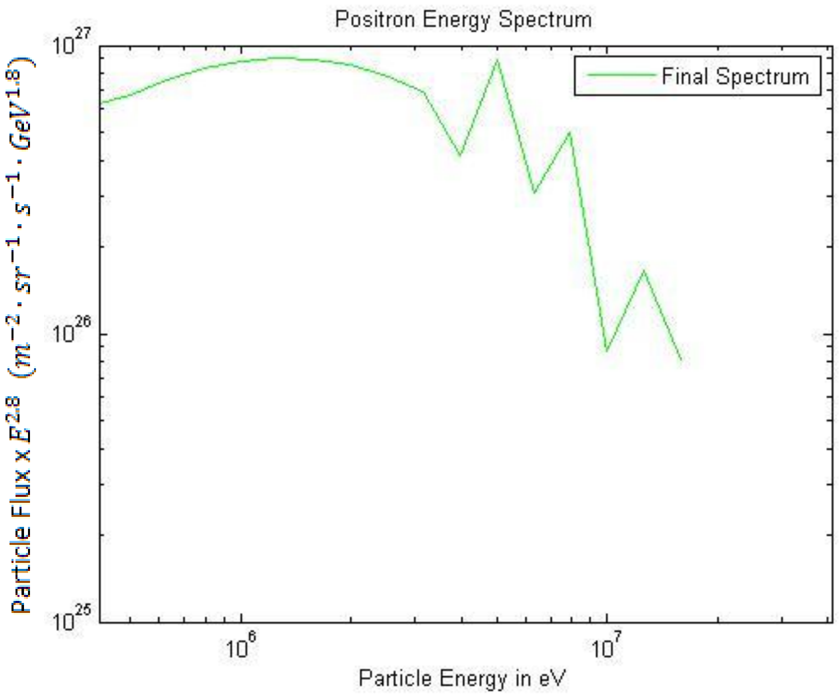


Figure 18: Close up of the highest energy part of the final spectrum. Achieved by multiplying the spectrum by $E^{2.8}$.

As is noticeable, even the farthest known galaxy to mankind could theoretically provide us with positrons and crucially, they seem to fit the bill nicely as their highest energies lie roughly in the few MeV region. However, there is a large barrier preventing such a hasty conclusion. We may recall that the density of ionised Hydrogen in the IGM depends on the redshift to the third power, which is a strong dependence but one which can be generally neglected for situations with near zero redshift, like in the vicinity of our Milky Way as this article presumes. But a redshift of 5 would increase the density by a factor of more than 200, thereby complicating the statement of all galaxies being viable candidates. For more on the dependence on density see Appendix C.

For both galaxies the plots may be explained by a quick look at the ELE and its constituent equations for each interaction. Two features stand out in both graphs. Both share the same basic shape in the area where a sudden termination occurs and both seem unchanged before the drop. Both effects can be explained by the ELE. Since the E^2 term is the dominant one in it for higher energies, as long as it's larger than the pre-factors it is multiplied with, the positron will steadily experience a healthy quadratic drop in energy. Once the E^2 term closes in on balancing out the pre-factors the energy decrease will become increasingly less pronounced and relatively small, incremental portions of energy will be lost. Ionisation only plays a significant role in energy regions not important to our case. This leaves the middle region where, as a quick look at the timescale of energy loss graphs show, the effect of all interactions combined is at its weakest and thus we see the positrons in that region nearly untouched.

These powerful results shouldn't be taken too seriously as more robust programming is needed to give more reliable outcomes. Nevertheless it is interesting to note that every known galaxy in the universe is a possible source of positrons and can thus contribute, albeit theoretically, to the 511 keV peak we detect. This leaves an inestimable number of galaxies to inspect more closely and not simply to analyse their involvement in the 511 keV peak mystery. A galaxy positioned towards us can be the source of a wealth of information, not least on galactic jets.

Discussion

The finds are interesting and evident. Not only are extragalactic sources a possibility, even the farthest known galaxies can function as a source to explain the 511 keV peak. Both Andromeda and UDFj-39546284 galaxy show that an emitted positron beam from those galaxies could theoretically reach the Milky Way. However there are still questions left unanswered among which is the uncertainty regarding the energy value of positrons injected in the MW. Considering they should have a few MeV of energy left the question is if a galaxy like Andromeda were to provide us with positrons then what role do the higher energy positrons in the beam play?

While for the sake of practicality this article used equations showing a gradual energy loss, which in fairness can be more easily applied to a beam of particles, for some interactions positrons can lose most of their energy in one or two collisions (Ginzburg 1979, p409). This especially holds for high energy positrons/electrons (creating gamma-rays which we can detect on earth). The plots then can be assumed not to necessarily indicate high energy particles shifting to middle energy levels but, going by the timescale of energy loss, one may presume them to be of such low energy after early interactions that they will be annihilated in the IGM before long. More plausible is the prospect of positrons with middle energies undergoing far fewer interactions and thus making it to the MW virtually unscathed.

One may also look into finer detail. Diffraction most certainly plays a role as the particle beam moves through the IGM. Perhaps this could prove to answer the uncertainty of the role of high energy positrons entering the MW by having them most likely to have scattered away from our galaxy. In the quest to finding a viable source candidate, galaxy orientations must be taken into account as well. In which direction should a particle beam be oriented were it to provide us with the positrons of exactly the energy to explain the 511 peak? The contents of the IGM also play a more significant role as for the purpose of this article they have been simplified. The true contents have not just more breadth in variety. Over large scales their composition may not be assumed to be homogeneous, especially regarding the magnetic fields which fluctuate between extremely disparate values. Therefore any trajectory between a particular particle jet and the MW has to be taken into account. Lastly, our detection equipment needs to be improved to deliver more detailed results and a better view of the 511 radiation from our galaxy. As stated by Bouchet et. al. (2010) the "modest angular resolution and limited sensitivity of γ -ray instruments" is still a hurdle that needs to be overcome.

For the interested reader Appendix C provides plots for several hypothetical scenarios for positrons travelling through different regions of space. It serves to exemplify the dominance of the different interactions in particular energy regions. Most interesting is to observe the clear possibility of positrons traveling from the edge of the Milky Way to the bulge. Though of less importance to the subject of this article, it does allow for theories of galactic sources. More information and comment, including the dependence of the results on varying magnetic field strengths and particle density, is included in the appendix.

As for the relation between an extragalactic beam of positrons and the high intensity of 511 radiation emitted by the galactic bulge, a number of scenarios may offer an explanation. Because of the long distance it has travelled the beam may be assumed to be practically homogeneous in density and non-divergent in the vicinity of the MW. It is then likely to interact with the MW mainly by way of gravity and by magnetic fields. Regarding interactions between magnetic fields of the M, the scope of this article did not accommodate an analysis substantial enough to provide meaningful explanations. A not unrealistic scenario could involve gravity. The more massive bulge (Djorgovski 2004) compared to the less dense and thin disk (Han 2012) could sway bypassing positrons toward the centre. One could imagine that a beam travelling parallel to the galactic plane would provide a more viable case as the more voluminous bulge would not only physically catch more positrons, its mass would attract particles that otherwise would have passed it by. Though these are mere conjectures and such a case would probably result in increased radiation intensity at the edge of the galactic disk.

To end, the long search for these mysterious sources responsible for injecting positrons in the Milky Way is so heavily focused on galactic objects that the clearly present possibility of the contribution of another galaxy is treated with near disregard. This article aimed to show that in theory another galaxy can provide the Milky Way with positrons that meet the criteria required to be responsible for the 511 keV peak and it has shown that indeed this is the case. While the methods and theory used were relatively rudimentary it still does not diminish the importance a closer inspection of possible extragalactic sources should be given. If not to find a (partial) explanation to the 511 keV peak, then to uncover the secrets of galaxies on the farthest stretches of the known universe. It was one of the few articles on this subject (Vecchio et. al. 2013) which inspired the writing of this one, but whereas it discussed the possibility of galactic magnetic fields keeping positrons from diffusing, it has become clear that neither such a detour is necessary nor even one involving magnetic fields holding positronium atoms stable to possibly reach the Milky Way (Giblin & Shertzer 2012).

Scientists must not forget that as with most everything in science curiosity is the final scapegoat in our continuing search for answers to the unknown. Whether here on earth on microscopic scales or in another galaxy. The poignant mystery revolving the significant 511 keV peak has been left with no clear answer in spite of more than 4 decades of research. The significant option of an extragalactic source must not be omitted to the extent that it is as it might prove to be the answer mr. Johnson had been looking for.

Further reading

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- Positronium figure inspired by: http://www.daviddarling.info/encyclopedia/P/positronium.html , accessed July 2013

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7. Appendix A. Matlab Code

A huge thanks to Prof. Olaf Scholten for his invaluable contribution and support to the building of this code

Code for the plotting of the source and final spectra

```
%ics and synch constants
    z = 3.75*10^-15;
    y = 1*10^-25;
%brems constants
    x = 1.37*10^-16;
    w = 12.78;
%ionization constants
    v = 7.62*10^-9;
    u = 60.26;

    efac = 210;% the number of energyvalues

wph = 1; %photon energy density in ev/cm3
h = 1*10^-6; %magnetic field strength in gauss
dens = 1.6*10^-7; %electron/hydrogen density in cm-3

%#################Set up of arrays to contain energy
values######################
flux0 = zeros(1,efac);
fluxf = zeros(1,efac);
e0 = zeros (1,efac);
ef = zeros (1,efac);
edel = zeros (1,efac-1);
efdel = zeros (1,efac-1);
npoints = 10^6;
tfinal = 4*10^17;

%#################Calculation of E0#######################
for l = 1:efac
    e0(l) = 10^((l+3)/10);
    flux0(l) = 10^27*e0(l).^-2.8;
end

%#################Calculation of E-delta######################
% The next loop calculates the midway points of two E0's: the delta Es
for kj = 1:(efac-1)
    edel(kj) = (e0(kj+1)+e0(kj))/2;
end

loglog(e0,flux0,'r'); % This will display the double-power plot of the synthetic
source spectrum
hold on;

e = zeros(npoints,1);

%#################Calculation of Efinal#######################
for m = efac:-1:1
    e(1) = e0(m);
    dt = 0.01;
    ttot = 0;
    step = 1;
```

```
        while ttot < tfinal
            e(step+1) = e(step) - dt*( (y*wph+z*h^2)*(e(step)^2)+
x*dens*(log(e(step))-w)*e(step) + v*dens*(log(e(step))-log(dens)+ u) );
            ttot = ttot + dt;
            ef(m) = e(step+1);
            if e(step+1)/e(step) > 0.99
                dt = dt*10;
            end
            step = step + 1;
        end
end

%################Calculation of Efinal-delta######################
for m = efac-1:-1:1
    e(1) = edel(m);
    dt = 0.01;
    ttot = 0;
    step = 1;
        while ttot < tfinal
            e(step+1) = e(step) - dt*( (y*wph+z*h^2)*(e(step)^2)+
x*dens*(log(e(step))-w)*e(step) + v*dens*(log(e(step))-log(dens)+ u) );
            ttot = ttot + dt;
            efdel(m) = e(step+1);
            if e(step+1)/e(step) > 0.99
                dt = dt*10;
            end
            step = step + 1;
        end
end

%################Calculation of final fluxes######################
dj = efac;
for start = efac:-1:2
        while ((e0(start) > ef(dj)) && (e0(start-1) < ef(dj)))
            fluxf(start) = fluxf(start) + flux0(dj);
            dj = dj - 1;
        end
end

%################Correction for 'spillage' due to two efinal values lying on
either side of an e0 value######################
dj2 = efac;
for start2 = efac:-1:3
    if ((e0(start2) > ef(dj2)) && (e0(start2-1) < ef(dj2)))
        while ((e0(start2) > ef(dj2)) && (e0(start2-1) < ef(dj2)))
            if (efdel(dj2-1) <= e0(start2-1))
                fluxf(start2) = fluxf(start2)-flux0(dj2)*((e0(start2-1)-
efdel(dj2-1))/(efdel(dj2)-efdel(dj2-1)));
                fluxf(start2-1) = fluxf(start2-1)+flux0(dj2)*((e0(start2-1)-
efdel(dj2-1))/(efdel(dj2)-efdel(dj2-1)));
                dj2 = dj2-1;
            elseif (efdel(dj2-1) >= e0(start2-1))
                fluxf(start2) = fluxf(start2)+flux0(dj2-1)*((efdel(dj2-1)-
e0(start2-1))/(efdel(dj2-1)-efdel(dj2-2)));
                fluxf(start2-1) = fluxf(start2-1)-flux0(dj2-1)*((efdel(dj2-1)-
e0(start2-1))/(efdel(dj2-1)-efdel(dj2-2)));
                dj2 = dj2-1;
            end
        end
    else
    end
end

%################Code for close up of plots######################
% for ph = 1:efac
```

```
%      fluxf(ph) = fluxf(ph)*(ef(ph).^(2.8));
% end

%################Plotting of the final spectrum and graph
information######################
loglog(e0, fluxf, 'g');
title('Positron Energy Spectrum')
xlabel('Particle Energy in eV')
ylabel('Particle Flux')
legend('Source Spectrum','Final Spectrum')
```


Code for the plotting of the Timescale of energy loss

```
%ics and synch constants
z = 3.75*10^-15;% synch
y = 1*10^-25;% ics
%brems constants
x = 1.37*10^-16;
w = 12.78;
%ionization constants
v = 7.62*10^-9;
u = 60.26;

efac = 18; % number of energy values
yf = 3*10^7; % seconds in a year--> YearFactor

wph = 1; %photon energy density in ev/cm3
h = 10^-6; %magnetic field strength in gauss
dens = 1.6*10^-7;%*10^-7; %electron/hydrogen density in cm-3

%################Sets up arrays for the values which will be
plotted######################
tm = zeros(1,efac);
flux0 = zeros(1,efac);
e0 = zeros (1,efac);
ef = zeros (1,efac);
npoints = 10^5; %number of steps
dtb = 10^20; %amount of seconds in one step for bremsstrahlung
dti = 10^23;
dtsi = 10^4;

%################Calculation of intial energies and flux######################
for l = 1:efac
e0(l) = 10^((l+3));
flux0(l) = 10^27*e0(l).^-2.8;
end

%################Calculation of half-times for each
interaction######################
%================================Bremsstrahlung===================================
===

e = zeros(npoints,1);
t = zeros(npoints,1);

for m = 1:efac
e(1) = e0(m);
t(1) = 0;
    for step = 1:npoints-1
        e(step+1) = e(step) - dtb*(  x*dens*(log(e(step))-w)*e(step) );
     t(step+1) = t(step) + dtb;
        if ((e(step) > e(1)/2) && (e(step+1) < e(1)/2))
```

```
            tm(m) = (t(step+1)+t(step))/2;
            ef(m) = e(step);
            disp (ef(m))

        end
    end
end

for ty = 1:efac
    tm(ty) = tm(ty)/yf; %conversion of second to year
end

loglog(ef,tm, '-r');
hold on;

%=====================================Synchrotron==============================

e = zeros(npoints,1);
t = zeros(npoints,1);
ef = zeros(1,efac);
tm = zeros (1,efac);

for m = efac:-1:1
    e(1) = e0(m);
    t(1) = 0;
    if mod (m,3) == 0
        dtsi = dtsi*10^2;
    end
    for step = 1:npoints-1
        e(step+1) = e(step) - dtsi*( (z*h^2)*(e(step)^2) );
        t(step+1) = t(step) + dtsi;
        if ((e(step) > e(1)/2) && (e(step+1) < e(1)/2))
            disp (e(step));
            tm(m) = (t(step+1)+t(step))/2;
            ef(m) = e(step);
        end
    end
end

for ty = 1:efac
    tm(ty) = tm(ty)/yf;
end

loglog(ef,tm, '-.b');
hold on
%========================================ICS=================================
e = zeros(npoints,1);
t = zeros(npoints,1);
ef = zeros(1,efac);
tm = zeros (1,efac);
dtsi = 10^4;

for m = efac:-1:1
    e(1) = e0(m);
    t(1) = 0;
    if mod (m,3) == 0
        dtsi = dtsi*10^2;
    end
    for step = 1:npoints-1
        e(step+1) = e(step) - dtsi*( (y*wph)*(e(step)^2) );
        t(step+1) = t(step) + dtsi;
        if ((e(step) > e(1)/2) && (e(step+1) < e(1)/2))
            disp (e(step));
            tm(m) = (t(step+1)+t(step))/2;
```

```
            ef(m) = e(step);
        end
    end
end

for ty = 1:efac
    tm(ty) = tm(ty)/yf;
end

loglog(ef,tm, '--g');
hold on

%=================================Ionization=================================

e = zeros(npoints,1);
t = zeros(npoints,1);
ef = zeros(1,efac);
tm = zeros (1,efac);

for m = efac:-1:1
    e(1) = e0(m);
    t(1) = 0;
    if mod (m,3) == 0
        dti = dti/(10);
    end
    for step = 1:npoints-1
        e(step+1) = e(step) - dti*(  v*dens*(log(e(step))-log(dens)+ u) );
        t(step+1) = t(step) + dti;
        if ((e(step) > e(1)/2) && (e(step+1) < e(1)/2))
            tm(m) = (t(step+1)+t(step))/2;
            ef(m) = e(step);
        end
    end
end

for ty = 1:efac
    tm(ty) = tm(ty)/yf;
end
loglog(ef,tm, ':ok');
legend('Bremsstrahlung','Synchrotron','Inverse Compton','Ionization');
title('Timescale of energy loss')
xlabel('Particle Energy in eV')
ylabel('Time in years')
```

8. Appendix B. Timescale Graph Comparison

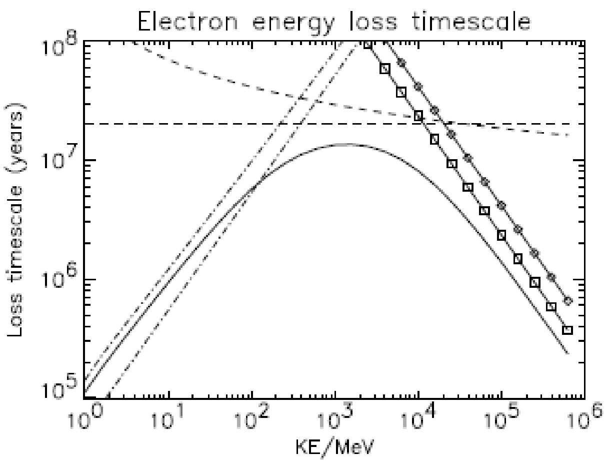
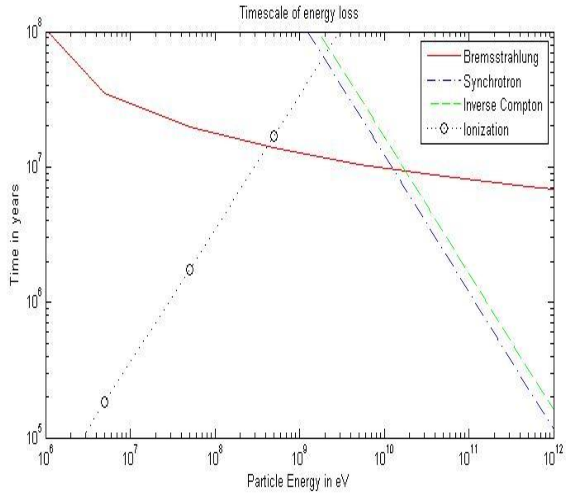


Fig. 5 . Energy loss timescales for electrons, illustrated for $n_{HI}=n_{HII} = 1\ \mathrm{cm}^{-3}$, $H_{\perp}=6\mu\mathrm{G}$, $W_{ph}=1\ \mathrm{eV\ cm}^{-3}$. Thick, thin dashed lines: bremsstrahlung on neutral and ionized hydrogen; thick, thin dash-dot lines: Coulomb losses on neutral and ionized hydrogen; squares: synchrotron; diamonds: inverse Compton. Full thick line: total for same parameters except that $n_{HII} = 0.1\ \mathrm{cm}^{-3}$).

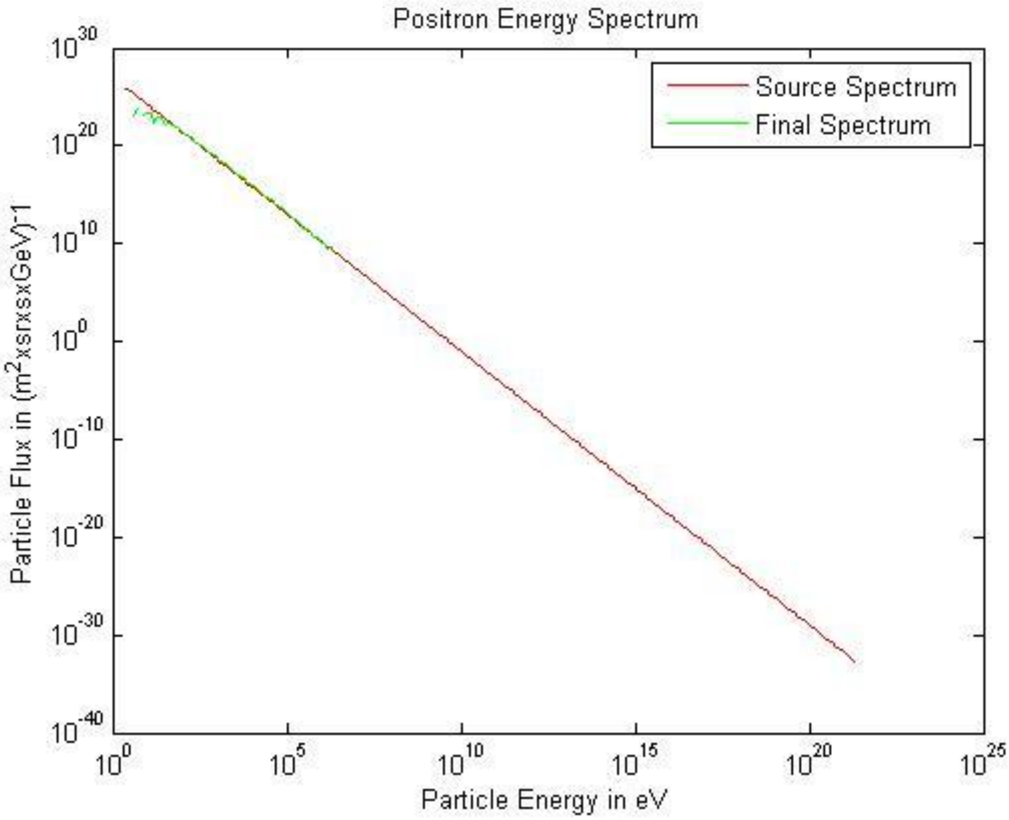
Figure from original article by Strong & Youssefi (1996)



Reproduced figure with same parameters with the code used for this article.

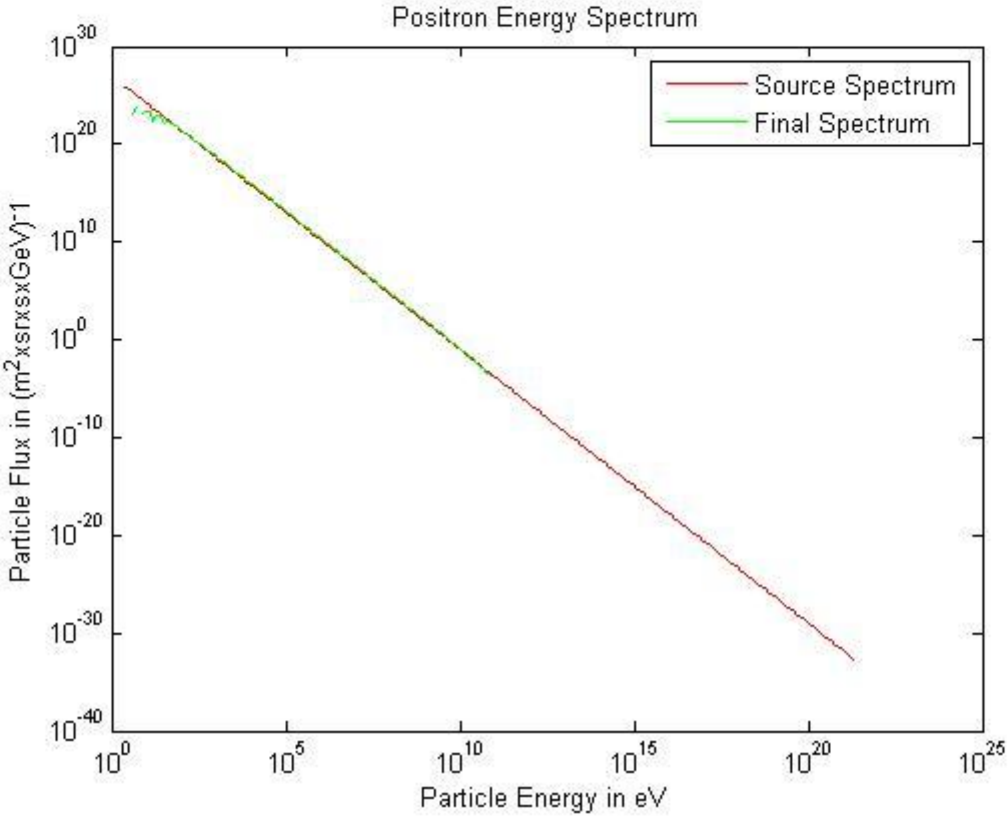
9. Appendix C. Hypothetical Scenarios

Dependence on magnetic field strength



The spectra for positron propagation from Andromeda with a magnetic field strength of H = 10^{-3} G

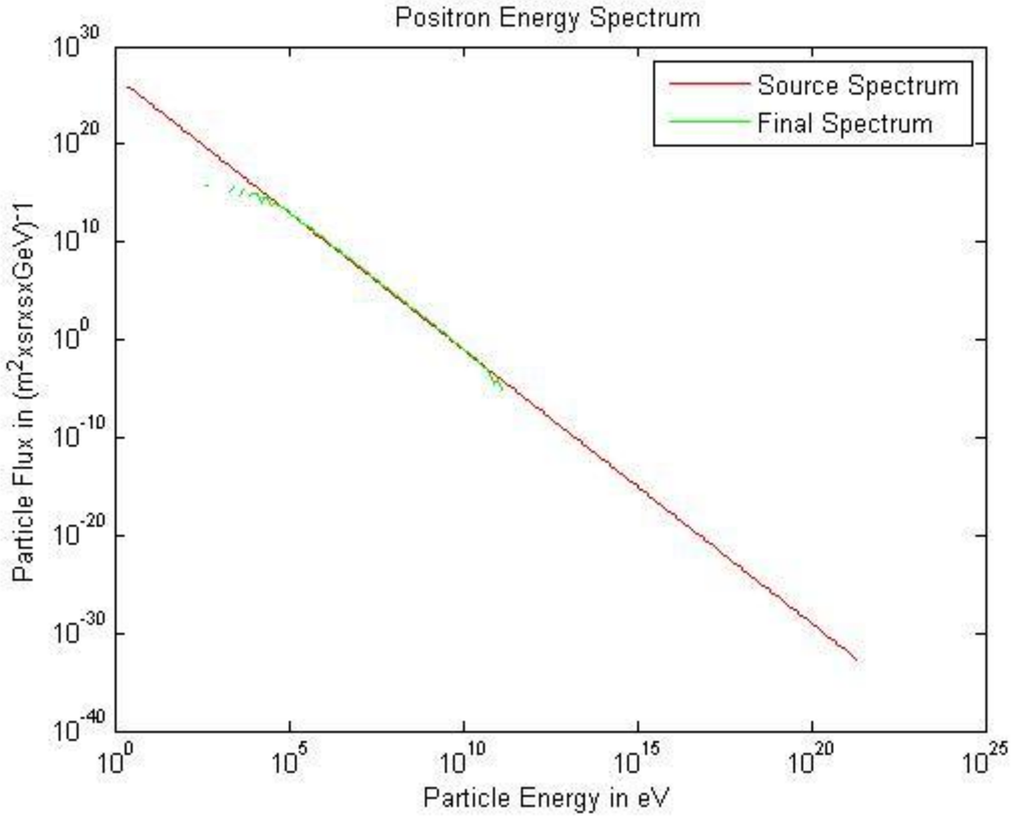
Positrons arriving from Andromeda with a magnetic field strength of 10^{-3} G experience a considerable depreciation of their average energy, to the extent that they readily find themselves prone to annihilation upon arrival at the Milky Way. This significant effect of a stronger magnetic field could put severe restrictions on positrons from another galaxy that travel through areas with particularly strong magnetic fields. It should be noted that the dependence on the square of the magnetic field certainly shows, whereas the dependence on the radiation field is linear.



The spectra for positron propagation from Andromeda with a magnetic field strength of H = 10^{-9} G

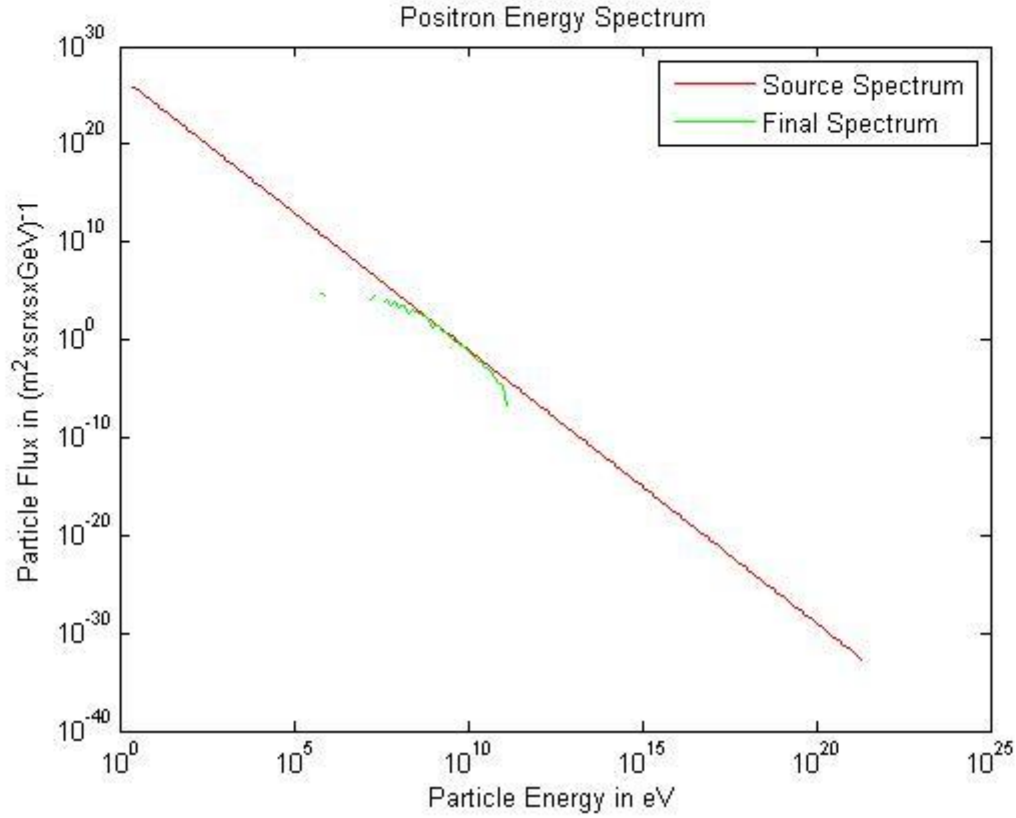
A weaker magnetic field (10^{-9} G) on the other hand incurs practically no change on the spectrum. This would be due to ICS maintaining its effect and thereby causing the highest energies to remain at around 10^{11} eV. This leads to the assumption that were either the strength of the magnetic field vary or the density of the radiation field, if the other were to remain at its presumed value the spectrum would barely exhibit change.

Dependence on particle density



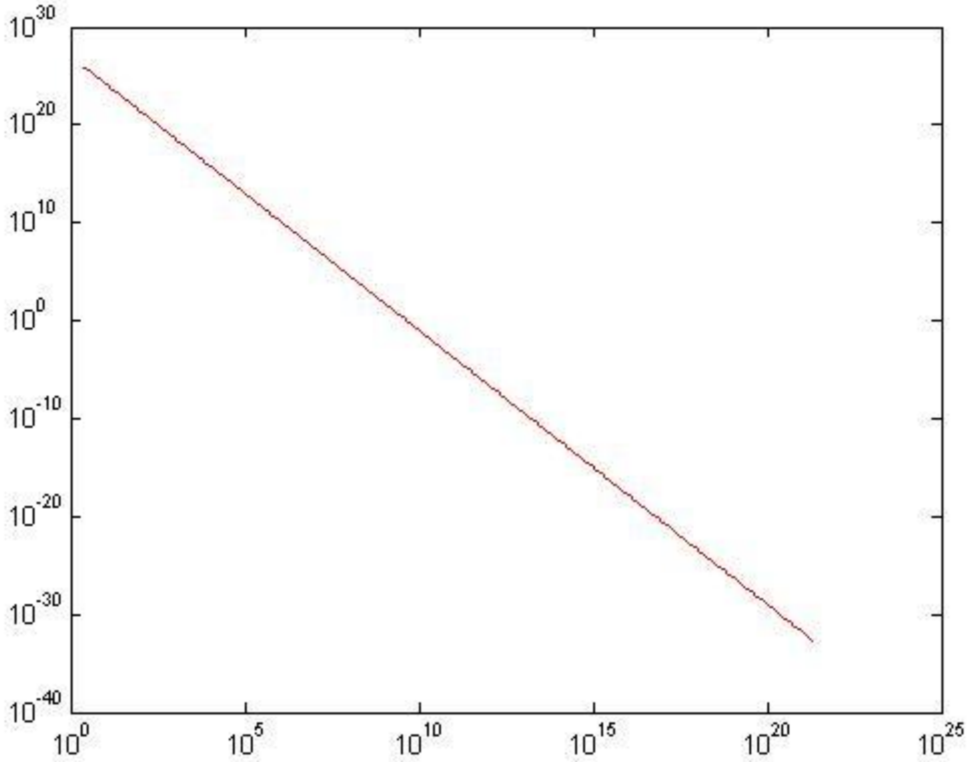
The spectra for positron propagation from Andromeda with a particle density of 1.6x10^{-4} cm^{-3}

A higher particle density (1.6x10^{-4} cm^{-3}) seems to have less severe ramifications than an increase in the magnetic field. Importantly, an increase of the particle density by a factor of 1000 does not affect the plot at energies of interest us.



The spectra for positron propagation from Andromeda with a particle density of 1.6 cm^{-3}

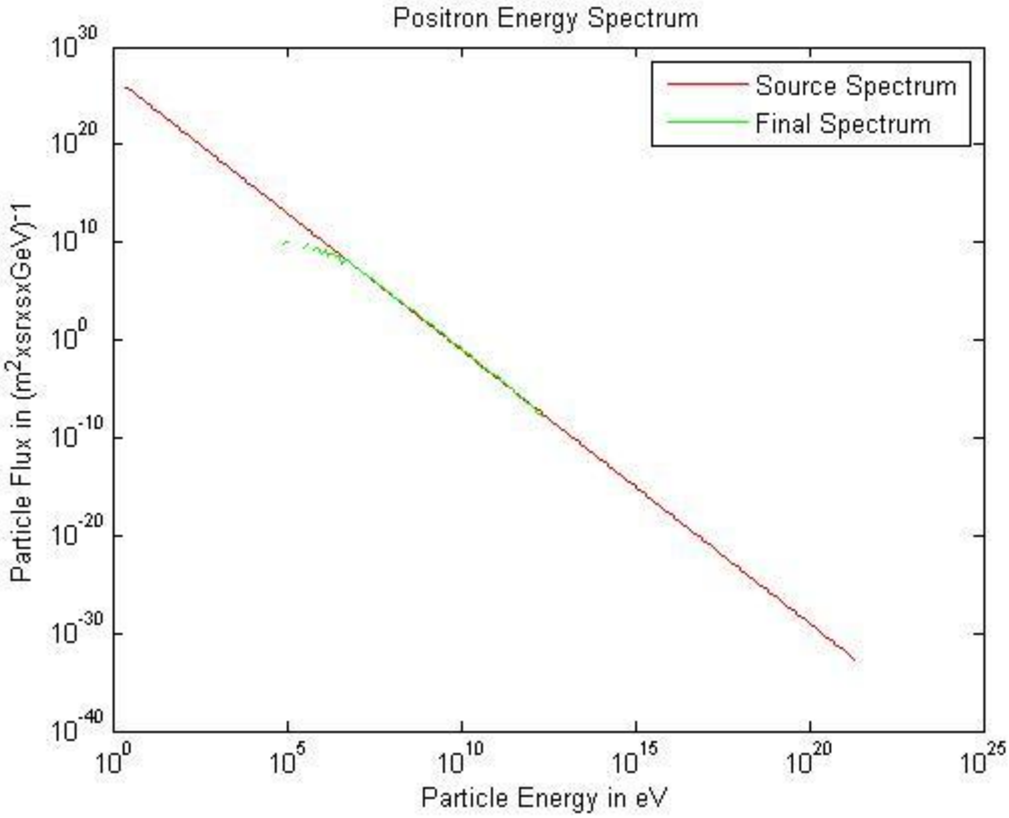
At a density of 1.6 cm^{-3} the effect is much more interesting as the final spectrum now shows appreciable decay near the exact energies of interest. Considering this is roughly the density of the ISM (Strong & Youssefi 1996) it can be presumed such a scenario is only important for the beam of positrons moving through large clouds of high density interstellar gas or large galaxies (for as the next section will show propagation through a galaxy like our own would have to be parallel to the plane of the galactic arms were it to have any noticeable effect).



The spectra for positron propagation from Andromeda with a particle density of 1.6×10^{2} cm^{-3}

As can be seen at very high densities (1.6×10^{2} cm^{-3}) the particle beam may be totally annihilated during propagation. Though it may be safely assumed that propagation would unlikely have taken place solely in the IGM as its density isn't nearly as high.

From the edge of the Milky Way



The spectra for positron propagation from the edge of the Milky Way to the bulge. Using a radius of 50.000 light years (Wikipedia, Milky Way)

The figure above shows the spectra for positrons propagating from the edge of the Milky Way to the bulge using parameters for the InterStellar Medium as found in Strong & Youssefi (1996). The relatively short propagation time still allows for synchrotron and ICS to stake their claim at high energies and the higher density of ionised hydrogen causes the decay of the spectrum at the lower energy regions.