Chapter 1

Introduction and historical background

As the observed data has bearing on gamma-ray band of the spectrum, we begin with an overview on gamma-ray astronomy. We also dwell on gamma-ray line emission and on the physics of positron annihilation mechanism, since the gamma-ray line is observed at 511 KeV on account of the annihilation of electron-positron pairs. We also dwell on the physics of production of electron-positron pairs and on the "conducive" sites producing positrons. We also explore the media and plausible mechanisms that would nurture the cooling process for these e+ - e- pairs to quench to their rest mass energies of 0.511 MeV - thereby generating a 511 KeV gamma-ray line in the process.

We also present the work on the 0.511 MeV line emerging from solar flares - the physics contributing this phenomena, in order to create a broad-based understanding on the subject, as solar physics is construed to be better understood.
GAMMA-RAY LINE
ASTRONOMY
1.1 **gamma-ray line astronomy**

Gamma-ray lines are the most direct probe of cosmic nuclear processes.

While it has been recognised for long that nuclear gamma-ray spectroscopy could provide basic information on such problems as solar activity, supernova dynamics and nucleosynthesis, positive observations of celestial gamma-ray lines have been made only recently.

The first cosmic gamma-ray lines were observed from solar flares. These lines are produced in nuclear processes on time scales of several minutes by the interaction of flare-accelerated particles with the solar atmosphere. Solar gamma-ray observations have provided important information on particle acceleration mechanisms, and on the flare process itself.

The strongest observed steady celestial gamma-ray line is at 0.511 MeV resulting from electron-positron annihilation. Many mechanisms can be attributed to galactic positron production, and two of these, energetic particle reactions and nucleosynthesis, also produce other detectable lines.
Cosmic gamma-ray lines from a transient event have been observed. These lines seem to result from energetic particle reactions similar to those that take place in solar flares, but not in similar environments. The identification of the lines requires a redshift of a magnitude that suggests the strong gravitational fields of compact collapsed objects.

Such gamma-ray line observations may probe nuclear reactions taking place in the vicinity of neutron stars and black holes, and measure the gravitational redshifts of such objects.

**Steady galactic gamma-ray lines:** The best observed nontransient galactic gamma-ray line is at 0.511 MeV from the galactic centre.

The observed line at 510.7 ± 0.5 KeV has an intensity of $1.2 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ and FWHM $< 3.2$ KeV. This observation was made in 1977 with a balloon-borne high purity Ge detector of opening angle 15° centred on the galactic centre. The line energy clearly identifies it as positron annihilation radiation; there is also some evidence for the three-photon continuum from triplet positronium annihilation.

The observed spectrum is shown in Fig. 1.1; the solid curve is the sum of the extrapolated low energy continuum (dashed curve) and a three-photon continuum assuming 90% annihilation by positronium.
Figure 1.1: $0.511$ MeV line and low-energy gamma-ray spectrum from the galactic centre

(Source: Leventhal et al. 1978)
PHYSICS OF POSITRON AND SPECTRAL LINE FEATURES
1.2 Physics of positron and spectral line features

Annihilation of positrons with electrons

When a positron annihilates with an electron two or more gamma rays are produced.

The interaction where both the positron and electron are at rest, and where only two gamma rays emerge, is of particular interest because each gamma ray then has the characteristic energy.

\[ E = \frac{1}{2} m_e c^2 = 0.511 \text{ MeV} \]

This line spectrum of radiation is referred to as annihilation radiation.

The electron and the positron both have spins of 1/2 and at low energies they may be in either two possible angular momentum states, namely \(^1S_0\) state with \(J=0\) or a \(^3S_1\) state with \(J=1\). As the initial spins of the two particles are randomly oriented the \(S_1\) state occurs three times as frequently as the \(S_0\) state.

Selection rules forbid the decay of \(^1S_0\) state into an odd number of gamma rays and the decay of the \(^3S_1\) state into an even number of gamma rays. In each case, the decay with the least number of photons is the most probable, so the \(^1S_0\) state usually decays into two gamma rays and the \(^3S_1\) state usually decays into three gamma rays.
The cross-section for the two-photon decay is given (Heitler 1954) by

$$\sigma_{2Y} = \frac{\pi \gamma_e^2 c}{\nu}$$  \hspace{1cm} (1)

where $\nu$ is the velocity of the positron relative to the electron and

$$\gamma_e = \frac{e^2}{m_e c^2}$$

The cross-section for the three-photon decay is given (Heitler 1954) by

$$\sigma_{3Y} = \frac{4}{3} \left( \pi^2 - 9 \right) \propto \frac{\gamma_e^2 c}{\nu},$$  \hspace{1cm} (2)

where

$$\alpha = \frac{e^2}{\hbar c}$$

From equations (1) and (2) we get

$$\frac{\sigma_{2Y}}{\sigma_{3Y}} \sim 372$$  \hspace{1cm} (3)

If the relative velocity of the electron and the positron is very small they may form a bound system before annihilating. The bound system, known as positronium, is analogous to a hydrogen atom.
The relative frequency of the two-photon and the three-photon decay of positronium differs from that given by equation (3) because, once positronium is formed in a definite angular momentum state, it remains in that state until annihilation occurs.

Statistically the $^3S_1$ state is formed three times as frequently as the $^1S_0$ state, so the relative frequency of the two decay modes of positronium is

$$\left[ \frac{\sigma_{2\gamma}}{\sigma_{3\gamma}} \right]_{\text{positronium}} = \frac{1}{3}$$

The two-photon decay produces a spectral line at $E = 0.511$ MeV. The natural width of this line that is given by $\Delta E \sim \frac{\hbar}{2}$, is only $5 \times 10^{-6}$ eV.

Spectral line broadening

Exclusive of instrumental imperfections, stellar spectral lines are broadened by two classes of causes.

A. Intrinsic causes

1. Natural width, which is due to the fact that an atom, like a radio station, cannot radiate at one sharp frequency, because the energy levels themselves have a certain width.
1. Doppler effect, which is due to random motions of atoms in any heated vapour.

2. Zeeman effect, which is the splitting of spectral lines by magnetic fields, as in a sunspot.

3. Stark effect, which is the splitting of a spectral line by an electric field; in stellar atmospheres the lines are broadened because the fields acting on any radiating atom are momentary and random.

4. Collisional broadening, which originates because radiating atoms may collide with neutral atoms and suffer a change in their radiated frequencies.

5. Hyperfine structure; certain lines of various elements are observed to be split into a number of very close components as a consequence of a magnetic interaction between the spin of the nucleus and the total angular momentum of the electron.

   The phenomenon is analogous to the interaction of the magnetic field of the spinning electron with the field produced by its orbital motion except that it is on a scale that is roughly a thousand times smaller.
B. **Extrinsic causes**

(1) Turbulence, or large-scale vertical motions of large masses of radiating and absorbing gases in a stellar atmosphere.

(2) Rotation of the star itself, which broadens all of the spectral lines; rotational speeds as high as 200-300 kilometers per second have been observed in A and B stars, whereas G and K white dwarfs, like the Sun, appear to rotate slowly.

(3) Loss of material to interstellar space. The atmospheres of many stars, particularly those of early spectral class, are subject to winds in which much material is lost to interstellar space. Sometimes, as in P Cygni or in Wolf Rayet Stars, material is blown out steadily; in exploding stars of novae, there occurs a violet outburst. These fast-expanding stellar atmospheres or winds produce broadened unsymmetrical lines.
POSITRONIUM IN
ASTROPHYSICAL ENVIRONMENT AND POSSIBLE
ANNIHILATION SITES
1.3 **Positronium in astrophysical environment and possible annihilation sites**

Bussard, Ramaty and Drachman (1979) have studied the annihilation of galactic positrons in order to evaluate the probabilities of various channels of annihilation and to calculate the spectrum of the resulting radiation.

The narrow width (FWHM < 3.2 keV) of the 0.511 MeV line observed from the galactic centre by Leventhal, McCallum, and Stang (1978a,b) implies that a large fraction of positrons should annihilate in a medium of temperature less than 10 K and ionization fraction greater than 0.05. H II regions at the galactic centre could be possible sites of annihilation.

Leventhal, McCallum, and Stang (1978a,b) reported observation of positron annihilation radiation from the galactic centre using a balloon-borne germanium detector. The observed line is at 510.7 +– 0.5 keV, and its full width at half-maximum (FWHM) is less than 3.2 keV. There is also some evidence for the three-photon continuum from triplet positronium annihilation. The 0.511 MeV line was previously seen from the solar flares of 1972 August 4 and 7 (Chupp, Forrest, and Suri 1975), but because the lower-energy resolution of the NaI detector used, only an upper limit of about 40 keV could be set on the line width from this observation.
Depending on the temperature and density of the ambient medium, positrons and electrons can either annihilate directly or form positronium. The importance of positronium formation in the interstellar medium was pointed out by Steigman (1968), by Stecker (1969), and by Leventhal (1973); and positron annihilation in solar flares, both direct and via positronium, was treated by Crannell et al. (1976). Positronium can form either in the singlet state which annihilates into two 0.511 Mev photons, or in the triplet state which decays by three-photon annihilation.

Positronium is formed by both radiative recombination with free electrons and charge exchange with neutral hydrogen (atomic or molecular). Charge exchange with heavier ions is much less important than these processes (Crannell et al. 1976). Once formed in a particular spin state, positronium in the interstellar medium annihilates from the same state, because the lifetimes of both singlet and triplet positronium (10^{-10} s and 10^{-7} s, respectively) are much shorter than typical collision times with interstellar gas.

Sources of galactic positrons are expected to include energetic particle interactions, long-lived radioactive nuclei from supernova explosions, and pulsars (Lingenfelter and Ramaty 1978; Ramaty 1978). All these sources produce positrons at relativistic energies.
Except for ultrarelativistic positrons, the probability for annihilation in flight is negligible until the positrons slow down to energies of the order of several hundred eV. (Ultrarelativistic positrons have a small probability 10% for annihilating in flight, but these annihilations produce only a broad continuum which in general cannot be observed above other continua). The purpose is to present the annihilation process at energies below a few hundred eV.

Thermal positrons will directly annihilate and radiatively recombine with free electrons, and if the gas is warm enough, they will form positronium by charge exchange with residual neutral hydrogen. The shape of the 0.511 MeV line from both singlet positronium annihilation following radiative recombination and direct annihilation with free electrons is expected to be a Gaussian of FWHM = 0.011 (KeV) (K)$^{1/2}$ (Crannell et al. 1976).

For example, if $T = 10^4$ K, the width is 1.1 KeV.

In a cold and neutral medium, about 95% of the positrons form positronium atoms in flight, and these atoms annihilate before undergoing further collisions if the density of the medium is less than $10^3$ cm$^{-3}$.
The shape of the 0.511 MeV line from positron annihilation in a cold neutral medium has a FWHM of about 5 KeV (Fig.1.2, panels (c) and (d)), and this width appears to be inconsistent with the observed width of the 0.511 MeV line from the galactic centre (<3.2 KeV) (Leventhal et al. 1978 a,b).

In a warm, partially ionized gas of temperature less than several times 10 K, only a fraction of the positrons form positronium in flight, and this fraction decreases with increasing ne/nH (Fig.1.3). At higher temperatures, essentially all the positrons thermalize before forming positronium or annihilating directly.

The rates for the various processes leading to thermal positron annihilation are shown in Figure 1.4. For temperatures less than 10 K, positronium formation is the dominant annihilation channel; while for higher temperatures, free annihilation dominates. The width of the 0.511 MeV line from thermal positron annihilation is about 3 KeV for \( T \sim 10 \) K and varies as approximately \( T^{1/2} \). The observed width from galactic centre suggests a temperature less than this value, and a degree of ionization larger than about 5%, for which half the positrons thermalize. For these conditions, more than 90% of the positrons annihilate after forming positronium, and this is consistent with the possible evidence for a three-photon continuum found by Leventhal et al. (1978 a,b).
Among the various galactic sites, the warm component of the interstellar medium, filaments or knots in supernova remnants, and the extended H II region in the nuclear disk could be sites for forming the 0.511 MeV line from positron annihilation. Plots of $P_p'(E)$ for various width resolution functions are given in Figure 1.5. The apparent redshift of the peak versus resolution is plotted in Figure 1.6.

The feature from the galactic centre region was detected (Fig.1.5) with a fitted energy resolution of 86 KeV (Johnson and Haynes 1973). According to Fig.1.6, a positronium annihilation spectrum would have appeared peaked at 490 KeV, which is consistent with the observation.
Figure 1.2: Profiles of 0.511 meV positron-annihilation line. Panels (a) and (b) show the profiles from positronium formation in flight in neutral molecular and neutral hydrogen, respectively. Panels (c) and (d) show the total line spectral for these cases, including the contribution of thermalized positrons annihilating directly with bound electrons.

(Source: Bussard et al. 1979)
Figure 1.3: Fraction of positrons forming positronium atoms (before thermalization) by charge exchange with atomic hydrogen as a function of the ionization fraction of the gas for two sets of parameters.

(Source: Bussard et al. 1979)
Figure 1.4: Rates at which thermal positrons form positronium by charge exchange with neutral H or by radiative recombination with free electrons, and annihilate directly with free electrons, or with bound electrons, as functions of the gas temperature.

(Source: Bussard et al. 1979)
Figure 1.5: Plots of detected positronium-annihilation function \( P'_{p}(E) \) for various energy resolutions (FWHM) of the gamma-ray detector. A Gaussian width of 3.2 KeV has been assumed for the singlet annihilations. The broken curve in the upper left-hand box is a plot of the pure, triplet annihilation function \( P(E) \).

(Source: Leventhal, 1973).
Figure 1.6: Plot of the apparent peak position of the detected positronium annihilation function $P_p(E)$ as a function of detector resolution (FWHM).

(Source: Leventhal, 1973)
Summary points

1. Narrow width FWHM < 3.2 KeV of 0.511 MeV line implies that positrons annihilate in a medium of temperature less than $10^5$ K and ionization ($n / n_e$) greater than 0.05.

2. Depending on the temperature and density of the ambient medium, positrons and electrons can either annihilate directly or form positronium.

3. Positronium is formed by both radiative recombination with free electrons and charge exchange with neutral hydrogen (atomic or molecular).

4. Except for ultrarelativistic positrons, the probability for annihilation in flight is negligible until the positrons slow down to energies of the order of several hundred eV.

5. There is little difference between line shapes for the atomic and molecular cases. The FWHM for both these cases is about 6.5 KeV.

6. For direct annihilation with atoms or molecules, the line shape is determined by the momentum distribution of the bound electron modified to account for the fact that the positron cannot approach the nucleus too closely.
7. The FWHM of the 0.511 MeV line in cold neutral hydrogen is about 5 KeV.

8. If the inclusion of excited states increases significantly the charge-exchange cross-section, then fewer positrons fall below the Ps formation threshold.

In this case, the line width is closer to the value of 6.5 KeV determined for positronium formation in flight.

9. The effect of the three-photon annihilation is manifest in a slight asymmetry in the line shape and a low-energy tail.

10. For annihilation in a partially ionized medium \((X > 0.05)\), most of the positrons thermalize rather than undergo charge-exchange in flight.

11. The shape of the 0.511 MeV line from both singlet positronium annihilation following radiative recombination and direct annihilation with free electrons is expected to be a Gaussian of FWHM = \(0.011(\text{KeV})^{4} K\); e.g., for \(T=10\) K, the width is 1.1 KeV.

12. More than 90% of the positrons annihilate after forming positronium, and this is consistent with the possible evidence for the observed three-photon continuum.
13. For the characteristic values of the cross-section for positronium annihilation in a gas collision of $7 \times 10^{-17}$ cm and positronium velocity of $2 \times 10^{-2}$ cm calculated for positronium incident on atomic hydrogen, the atom density is found to be of the order of $10^{-3}$ atoms cm (Massey & Mohr 1954).

Since densities as large as $10^{15}$ atoms cm$^{-3}$ are found only in the vicinity of condensed objects, a predominantly positronium annihilation spectrum is expected in many astrophysical situations.
PHYSICS OF 0.511 MeV LINE FROM SOLAR FLARES—DRAWING SOME INSIGHTS
1.4 *Physics of 0.511 MeV line from solar flares — drawing some insights*

*Formation of the 0.511 MeV line in solar flares*

The gamma-ray line produced at 0.511 MeV in solar flares is the result of either the free annihilation of positrons with electrons or the formation and decay of positronium by two-photon emission.

Positron annihilation from the bound state of positronium may also proceed by three-photon emission, resulting in a continuum with energies up to 0.511 MeV. The temperature, density, and state of ionization of the plasma in which the positrons annihilate determine the width of the 0.511 MeV line and the ratio of three-photon to two-photon emission.

Gamma-ray line emission at an energy of approximately 0.511 MeV was observed by Chupp et al. (1973, 1975) from the 1972 August 4 and August 7 solar flares.

This line is believed to be due to the annihilation of positrons that result from the decay of $^+\pi$ mesons and radioactive nuclei produced in nuclear reactions of flare-accelerated particles with constituents of the solar atmosphere (Lingenfelter and Ramaty 1967; Ramaty and Lingenfelter 1973; Ramaty, Kozlovsky, and Lingenfelter 1975).
Their study shows that the formation of the 0.511 MeV line depends on the sources of positrons, on the propagation of positrons in the solar atmosphere, on the density and temperature of the ambient medium in which positrons slow down and annihilate, and on the mode of positron annihilation since the positrons may annihilate freely or from a ground state of positronium.

This leads to four distinct observable parameters related to the annihilation of positrons that lead to the information about the ambient medium and the source of positrons.

These are -

1. the width of the 0.511 MeV line,
2. the strength of this line relative to the intensity of other gamma lines,
3. the strength of the $3\gamma$ continuum below 0.511 MeV that comes from triplet positronium decay, and
4. the time dependence of the 0.511 MeV line.

Here we put forth the observations of studies related to the slowing down and annihilation of positrons and the formation of positronium in a solar flare plasma. The results also show how the width of the 0.511 MeV line and its strength relative to the $3\gamma$ continuum from positronium decay depend on the temperature and density of the medium in which positrons come to rest.
Figure 1.7 shows the positron evolution for Ne/Nn=0.1 and Ne+Nn=10. In this case 94 percent of the positrons form positronium by charge exchange before the distribution thermalizes.

Figure 1.8 shows the fraction of positronium having formed as a function of time for two ratios of plasma to neutral density. There are two regions of development. First, the positronium fraction rises rapidly until the remaining positrons have thermalized. This is followed by a region of slow increase that is approximately linear in time. As positrons in the thermal tail are lost through positronium formation, the tail is repopulated by positrons that gain energy.

For Ne/Nn=0.1, most of the positronium is formed in the first stage so that the second stage is of no great importance. The duration of the first stage is approximately 10^-6 s, consistent with the charge exchange cross section given in Table 1.1.

For Ne/Nn=1.0, a large fraction of the positronium is formed in the second stage. Since the number of positronium atoms exhibits linear growth, the curve is extrapolated for Ne/Nn=1.0, to determine the time for which all the positrons can be converted to positronium.
The results of this extrapolation are presented in Table 1.2. From Table 1.2, it is seen that the rate of formation is of the order of $10^{-10}$ positronium much faster than the free annihilation rate given in Figure 1.9.

Figures 1.10 and 1.11 show the distribution of energies at which positronium has formed as a function of time. At large times, a sharp peak begins to develop at low energies. This is due to positrons being thermalized upward until they are above the threshold energy for the charge exchange cross-section. This effect can be seen more clearly if the plasma temperature is slightly larger.
Figure 1.7: Positron distribution as a function of velocity in units of $V/V_e$, where $V_e$ is the velocity of an electron with kinetic energy $K_T$ at various times.

(Source: Crannell et al. 1976)

Figure 1.8: Fraction of positrons that have formed positronium as a function of time.

(Source: Crannell et al. 1976)
Figure 1.9: The rates for radiative capture and for free annihilation of positrons as a function of temperature.

(Source: Crannell et al. 1976)
Figure 1.10: Fraction of positrons that have formed positronium as a function of energy at various times.

(Source: Crannell et al 1976)
Table 1.1: Charge exchange cross-sections on atomic hydrogen
(Source: Crannell et al 1976)

<table>
<thead>
<tr>
<th>Positron Energy (eV)</th>
<th>Cross Section ($\sigma_{pp}$)</th>
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<tbody>
<tr>
<td>7.5</td>
<td>0.50</td>
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<tr>
<td>10.0</td>
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<tr>
<td>15.0</td>
<td>3.3</td>
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<td>2.0</td>
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<td>50.0</td>
<td>0.41</td>
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<tr>
<td>75.0</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 1.2: Time to convert all positrons of initial energy 50 eV to positronium in a 1 eV plasma.
(Source: Crannell et al 1976)
Figure 1.12: Fate of positrons in a solar flare and the resultant photon signature.

(Source: Crannell et al 1976)
Summary points

From the results of this study, we summarize the fate of a positron in a solar flare plasma.

1. For temperatures greater than 10 K, positrons annihilate via free annihilation at a rate of about $-14 \times 10^{-1}$ Ne S, as can be seen in Figure 1.9. For this case the width of the 0.511 MeV line is determined by the centre of mass motion of the $e^+e^-$ pair that is a function of the temperature of the medium.

2. For temperatures just below 10 K, radiative recombination dominates over free annihilation. The relative importance of radiative recombination and charge exchange is determined by the residual neutral hydrogen abundance. For the fractional neutral densities characteristic of the quiescent solar atmosphere (Gabriel 1971), charge exchange is expected to be the dominant process.

3. At temperatures below a few times 10 K, positronium formation through charge exchange is the dominant reaction through which positrons annihilate.

The relative rates of the competing processes of slowing down and of forming positronium depend primarily on the fractional ion density of the annihilation region.
4. When Ne/Nn ≥ 0.5, most of the positrons first thermalize and then form positronium by charge exchange.

This sequence of events could be maintained even if the mean energy of the ambient electrons were less than the threshold for positronium formation (6.8 eV).

5. When the fraction of ions is low, Ne/Nn < 0.5, most of the positrons tend to form positronium before they are slowed below a kinetic energy of about 15-20 eV for which the charge-exchange cross-section is a maximum.

The rate of annihilation in this case is determined by charge-exchange and is approximately \(3 \times 10^{-8} Nn \) S. Since the \(2\gamma\) decay occurs well before the positronium atom can thermalize, the Doppler broadening is determined by the mean kinetic energy of the positronium atoms.

6. The values of the measurable quantities \(N3\gamma/N2\gamma\), the ratio of the number of \(3\gamma\) to the number of \(2\gamma\) decays, and Er that may be expected for various regimes of temperatures and densities are shown in Figure 1.12
7. For high temperatures, \( T > 10^6 \), or high densities, \( N > 10^{-3} \) cm, \( N_3Y/N_2Y = 0 \). Since the temperature in regions of densities greater than \( 10^{-3} \) cm, even during flares, is not expected to be greater than a few times \( 10^6 \) K, these two cases can be distinguished by the width of the 0.511 MeV line.

For high temperatures, \( E_Y > 10 \) KeV; and for high densities, \( \Delta E_Y < 3 \) KeV.

For temperatures lower than \( 10^6 \) K and densities less than \( 10^{-3} \) cm, all positrons form positronium that annihilate before it dissociates. Here \( N_3Y/N_2Y \rightarrow 4.5 \).

8. The state of ionization of the medium and its temperature determine the width of the 0.511 MeV line.

The largest width, \( \Delta E_Y \approx 10 \) KeV is obtained for \( T \approx 10^6 \) K, and the smallest width, \( \Delta E_Y \approx 1 \) KeV is obtained for \( T < 7 \times 10^4 \) K and \( Ne/Nn > 0.5 \).

If \( Ne/Nn < 0.5 \), the width becomes larger, rather than smaller. From Figure 1.12 one can predict that there is virtually no \( 3Y \) continuum radiation and that the width of the \( 2Y \) line is \( \approx 3 \) KeV.