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Models for the positive latitude e^-e^+ annihilation feature

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Abstract. Galactic maps of e^-e^+ annihilation radiation based on CGRO-OSSE, SMM and TGRS data have indicated the existence of an extended component at positive Galactic latitudes ($l \approx -2°$, $b \approx 7°$), in addition to the emission from the galactic bulge and disk (Purcell et al. 1997; Cheng et al. 1997; Milne et al. 2000; Milne et al. 2001). This Positive Latitude Enhancement (PLE) was first attributed to an "annihilation fountain" in the Galactic center (Dermer & Skibo 1997) but has since been the object of several models.
After discussing the observational evidence for the PLE, we investigate various models for the PLE: besides the scenarios proposed in the literature, we have introduced a number of models requiring relatively modest positron rates due to a local origin of the e^-e^+ emission (local galactic-, solar system-, earth- and spacecraft-environment origins). The various scenarios for the PLE are constrained in the light of the latest OSSE-SMM-TGRS data analysis results: we have looked at the possible positron production mechanisms as well as the annihilation conditions in the different physical environments (temperature and dust grain content) proposed for the positive-latitude region. By constraining those parameters, based on the recent limits for the line width and the positronium fraction, we found that some of the models can essentially be discarded. A number of other scenarios will have to await further measurements and maps, such as will be possible with INTEGRAL's SPI and IBIS instruments. We present a table/checklist of model-falsification criteria.

Key words. elementary particles – ISM: bubbles – ISM: clouds – ISM: supernova remnants

1. Introduction

the question of the existence of antimatter in the Universe has puzzled astrophysicists. Besides the production of positrons in the laboratory and by cosmic rays in our atmosphere, it was supposed that they might be produced in a multitude of astrophysical environments (nucleosynthesis, neutron stars, pair plasma etc.).

The positron's signature is the gamma-ray line at 511 keV that is emitted when it annihilates with an electron. Upon encountering their nemeses, positrons can either annihilate directly or form a positronium (Ps) "atom." In the first process, which can occur with free electrons, bound electrons, or electrons in grains, two photons are produced at ~511 keV (plus whatever kinetic energies are available). In the second process, depending on the spin state of the positronium, the annihilation (disintegration) produces either two photons of equal energies (in the "para", or anti-parallel state, which occurs 25% of the time) or three photons (in the "ortho", or parallel state, which occurs 75% of the time) with a continuous distribution of energies between 0 and 511 keV. Depending on the physical conditions of the environment (temperature, ionization state, dust content, etc.), the annihilation of the positrons will proceed via several possible routes: direct annihilation with free or bound electrons (including those in dust grains) or positronium formation with free electrons, charge exchange with atomic and molecular hydrogen, helium, etc. (see Guessoum et al. 1997a).

Line emission at 511 keV from the Galactic Center region has been observed since the early seventies in balloon and satellite experiments. In two balloon flights from Argentina, Haymes' group at Rice University first measured a gamma-ray line at 476 ± 26 keV (Johnson et al. 1972). Later it was suggested that the detected line was actually the annihilation line, but that the shifted peak could have resulted from the convolution of the broad energy response of the NaI scintillators with the Galactic Center spectrum consisting of a narrow 511 keV line and the accompanying orthopositronium continuum. In 1977, high energy-resolution germanium (Ge) semiconductors were flown for the first time on balloons, enabling scientists to establish the narrowness of the annihilation line at 511 keV, with a width of only a few keV (Albernhe et al. 1981; Leventhal et al. 1978). The eighties were marked by ups and downs in the measured 511 keV flux through a series of observations performed by the balloon-borne germanium detectors (principally the telescopes of Bell-Sandia and GSFC). The fluctuating results were interpreted as the signature of a compact source of annihilation radiation at the Galactic Center

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(see e.g. Leventhal 1991). Additional evidence for this scenario came initially from HEAO-3 (Riegler et al. 1981) reporting variability in the period between fall 1979 and spring 1980. Yet, during the early nineties, this interpretation was more and more questioned, since neither eight years of SMM data (Share et al. 1990) nor the revisited data of the HEAO-3 Ge detectors (Mahoney et al. 1993) showed evidence for variability in the 511 keV flux.

In Fall 1990, the imaging SIGMA telescope showed a strong feature in the spectrum of 1E 1740.7-2942, a source located close to the Galactic center (Bouchet et al. 1991). This emission appeared and vanished within days in the energy interval 300–700 keV. Stimulated by this observation, Mirabel et al. (1992) performed several radio observations of 1E 1740.7-2942 with the Very Large Array (VLA), revealing two radio jets emanating from the central compact object. Since the discovery of that first galactic "microquasar", several similar Galactic sources were detected by SIGMA and CGRO-BATSE. The spectral and temporal behavior of 1E 1740.7-2942 earned this source the nickname "great annihilator"; the data could in fact be explained by a pair plasma in the vicinity of a compact object. Yet, no narrow annihilation line from any of the sources (compact or diffuse) in the Galactic center region was observed by SIGMA (Malet et al. 1995). A review of the pre-CGRO/GRANAT observations is found in Lingenfelter & Ramaty (1989), a summary of the 511 keV situation during the CGRO/GRANAT era is in Kurfess et al. (1999).

Throughout the nineties, CGRO's Oriented Scintillation Spectrometer Experiment (OSSE) measured steady fluxes from a galactic bulge and disk component, but in 1997 a third component, the "Positive Latitude (Annihilation) Enhancement" (PLE) feature was identified and has since provoked a flurry of models and press releases. Combining the data from CGRO-OSSE, the Transient Gamma-Ray Spectrometer (TGRS) and Solar Maximum Mission (SMM) instrument, Purcell et al. (1997) produced a first and rudimentary map of the 511 keV positron annihilation line radiation showing a positive-latitude e^-e^+ annihilation feature. Depending on the method for deriving the flux of this feature, values between $2.2 \pm 0.2 \times 10^{-4}$ ph cm^{-2} s^{-1} (integrated flux within the PLE region) and $8.8 \pm 0.5 \times 10^{-4}$ ph cm^{-2} s^{-1} are obtained (model fit of a PLE component).

With the enhanced exposure of the current datasets (more OSSE exposure and reanalyzed TGRS data) Milne et al. (2000) found lower fluxes for the PLE while confirming its existence. The most recent review by Milne et al. (2001) changed the situation again rather considerably: 1) the map still showed some positive latitude excess, but much less than the earlier maps showed, as the flux of the emission was found to be $\leq 1 \times 10^{-4}$ photons cm^{-2} s^{-1}, much less than previous levels; 2) the positronium (Ps) continuum emission of the region shows no local enhancement; or equivalently, as Milne et al. (2001) put it, there is "a deficit for positronium continuum" in the positive-latitude annihilation. We will also adopt the line width as a mild constraint, even though there has been no measure of it directly from the PLE; however, TGRS measured the width of the annihilation line from the Galactic Center region and found it to be narrow (≈2.5 keV) (Fig. 3 of Teegarden et al. 1996), consistent with previous measurements (e.g. the GRIS balloon measurements, Gehrels et al. 1991); moreover, the spatial distribution of the radiation inferred by TGRS is in broad agreement with the more recent maps of OSSE (Harris et al. 2000).

Table 1 shows the evolution of the PLE measured parameters (flux, location, and size) since 1997. It must be stressed that all the values shown are model-dependent (dependent on analysis methods, model components included, etc.) – e.g. the errors in Purcell et al. (1997) are derived assuming only a single parameter. A more complete error analysis would reduce the significance of these parameters. Yet, aside from indicating its existence and substantial flux, the present measurements do not clearly point to the nature and characteristics of the positive-latitude feature; indeed OSSE's angular resolution is limited by its wide field of view ($4° \times 11°$), and its scintillator energy resolution (of ~50 keV at 511 keV) does not allow the line width to be measured. Interestingly, however, Table 1 indicates that the flux – and the significance – of the feature have decreased as the analysis techniques were refined more and more. Moreover, the existence of the PLE feature is questioned by the fact that no evidence for such a phenomenon has been observed at other wavelengths – at least not on a galactic scale.

It is thus of paramount importance that this feature be observed and measured precisely, as well as studied theoretically. If the feature is real, the background subtraction of older 511 keV measurements might have to be revisited since the PLE region is a privileged site for "off" pointings.

In this context, it might be (historically) noteworthy to point out a possible link between the PLE and the supposed variability of the 511 keV source at the Galactic Center as measured by balloon instrumentsin the early eighties.

Although the observations of these balloon spectrometers can already be understood by their limited statistics, it is interesting to note that a classical off-pointing for background subtraction – that is, taking the same zenith angle as the target but an azimuth+180° – will fall on the fountain region for GC pointings with high elevation (low atmospheric absorption) for flights from Alice Springs. So if it turns out that there really *is* 511 keV emission from the fountain region, the azimuth+180° off-pointing strategy would have resulted in a subtraction of the PLE flux from the GC signal. This would have further weakened the already poor source statistics of a balloon observation and could actually lead to the interpretation of a source in an "off" state. Table 1 summarizes the history of the supposed "ON – OFF – ON" state of the Galactic Center 511 keV source in relation to the off-pointing strategies of the observations made with balloon-borne germanium spectrometers – note the possible correlation between the background subtraction technique and the "state" of the Galactic Center source. ESA's INTErnational Gamma-RAy Laboratory INTEGRAL, which is to be launched in October 2002, is well adapted to study the existence of the positive latitude enhancement of 511 keV annihilation radiation. The complementary performances of its two main instruments, the spectrometer SPI (Mandrou et al. 1997) and the imager IBIS (Ubertini et al. 1997), will allow the gamma-ray community to lead a comprehensive study of 511 keV sources on various angular scales and

Table 1. PLE measured parameters.

	Purcell 1997 OSSE	Purcell 1997 OSSE TGRS + SMM	Cheng 1997 OSSE TGRS + SMM	Milne 2000 OSSE TGRS + SMM
Flux [10^{-4} ph cm^{-2} s^{-1}]	5.4 ± 1.5	8.8 ± 0.5	2.0 ± 0.58	0.7–1.2
Long. centroid [deg]	−1.1 ± 2.0	−1.8 ± 2.4	−4	−2
Lat. centroid [deg]	9.0 ± 1.3	11.6 ± 1.3	7	8
Size [deg *FWHM*]	11.4 ± 2.8	16.4 ± 1.8	not published	not published

Table 2. Balloon measurements of the presumably variable 511 keV source at the Galactic Center and off-pointing strategies; refs.: 1 = Leventhal et al. (1978); 2 = Leventhal et al. (1980); 3 = Leventhal et al. (1982); 4 = Leventhal et al. (1986); 5 = Leventhal et al. (1989).

Date	*Experiment*	*FOV*	511 *keV flux* 10^{-3} ph cm^{-2} s^{-1}	*Off − pointing strategy*	*GC status*	*ref.*
1977.86	*Bell − Sandia*	4.5°	1.22 ± 0.22	*E − W symmetry*	*ON*	1
1979.30	*Bell − Sandia*	15.7°	1.24 ± 0.43	*E − W symmetry*	*ON*	2
1981.89	*Bell − Sandia*	15.0°	0.00 ± 0.76	**azimuth + 180°**	**OFF**	3
1984.89	*Bell − Sandia*	15.7°	0.06 ± 0.88	**azimuth + 180°**	**OFF**	4
1988.33	*GRIS*	17.0°	0.75 ± 0.17	*azimuth* + 200 − 240°	*ON*	5
1988.83	*GRIS*	17.0°	1.21 ± 0.16	*azimuth* + 200 − 240°	*ON*	5

spectral resolutions. During the Galactic Center Deep Exposure (GCDE) of INTEGRALs core program, the inner Galaxy ($\Delta l = +/-30°$ and $\Delta b = +/-20°$) will be observed using a pattern of rectangular pointing grids during $\sim 4 \times 10^6$ s. With this exposure, SPI's 3 σ line sensitivity for a 511 keV point source in the PLE region is $\sim 3 \times 10^{-5}$ photons cm^{-2} s^{-1}. The sensitivity for an extended source depends on the latitude and angular size of the source due to the non-uniform exposure over the galactic fountain region – for sources with extensions of the order of 10° *FWHM*, sensitivities are of the order of 10^{-4} photons cm^{-2} s^{-1}. During the GCDE, IBIS' 3 σ line sensitivity for a point source in the inner galaxy is of the order of 7×10^{-5} photons cm^{-2} s^{-1} at $b = 10°$. Constraining the various models requires a detection with an improved significance, and with uniform exposure over the entire PLE region, in order to take advantage of SPIs imaging capabilities and outstanding energy resolution. Besides the core program, three proposals from General Observers (GOs), enhancing the exposure of the PLA region by up to 4×10^6 s, have been selected for observation during the "open time" of INTEGRALs AO-1 cycle.

2. Models for the positive latitude enhancement

2.1. Galactic origin models

In order to explain $\sim 10^{-4}$ photons cm^{-2} s^{-1} in a narrow 511 keV line at the Galactic Center (8 kpc), the annihilation of 10^{41} to 10^{42} positrons per second is required.

2.1.1. The "Galactic fountain"

In this model, the earliest and most widely known one for the PLE feature, the e^+ source is a recent starburst episode (SN of most probably type II) within the inner few hundred parsecs of our Galaxy. With 10^{52} e^+ per supernova, a SN rate of 2-4 century^{-1} is required. The positrons are convected "upward" due to an asymmetry in the confining gas. After losing their energy, the positrons annihilate 1–2 kpc above the Galactic plane.

There are two major constraints that may pose some difficulties for this model: 1) in such a hot environment (Dermer & Skibo 1997), the width of the 2γ 0.511 MeV line from the annihilation will be broader than that of the Galactic disk line emission (see Ramaty & Meszaros 1981; Guessoum et al. 1991), although this depends rather strongly on the dust content of the fountain; 2) it is quite difficult to prevent any continuum positronium emission (as now required by the latest PLE data analysis – see Milne et al. 2001) in such physical conditions, so the 3γ positronium (Ps) continuum fraction f_{Ps} will not only be greater than zero, it will also be spatially varying across the whole region, from the disk to the top of the "fountain", an effect which INTEGRAL should be able to exhibit. We have run our program for positronium annihilation in a thermal environment (Guessoum et al. 1991, updated in Guessoum et al. 1997a) for a hot medium of various temperatures and grain fractions (x_{gr}, as defined in Guessoum et al. 1991, where $x_{gr} = 0$ represents a total absence of grains, $x_{gr} = 1$ represents a density of dust equal to the average interstellar amount). We have found that if the dust is completely absent ($x_{gr} = 0$), then the annihilation line produced is wide for $T >$ a few times 10^5 K: ($\Gamma \geq 10$ keV when $T > 10^6$ K). If dust is present, with roughly normal amounts ($x_{gr} \approx 0.1$–5.0), then the line is narrow enough ($\Gamma \approx 2.0$–3.0 keV), but the positronium fraction f_{Ps} (which represents the fraction of positrons that annihilate via formation of positronium and indirectly gives a measure of the 3γ continuum emission) is found to always be larger than 0.1. It is not clear from the Milne et al. (2001) paper what the PLE emission f_{Ps} fraction is found to be (and with what uncertainties). Here we simply wish to point out that this quantity (which is inferred to be very low in the PLE but which *can never be exactly zero*, see Guessoum et al. 1991), can constrain the model and its physical parameters.

This model also predicts that the peak enhancement of the fountain's annihilation flux occurs >100 pc above the Galactic plane. Long-lived radioactivity is produced by supernovae and is convected upward with the gas flow. According to Dermer and Skibo, diffuse 1.809 MeV emission from ^{26}Al should be observed at a flux level comparable to the INTEGRAL telescope's sensitivities.

2.1.2. Electron-positron pairs jet from GC black hole

In this scenario (Purcell et al. 1997), a black hole at or near the Galactic Center is channeling energy into a mildly relativistic, one-sided electron-positron pair jet. The required positron production rate is achieved if, for example, a solar-mass black hole is converting ~1% of its Eddington luminosity into a collimated, mildly relativistic pair-plasma outflow. The requirements are even less severe for a massive ($\sim 10^6\ M_\odot$) black hole such as that believed to be associated with the radio source Sgr A* at the dynamical center of the Galaxy. The positrons would require $\sim 10^5$ years to slow down, if produced with an initial energy ~1 MeV. The details of the positron transport into the Galactic bulge are not clear, but it is conceivable that processes of diffusion and/or convection could propagate positrons to these distances.

It is difficult to falsify this model or compare it with present and/or future data, as its authors do not give any indication about the physical parameters of the medium where the positrons would annihilate, and this makes it impossible for us to constrain the model by calculating its predicted annihilation feature characteristics (line width Γ and f_{Ps} fraction). Moreover, no evidence for the transport of positrons in such environments exists from other observations or even for jets in other wavelengths.

2.1.3. Gamma-ray burst

According to this scenario, a gamma-ray burst (GRB) occured near the Galactic Center sometime during the last million years and produced not only the bulge annihilation but also the PLE feature via some positron transport (Purcell et al. 1997). In a single massive explosive event occurring near the Galactic center, the total number of positrons in the annihilation region can be related to the observed 511 keV line flux and ambient electron density through n_e: $N_+ \approx 1.4 \times 10^{60} F_{511}/n_e$. To account for the annihilation flux from the Galactic center region (bulge and PLE) of $\sim 10^{-3}$ photons cm^{-2} s^{-1} one requires $N_+ \approx 10^{57}$ positrons for $n_e \approx 1$ cm^{-3}. The energy required (10^{51} ergs – to account for the Galactic center 511 keV luminosity) is close to the total energy directed into pair plasmas in cosmological gamma-ray burst models.

In another variation on this burst scenario, Dermer & Boëttcher (2000) proposed a gamma-ray burst at positive latitude, which would cancel the need for positron transport. According to these authors the high-latitude annihilation could reveal a site of a past gamma-ray burst. If GRBs originate from (or are related to) the collapse of massive stars, then circumstellar clouds near burst sources will be illuminated by intense gamma radiation. If the energy intercepted by a single cloud is converted to pairs with a conservative 1% pair yield, past GRBs in the Milky Way would indeed be revealed by measurable annihilation radiation. Here again, the f_{Ps} fraction constitutes a strong constraint (the width of the line can easily, and within various medium temperatures, ionization fractions, and dust content, be made to satisfy the constraint we have set, i.e. $\Gamma \lesssim 6.0$ keV). A low value of f_{Ps} in the PLE is best obtained, our simulations show, by making the medium as hot as possible, as fully ionized as possible, and as full of dust as possible, although a moderate (normal) abundance of grains is sufficient. In such a case (say $T \approx 10^6$ K), the value of f_{Ps} is found to be ≈ 0.15 – still non-negligible.

Finally, it is worth noting that the high-latitude annihilation feature – and other localized hot spots of annihilation radiation that will be mapped in detail with INTEGRAL's instruments, could reveal sites of past GRB explosions.

2.1.4. Unidentified EGRET sources

The discovery of a population of faint, mid-latitude gamma-ray sources among the already known 170 unidentified EGRET point sources has been recently reported by Gehrels et al. (2000). Contrary to the spatial distribution of bright sources which is highly concentrated along the Galactic plane, these objects (with steady fluxes of 2.4×10^{-7} photons cm^{-2} s^{-1} for $E > 100$ MeV) are found to be roughly aligned with the so-called Gould belt, which is formed by a concentration of massive, young stars and molecular clouds at about 0.2 kpc distance and inclined at about 20 degrees to the Galactic plane. About 20 of these sources are clustered north of the Galactic Center, extending up to about 30 degrees, and a few of them are in the region of the PLE. Precisely, we find a total of 8 unidentified EGRET sources contained in a field of 25×15 degrees centered on the grid center position (see Table 3). Of these objects, five can be regarded as faint sources. On the other hand, Milne et al. (2001) remark that some compact sources, a few of which have been identified, could distort the picture if they happen to be flaring in the hard X-rays while the observation of the annihilation radiation is conducted and/or have a previously undetected hard tail. And when simple models (e.g. simple power-laws or exponentials) are used to fit the data, determining precisely what enhancement or deficit results in the annihilation line and positronium continuum becomes a very

Table 3. EGRET unidentified sources in the direction of the PLE.

Source	$l_{\rm II}$	$b_{\rm II}$	Flux ($E > 100$ MeV) photons cm^{-2} s^{-1}
$2EG_J1631-2845$	350.40	13.26	$34.2 \pm 6.7 \times 10^{-8}$
$2EG_J1635-1427$	359.72	19.56	$13.0 \pm 3.5 \times 10^{-8}$
$2EG_J1642-2659$	353.46	12.48	$23.6 \pm 6.6 \times 10^{-8}$
$3EG_J1612-2618$	349.40	17.90	$92.2 \pm 27.7 \times 10^{-8}$
$3EG_J1627-2419$	353.36	16.71	$23.4 \pm 4.2 \times 10^{-8}$
$3EG_J1649-1611$	3.35	17.80	$12.1 \pm 2.7 \times 10^{-8}$
$3EG_J1653-2133$	359.49	13.81	$59.7 \pm 17.5 \times 10^{-8}$

murky issue, leading to uncertain parameters and further complicating the modeling and constraining of the emission process. Here again INTEGRAL's capabilities will have a unique opportunity to clarify the situation.

The possibility that these sources may contribute to the 511 keV emission of the PLE should still be considered. Furthermore, the Gould belt is rich in molecular clouds which are potential sources of annihilation radiation by means of cosmic rays irradiating the cloud and reacting with ambient nuclei, thereby producing positron-emitting nuclei. Guessoum et al. (2001) have considered the 511 keV radiation from nearby giant molecular clouds and have determined the expected flux as a function of the cloud's mass and distance, as well as of the composition of the bombarding cosmic rays. Applying the results of that work to the Gould belt, one can conclude that unless the molecular clouds contributing to the annihilation radiation have a total mass of more than $\sim 2 \times 10^5\ M_\odot$, or unless the cosmic rays are made predominantly of metals, in which case one needs clouds smaller by an order of magnitude, unless these conditions are fulfilled the Gould belt is unlikely to explain the enhanced annihilation.

2.2. Local galactic origin

The high galactic latitude can also be regarded as suggestive of a local galactic origin of the PLE. The required positron generator would then be more modest: explaining $\sim 10^{-4}$ photons cm^{-2} s^{-1} in a narrow 511 keV line from the local Galactic environment (80–200 pc) would require annihilation of $1-6 \times 10^{38}$ positrons per second.

2.2.1. Modest burst of star formation

In this model a modest burst of star formation or enhanced cosmic-ray activity occurring at much smaller distance within the last 10^6 years could explain the PLE. Purcell et al. (1997) mention this possibility but consider the coincidence of this event occurring so near the direction of the Galactic center as too unlikely a possibility, unless there is a large enough number ($\sim$10–50) of such regions around the sky or near the plane of the Galaxy (OSSE had enough exposure to observe such a feature only in the Galactic Center region and disk). The hypothesis would thus be strengthened if INTEGRAL detects other such features, particularly when linked to starburst regions.

2.2.2. Annihilation in the Ophiuchus molecular clouds

This cloud region is quite naturally an interesting candidate for the interpretation of the PLE since it fills an extended region ($l \approx -3°$ to $-12°$ and $b \approx 10°$ to $20°$) in the direction of the PLE region, and the distances of the clouds are 80 ± 20 pc (near edge) to 170 ± 35 pc (far edge). Moreover, molecular clouds are good sites for the annihilation of positrons since their densities are larger than that of the ISM. At the mean distance considered for the Ophiuchus cloud the PLE should correspond to an annihilation rate of about 10^{38} s^{-1}.

Observations performed by de Geus (1992), de Geus & Burton (1991), and de Geus et al. (1989) show an interaction of the slow expanding shell of the Upper-Scorpius association with the Ophiuchus clouds. This shell is driven by stellar winds and, as suggested by de Geus (1992), by a supernova explosion of a 40 $M_\odot$ star that would have occurred 1 to 1.5 Myr ago.

A 40 $M_\odot$ should produce about 0.7 $M_\odot$ of ^{56}Ni, $2.3 \times 10^{-4}\ M_\odot$ of ^{44}Ti (Woosley & Weaver 1995) and $6 \times 10^{-5}\ M_\odot$ of ^{26}Al (Woosley et al. 1995). Even if only a small fraction of the positrons from ^{56}Ni survive (0 to 10%), we estimate the rate of positrons penetrating the Oph clouds ranging between 0.1×10^{38} to 3.4×10^{39} s^{-1}. This estimate takes into account the uncertainties in the age of the SN, it assumes that the positrons released by the above isotopes are diluted in the 10–15 km s^{-1} expanding 1–4 pc thick shell (radius $\approx$40 pc). The amount of ^{26}Al, considering the SN age (between 1 to 1.5 Myr) and its dilution in the 30° diameter shell would have made its 1.8 MeV emission undetectable for GRO-COMPTEL.

Annihilation in a molecular cloud has been treated by Guessoum et al. (1997b) who considered the Orion cloud and produced calculated annihilation line shapes; and as referred to previously Guessoum et al. (2001) considered the annihilation of positrons in giant molecular clouds such as Ophiuchus, and indeed considered this cloud (and others) specifically, but only in the context of cosmic-ray bombardment. It was found that the line width does remain within the constraints set by the TGRS measurements ($\approx$2.5 keV), although the line sometimes displays a wide ($\Gamma \approx 6.4$ keV) base surmounted by a narrower ($\lesssim$2 keV) line. The positronium fraction, however, we find to be very difficult to reduce below about 0.4 (averaged over the cloud phases, although the filling factors are not always known to a good accuracy), even with strong dust content ($x_{\rm gr} \sim 5.0$).

In a future treatment, we plan to consider this scenario of wind-driven positron annihilation in nearby molecular clouds like Ophiuchus in greater detail, taking into account the propagation/diffusion of the positrons (by the supernova bubble) through the SN shell and into the cloud, and obtain predictions for 511 keV line fluxes and spectra.

2.3. Local origin

Since we have no way to gauge the origin and distance to the emission, and since past experience (e.g. the "Orion story" of nuclear gamma-ray line "detection") has taught observers to be careful not to mistake local emission with cosmic radiation, one needs to consider various possibilities that we group under the label "local". Indeed, one or several of the following physical origins could provide 511 keV emission: the solar system, the earth's space environment, or the CGRO platform itself.

Knowing all too well the difficulties of observational gamma-ray astronomy, particularly in the 511 keV band where a multitude of instrumental effects make background subtraction an extremely sensitive task, we have decided not to a priori exclude the possibility that the PLE could be an artifact. Even in this astrophysically uninteresting case, it is important to understand the local or instrumental origins of such an effect. Beyond the astrophysical implications, INTEGRAL's observational strategies and future gamma-ray instrumentation would largely benefit from such a lesson.

2.3.1. Ecliptic plane enhancement

Some of the recent annihilation radiation skymaps (Kurfess et al. 1999; Milne et al. 2001) hint at a coincidence of the PLE feature with the ecliptic plane. Produced and accelerated by whatever mechanisms (radioactivity, micro-quasar jets, supernova superbubbles, etc.), positrons follow the magnetic field lines of the Galaxy; some of them do reach the solar system, where we observe them as a component of the CR (a fraction of the electron component). Sooner or later some of these positrons will encounter matter and annihilate, and clearly the chances for this to happen is much greater in the ecliptic plane where the bulk of the mass of our solar system is concentrated, in the form of: dust; planets and their plasmatails; asteroids; satellites; etc.

We have estimated the annihilation rate and flux from these "primary positrons". For this we needed the flux of primary CR positrons entering the solar system. Measurements of such particles are usually made for energies higher than about 1 GeV, and the spectrum of these particles is a power law (of index ≈ -3; see for example Longair 1994) for high energies but flattens out around 1 GeV due to solar wind modulation. CR protons have an integrated flux of about 1800 protons/m^2/str/sec; electrons are fewer by about 2 orders of magnitude, and positrons are less abundant than electrons by a factor of 10 (for recent, accurate measurements of energy spectra of electrons and positrons, primary plus secondary, at $E \gtrsim 1$ GeV, see Boezio et al. 2000). For the ambient matter, we need the density and the temperature in the disk for the various types of particles (free electrons, neutral atoms, dust). For free electrons, Petelski et al. (1980) give measurement data for n_e, T_e, n_H (and other quantities) at 1 AU, 10 AU, and 100 AU, which we interpolate to obtain the following approximate expressions:

$$n_\mathrm{e}(r) \approx \frac{5\ \mathrm{cm}^{-3}}{r^2}, \tag{1}$$

$$T_\mathrm{e}(r) \approx \frac{1.5 \times 10^5\ \mathrm{K}}{\sqrt{(r)}}, \tag{2}$$

$$H(r) = 0.14\ \mathrm{AU}\, r^{5/4}, \tag{3}$$

where r is in units of 1 AU and H is the scale height at r.

The cross section for e$^+$-e$^-$ direct annihilation is $\sigma_{\mathrm{e}^+-\mathrm{e}^-} \approx 10^{-20}\ \mathrm{cm}^{-2}$, which combined with the above information gives a flux of emission of 511 keV photons of $\sim 10^{-10}$ photons cm^{-2} s^{-1}, which is several orders of magnitude lower than the PLE emission.

For neutral atoms in the disk, again by interpolating from the data of Petelski et al. (1980) we write the following approximate relation: $n_\mathrm{H}(r) \approx 2 \times 10^{-3}\ r\ \mathrm{cm}^{-3}$. The cross section in this case is that of the "charge exchange" process (e$^+$ + H $\longrightarrow$ Ps + p): $\sigma \approx 10^{-16}\ \mathrm{cm}^{-2}$. Integrating these quantities over the extent of the ecliptic ($\approx$100 AU), we obtain a rate of 511 keV of $\approx 10^{-8}$ photons cm^{-2} s^{-1}, which must be regarded as an upper limit, since this figure assumes a density of hydrogen that rises linearly with distance (and a constant ecliptic matter scale height).

Thirdly, we need to consider the annihilation of positrons on the dust. Observations indicate a total dust mass of $\approx 10^{20}$ g (Grün et al. 1997). Assuming typical dust grains (of radius $\sim$0.1 μm, density $\approx$1 g/cm^3, normal metallicity), one obtains a total number of dust grains of $\approx 10^{34}$. This translates into an average dust grain density of $\sim 10^{-9}$ cm^{-3}, which implies a totally negligible contribution to any annihilation emission from the disk, especially since the positron-grain cross section is also very low: $\approx 10^{-21}$ cm^2, for the typical grain parameters we have adopted (see Guessoum et al. 1991; Zurek 1985).

There remains one possibility: that the thousand-fold more abundant primary CR protons would produce, through nuclear reactions with the ambient nuclei, enough secondary positrons to produce substantial annihilation from the disk. Using the above free-electron density as a measure of ambient proton density, a cross section of proton-proton production of positrons of $\approx$30 mb, multiplied by the yield in pions/positrons for each CR proton, and a positron mean free path of (at most) $\sim 10^{15}$ cm, we obtain a fraction of secondary positrons (to primary protons) of $\sim 10^{-9}$, which is many orders of magnitude lower than the primary positron abundance. This is indeed confirmed by the data of Boezio et al. (2000), which show the data for primary plus secondary positrons to be almost exactly equal to the ratio of primary positrons to primary protons, i.e. the negligibility of secondary positrons produced by the ecliptic disk.

We have concluded that in all of the above variations on the "ecliptic plane annihilation" scenario, although some 511 keV photons will be produced, the flux of such an emission seems to be largely insufficient to explain the observed PLE flux.

2.3.2. Earth's space environment

The basic idea of this scenario is that since the main evidence of the PLE came from OSSE, the detected radiation might have originated from natural or artificial "positron pollution", especially since CGRO-OSSE was operating in a low Earth orbit ($\approx$400–500 km). The PLE might then be due to the annihilation of such positrons, whereby they would get stored by the geomagnetic field until they annihilate in the zones of the earth's radiation belts or plasma sheets, producing a diffuse zone of annihilation that could follow the Sun-Earth symmetry, should the geometry lead to such an effect. Since the distances to the annihilation site are no longer "astronomical", the number of positrons required to produce a PLE-like signal might then be comparable to the positron abundances that can be found in such magnetic regions.

Artificial injection of positrons into that region of space was discovered in the eighties by SMM when radiation at 511 keV was detected from unshielded satellite-borne reactors (Rieger et al. 1989; Share et al. 1989). This "nuclear noise" cannot explain the PLE radiation simply because the latter is not a series of regular, short timescale events that could be linked to specific injections. Indeed, the positrons in that region (height ∼500 km) would not survive more than a few hundreds or thousands of seconds, and would therefore need to be continuously resupplied.

On the other hand, natural injection of positrons into "plasma sheets" (in shells of inner and outer radii that depend on the positrons' kinetic energies) is known to occur, mainly by albedos of pairs produced by high-energy cosmic rays hitting the dense layers of the atmosphere (at a height of ∼100 km). Indeed, the recent Alpha Magnetic Spectrometer (AMS) experiment aboard the International Space Station measured fluxes of positrons (along with electrons, protons, helium nuclei, etc.) and found surprising levels of energetic ($E \gtrsim 1$ GeV) positrons at altitudes of 400 km or more (Alcaraz et al. 2000; Lipari 2002). It was thus tempting to investigate whether the annihilation of such positrons would produce an emission that would appear to come from a specific direction ofspace, namely the ecliptic, especially if the solar wind does rearrange the plasma sheets in such a way as to produce a symmetry with respect to the ecliptic plane.

It appears that the solar wind has too small an effect at such altitudes for it to significantly reshape the plasma sheets and give them a preferred direction of annihilation along the ecliptic. The spacecraft (CGRO in this case), being at about the same altitudes as the plasma sheets, would practically bathe in them and therefore not only see no preferred direction but moreover find no difference between the "on" and "off" directions of observations.

Finally, we should should point out that this scenario is one of the easiest to check with INTEGRAL, since the latter conducts 90% or more of its observations above the radiation belts. No PLE feature would then be observed with INTEGRAL.

2.3.3. Sun-Earth-CGRO symmetry

Although the authors of the various studies of OSSE data believe that the PLE is not caused by non-uniform OSSE exposure (the feature is not located in a region of high exposure, no similar feature is seen in the reconstructed map from the simulated data, and the feature is clearly present in all of the datasets, analysis methods and in bootstrap data sets), a scan angle effect or any other systematic effect might enhance the rich background.

CGRO's solar panels (and other observational constraints) did not allow OSSE observations of any region of the sky at any given time. Over many observations, the ecliptic plane is necessarily introduced as an "averaged" symmetry. We know that the earth's space environment is the principal source of background, although the net effect for a single observation might often be marginal (depending on CGRO's orientation). Over time, such symmetries might add up to a positive excess in what seems to be the ecliptic plane. The reported positronium continuum *deficit* in the PLE (Milne et al. 2001) is readily explained in this scenario: as the positrons are quickly slowed down by the dense spacecraft material, they will lack the necessary energy to induce charge exchange (Ps formation) with atoms – as a result, the annihilation produces mainly 511 keV photons.

Table 4. Positronium fraction $f_{\rm Ps}$ and line width Γ_{FWHM} in a hot and dusty medium.

T (K)	$x_{\rm gr}$	$f_{\rm Ps}$	Γ_{FWHM} (keV)
1.0×10^4	0.0	0.985	1.50
	0.1	0.984	1.50
	0.5	0.980	1.50
	1.0	0.974	1.50
	2.0	0.964	1.50
	5.0	0.935	1.50
1.0×10^5	0.0	0.749	3.50
	0.1	0.674	2.75
	0.5	0.493	2.10
	1.0	0.382	2.00
	2.0	0.280	1.90
	5.0	0.186	1.88
1.0×10^6	0.0	0.420	10.9
	0.1	0.190	2.00
	0.5	0.123	1.84
	1.0	0.112	1.82
	2.0	0.106	1.80
	5.0	0.102	1.80
1.0×10^7	0.0	0.007	40.0
	0.1	0.10	2.84
	0.5	0.10	2.78
	1.0	0.10	1.95
	2.0	0.10	1.85
	5.0	0.10	1.82

Again in this scenario, INTEGRAL should not see any 511 keV PLE feature. In addition to being more sensitive, INTEGRAL's instruments have a different architecture and observation scheme, so that if artifacts appear at the sensitivity limit, they are unlikely to coincide with the PLE's "location".

3. High temperature and dust: No need for additional positrons?

As we have emphasized in the previous sections, one of the most important results and constraints to consider in any modeling or interpretation of the PLE feature is the result of Milne et al. (2001) that there is a *deficit* of positronium emission in that feature. The authors realize and state that any additional source of positrons would almost automatically result in an enhancement of both the line emission and the continuum. One of their suggestions is that instead of an additional source of positrons, perhaps there is simply a variation of $f_{\rm Ps}$,

Table 5. INTEGRAL falsification criteria for the PLE models investigated in this work.

Model	Falsification Criterion	Falsification Possibility
Galactic Fountain	SPI: narrow 511 keV line; IBIS/SPI: constant f_{Ps} over PLE	Yes
Pair Jet	Unfalsifiable Hypothesis (only non detection by SPI/IBIS)	No
Gamma-Ray Burst	f_{Ps} in SPI/IBIS (no other features)	Yes
EGRET Sources	IBIS: non-detection of point sources + SPI: detection of the PLE	Yes
Modest starburst	SPI: emission not coincident with association/starburst regions	Yes
Ophiuchus Cloud	IBIS/SPI: PLE not coincident with position of Oph. cloud	Yes
Ecliptic Plane	SPI: non detection of the PLE out of the ecliptic plane	Yes
Space Environment	SPI: detection of a PLE	Yes
Sun-CGRO Symmetry	SPI: detection of a PLE	Yes

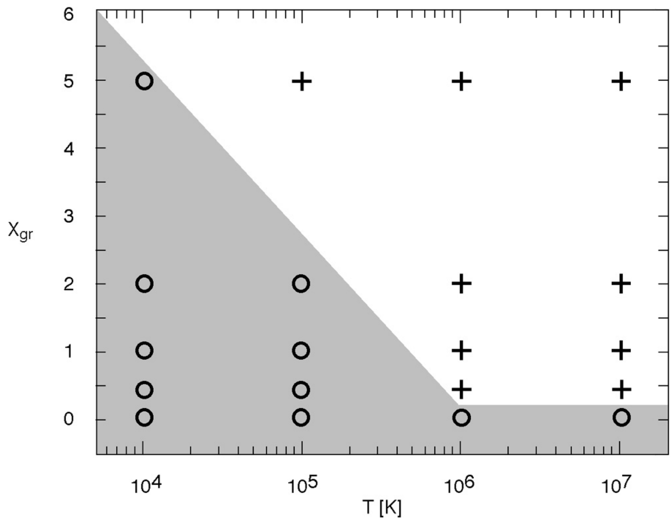

Fig. 1. The "+" data points refer to values of the $T - x_{gr}$ parameters that produce satisfactory results for the constraints on f_{Ps} and Γ; the "o" points refer to parameters that violate one or both of the constraints. The shaded region is that where the parameter-space produces unsatisfactory results for f_{Ps} and Γ in the PLE.

the positronium fraction, over the PLE region, such that the emission displays a deficit in the continuum and an enhancement of the line.

A relatively simple way to, physically but not quite astronomically, achieve this is to make the medium fully ionized, in order to destroy the neutral hydrogen, which has the highest cross section for positronium formation. The hotter the medium, the fewer hydrogen atoms there will be; however, increases in the temperatures lead to a widening of the emission line, which is supposed to be "narrow", as we discussed previously. This latter constraint is dealt with best by increasing the dust content of the environment, assuming as usual that the line from grains has a fixed width of 1.8 keV for direct annihilation and 2.5 keV for annihilation via positronium, independent of the temperature (an assumption that is not quite experimentally confirmed either). We have thus run our program for various values of the temperature and the grain factor x_{gr} (the ratio of dust abundance in the medium compared to the normal ISM abundance) and determined the values of f_{Ps} and Γ_{FWHM} in each case. Table 4 shows our results, and Fig. 1 shows the regions of the $T - x_{gr}$ parameter space that would be consistent with the constraints from f_{Ps} and Γ_{FWHM}.

The results show that a parameter space of roughly high temperatures ($\gtrsim 10^5$ K) and high dust abundances ($x_{gr} \gtrsim 2$) would satisfy the constraints on f_{Ps} and Γ. It is not clear, of course, whether such conditions could exist in the PLE region ($z \sim 1$ kpc above the galactic plane).

4. Summary and conclusions

ESA's INTErnational Gamma-RAy Laboratory INTEGRAL, which is to belaunched in October 2002, will allow us to first verify the existence of the positive latitude enhancement of 511 keV annihilation radiation. If the feature turns out to be real, INTEGRAL will determine its intensity and localize the emission region spatially. It will further measure the line width and determine the spectral and angular shape of the radiation, as well as the positronium continuum emission relative to the line.

The combined analysis of IBIS and SPI data will enable us to discriminate between all the presently existing models, with an uncertainty only regarding one hardly falsifiable model (pair jet).

Table 5 lists the models of the previous sections, showing the criteria for their testing/falsification by INTEGRAL. Aside from the discrimination between the existing PLE models, we do not exclude that the high quality of INTEGRAL data will result in a new and probably totally unexpected view of the e^+e^- annihilation in the inner Galaxy.

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