

# Annihilation Puzzles for INTEGRAL

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## Abstract

The instrument is operational, the analysis team assembled and the observations have begun. As we are on the precipice of the INTEGRAL era of annihilation radiation science, it is timely to review the findings of the CGRO/OSSE instrument by posing four new puzzles for the INTEGRAL satellite's SPI and IBIS teams. The puzzles are: 1) Is there a Galactic Center point source?, 2) What is the Bulge-Disk ratio?, 3) Does the annihilation fountain exist?, 4) Is there Gould Belt emission? Answering these four puzzles will not be easy, and will likely require dedicated observations beyond those scheduled as part of the *Core Program*. However, if all four can be definitively answered, annihilation radiation science will have moved very close to being able to account for the production of galactic positrons, and will be ready to use positron annihilation to probe the Galaxy.

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Positron annihilation radiation has long been considered a part of "Astronomy with Radioactivities" because positron-producing  $\beta^+$  decays are expected to be present at most nucleosynthesis sites. Many other mechanisms have been suggested to account for galactic positrons, but  $\beta^+$  decay positrons are almost certainly a significant contributor. The OSSE instrument on-board the Compton Gamma-Ray Observatory (CGRO) spent nine years observing the Galaxy, permitting study of the galactic distribution of annihilation radiation. Based on results from analysis of those observations, I pose four questions that I feel are the most important questions for INTEGRAL to answer. Before proceeding to these questions, I first review annihilation radiation and OSSE findings.

Most suggested mechanisms of positron production lead to the creation of highly energetic positrons. Cross sections for the annihilation of positrons with electrons decrease with energy (below the cross sections for scattering off of electrons), so positrons tend to thermalize into a given medium before annihilating (or slowing to very nearly thermal velocities). This leads to a

time delay between positron production and positron annihilation, and for many scenarios spatial separation between the production site and the annihilation site. Eventually, the positrons slow and annihilate. Depending upon the composition, and ionization state of the medium in which the positrons annihilate, the positron-electron annihilation can produce either a pair of 511 keV photons (in the rest frame of the annihilating medium) or a continuum of three photons where the total energy of the photons equals 1022 keV. The positronium continuum flux increases with energy up to 511 keV and falls abruptly to zero. The ratio of continuum to line photons varies from 0.0 to 4.5 and is then a measure of the conditions of the annihilation medium. When detected by an instrument with energy resolution of 5 keV or better, the line is a dominant feature that is easily resolved from the positronium continuum. The TGRS instrument was such an instrument and made wide FoV observations that determined that the integrated galactic annihilation radiation has a continuum to line photon ratio of  $\sim 3.6$  (Harris et al. , 1998). The OSSE instrument had poorer energy resolution ( $\sim 45$  keV @ 511 keV), but superior spatial resolution ( $3.8^\circ \times 11.4^\circ$  FoV) and arrived at the same ratio for the inner Galaxy (Kinzer et al. , 2001). The line component is easier to extract from the observed spectrum than the continuum component and line fluxes have dominated the published results. However, there are more photons in the continuum, so reporting only the line results ignores the majority of the annihilation photons.

The observing strategy for the OSSE observations was only partially guided by the effort to map annihilation radiation. The exposure map for the annihilation radiation data-set is dominated first by the galactic center region, and second by the galactic plane. This translates to OSSE studies largely concentrating on the inner radian of the Galaxy, with very non-uniform exposure outside the inner radian. OSSE has resolved two components to the emission, an intense bulge and a fainter disk. Purcell et al. 1997 (Purcell et al. , 1997) also reported the detection of a positive latitude enhancement that was subsequently termed an “annihilation fountain” (Dermer and Skibo , 1997), although follow-up observations did not support the existence of a fountain (Milne et al. , 2001). The OSSE findings are the basis for the following.

## **1 Is there a galactic center point source?**

From the very first observations of annihilation radiation, it has been suspected that the emission is brightest from the direction of the galactic center. The apparent variability of two observations made five months apart (Riegler et al. , 1981) led to speculation that the dominant source of galactic positrons is a galactic-center point source (it was even named the “Great Annihilator”). The claim of variability appeared to be supported by the fact that a number

of balloon instruments measured different fluxes when pointed at the galactic center. Re-analysis of the HEAO-3 observations (performed 8 years later) revealed that the likely cause of the observed variability was detector degradation while performing the observations, and not any true variation in the flux level (Mahoney , 1988). The existence of a time-variable “Great Annihilator” was further cast into doubt by two other pre-OSSE developments during the 1980s. The SMM instrument observed the galactic 511 keV emission for nine years (1980-1989) and found no significant variability in the emission (Share et al. , 1990). Von Ballmoos (1989) demonstrated that the observed fluxes from 11 instruments could all be explained if the emission were due to an intense bulge and a fainter, but longitudinally-extended disk (Von Ballmoos , 1989).

Observations made by the OSSE instrument permitted dramatic improvements of the understanding of the galactic center region’s annihilation. The galactic center was observed sporadically during the entire mission and exhibited no significant variability in the emission. The improved sensitivity of the OSSE instrument over the SMM instrument greatly constrained the allowed level of variability. Further, OSSE determined that the bulge component is best explained as an extended source ( $\sim 5^\circ$  FWHM) rather than as a point source (Kinzer et al. , 2001; Purcell et al. , 1997; Milne et al. , 2001). The “Great Annihilator” has thus been replaced by an extended bulge as the principal contributor of the bulge emission.

This is not to say that a point source could not contribute in addition to an extended bulge, or that a collection of point sources could not replace the entire bulge. Indeed, an earlier OSSE study suggests that four point sources at specific locations near the galactic center would explain the OSSE observations as well as an extended bulge (Milne and Leising (1997)). Back-of-the-envelope combinations of point plus extended bulges suggest a  $3\sigma$  upper limit of  $1.5 \times 10^{-4}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  for the 511 keV flux from a galactic center point source from OSSE observations. The puzzle to SPI and IBIS is to determine whether a point source near this level is present. The SPI instrument will be capable of detecting the 511 keV line and the positronium continuum emissions with far better spatial resolution than OSSE possessed. Between the *Core Program* Galactic Center Deep Exposure (GCDE) observations and the additional galactic center observations awarded to Sunyaev and to Goldwurm sufficient exposure should be realized in the first two cycles to independently confirm or reject the existence of a point source. The IBIS instrument will also be able to contribute to this study. IBIS will be capable of detecting the lower-energy portion of the positronium continuum emission from a galactic center point source, if one is present. The order-of-magnitude better spatial resolution of IBIS compared with SPI will simplify extracting any point source emission from the diffuse emission.

If neither instrument detects point source emission, theorists must finally let

go the notion of an *in-situ* “Great Annihilator” and begin to understand the ramifications of a diffuse bulge. Bear in mind that a galactic center source of positrons might be capable of producing a diffuse bulge component if most positrons escaped the inner 100-400 pc of the galactic center region (thus being better named a “Great Positron Producer” than a “Great Annihilator”), but one would expect some observable consequence of this mechanism at the galactic center.

## 2 What is the Bulge-Disk Ratio?

The spatial resolution of the OSSE instrument enabled various distributions of annihilation radiation to be compared with the observations. In addition, maps were generated from the data-sets. Between the bulge-disk model fitting and the generation of maps, a basic picture has emerged, an intense bulge emission and a fainter disk emission. The exact B/D ratio was estimated to lie between 1/3 and 3. While this appears to be a large range for that parameter, the lowest value is larger than most potential tracers would suggest. The bulge-disk pairs that best explain the OSSE 511 keV observations also best explain the OSSE/SMM/TGRS 511 keV observations as well as the OSSE positronium continuum observations. While this agreement doesn't necessarily demonstrate that the two emission components follow the exact same spatial distribution, it does argue that they are similar.

The OSSE observations essentially permit three families of solutions (Milne et al. , 2001). If the bulge has a halo (or wings), such as an  $R^{1/4}$  distribution would possess, then the thickness of the disk is rather arbitrary. Thin disks ( $\sim 2^\circ$  latitudinal FWHM) lead to B/D ratios of perhaps 3.0, and could be called “bulge dominated” solutions. Thick disks (up to  $15^\circ$  latitudinal FWHM) lead to B/D ratios of roughly unity and could be called “equal contribution” solutions. If the bulge lacks this halo (Gaussian bulges lack a halo), the disk must be thick and the B/D can be as low as 1/3. These solutions could be called “disk dominated” solutions. The possibility that the disk also possesses a halo component has not been investigated, but if present would shift the range of B/D ratios to lower values.

The SPI instrument will be able to improve the study of the B/D ratio by constraining the thickness of the disk. The preliminary SPI map of 511 keV emission shown at this meeting lacks a recognizable disk component. This might be indicative of a thick disk. If the disk is thick, the analysis of the *Core Program* Galactic Plane Scan (GPS) will be very complex.

### 3 Does the Annihilation Fountain Exist?

One of the most exciting early findings of the OSSE annihilation observations was that there appeared to be an excess of emission at positive latitudes, almost directly above the galactic center. This so called “annihilation fountain” was variously reported to have a total 511 keV line flux of  $(1-5) \times 10^{-4}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  depending upon how it was characterized (Purcell et al. , 1997). Subsequent observations showed no evidence of a fountain at the previously reported location and established upper limits for the fountain flux as low as  $1 \times 10^{-4}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . None of the subsequent observations possessed the exposure time required to conclusively confirm or reject the existence of an annihilation fountain. Further analysis of the entire OSSE data-set revealed that the location of the 511 keV excess corresponded to a location of a positronium continuum deficit. This contrasts with the anti-fountain direction, where the line and continuum emissions follow similar distributions. Thus, either there exists in the Galaxy, above the galactic center, a region of anomalous positronium fraction, or observations in that region have been biased by the underlying continuum emission. There are indications that the latter explanation might be the correct one. CGRO/BATSE monitoring of point sources via earth-occultation have revealed that the source, GRS 1716-249, was active during the period in which some of the OSSE observations were performed. While observations made during the source’s primary flare were not included in the data-sets, observations made during a series of secondary flares were. Indeed, these observations exhibited the 511 keV excess and continuum deficit seen in the maps. Simulations of those observations confirmed that a hard thermal bremsstrahlung component combined with a hard power-law tail could generate “false” annihilation fluxes values *if not carefully fitted*. While this explanation cannot account for every observation that favors an annihilation fountain, it does remove any significance to the fountain feature.

The CGRO mission was terminated before the OSSE instrument was able to perform the needed deep exposures of the fountain region. By contrast, the INTEGRAL instruments will accumulate appreciable exposure to the region via the GCDE (and potentially the Von Ballmoos observations). The SPI instrument possesses one important advantage to OSSE with respect to this investigation: the far superior energy resolution will greatly improve the ability to extract annihilation radiation emission from the spectral fits. The IBIS instrument can also contribute to this investigation by obtaining simultaneous observations of the active point sources in the FoV, which will assist the SPI spectral analysis. If SPI detects a 511 keV excess, the previous explanation of a point source induced bias would be invalid, and the reality of the feature would be confirmed. If, however, the fountain region emits at the level expected from spherical symmetry, the fountain would be rejected. Clearly, INTEGRAL will be able to complete the determination of whether there exists an annihilation

fountain.

#### 4 Is there Gould Belt Emission?

By far the most speculative of the four puzzles is the determination of whether there is annihilation radiation associated with the Gould's Belt. As the Gould's Belt is a very local region of enhanced star formation, it is a natural candidate for nearby massive stars and recent core-collapse supernovae (Comeron, Torra and Gomez , 1994). It is suggested to have at least 300 stars with masses in excess of  $8 M_{\odot}$ , and estimates suggest a current SN II rate of  $42 \text{ Myr}^{-1} \text{ kpc}^{-2}$  Grenier (2000). These objects are sources of  $^{26}\text{Al}$  and  $^{44}\text{Ti}$ , which produce positrons as part of their decay chains. Thus, there is a reasonable expectation that the Gould's Belt should be a source of positron annihilation. The difficulty lies in predicting where in the Gould's Belt the emission should be detectable.

Both the CGRO/COMPTEL and the CGRO/OSSE instruments have reported hints that the Gould's Belt might contain gamma-ray line emission. Diehl (1998) reported a weak correlation between the Gould's Belt and the 1809 keV  $^{26}\text{Al}$  maps (Diehl , 1998). OSSE maps also exhibit emission features that appear to follow the Gould's Belt, but the non-uniform exposure of the OSSE instrument makes characterizing the individual sources very difficult. Thus, the determination of whether there exists Gould's Belt annihilation radiation falls to the INTEGRAL instruments. As an old supernova remnant is the suggested source of these positrons, it is almost certain that these emission features would be extended. This means that detecting this emission will likely to be the responsibility of the SPI instrument rather than the IBIS instrument. The specific locations to search for this emission can be directed by the OSSE maps, or by the regions where the Gould's Belt is maximally separated from the galactic plane. This separation is desirable to minimize ambiguity between Gould's Belt and galactic plane sources. The O and B stars in the Gould's Belt follow a roughly sinusoidal distribution,  $l = A \cdot \sin b + C$ , where  $l$  and  $b$  are the galactic longitude and latitude,  $A=22.3^{\circ}$ , and  $C=284.5^{\circ}$ . A visual best-fit to the OSSE features yields,  $A=25.3^{\circ}$ , and  $C=325^{\circ}$ . Considering the Gould's Belt is at least  $30^{\circ}$  thick and the OSSE features are poorly mapped, these differences can be considered minor.

The most systematic way to study this emission would be to conduct a mid-latitude scan in the 3rd and 4th cycles that would match the GPS. Supernova remnant  $^{44}\text{Ti}$  (1173 keV) and diffuse  $^{26}\text{Al}$  (1809 keV) emission might also be mapped using these observations. In addition, this scan would be able to study the mid-latitude EGRET sources and determine if they are also correlated with the Gould's Belt (Grenier , 2000).

## 5 Summary

OSSE observations of positron annihilation radiation have helped to refine the understanding of where positrons annihilate in the Galaxy. From these studies I have posed four questions that I think INTEGRAL will be able to answer. By the end of the INTEGRAL mission it might not be overly optimistic to predict that we will begin to understand the sources of galactic positrons. As the understanding of positron production improves, the opportunities to utilize positron annihilation to probe the Galaxy and the Galaxy's million-year history will increase.

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