Detection of the 511 keV Galactic Positron Annihilation Line with COSI

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Abstract

The signature of positron annihilation, namely the 511 keV γ-ray line, was first detected coming from the direction of the Galactic center in the 1970s, but the source of Galactic positrons still remains a puzzle. The measured flux of the annihilation corresponds to an intense steady source of positron production, with an annihilation rate on the order of \( \sim 10^{43} \, e^+ \, s^{-1} \). The 511 keV emission is the strongest persistent Galactic γ-ray line signal, and it shows a concentration toward the Galactic center region. An additional low-surface brightness component is aligned with the Galactic disk; however, the morphology of the latter is not well constrained. The Compton Spectrometer and Imager (COSI) is a balloon-borne soft γ-ray (0.2–5 MeV) telescope designed to perform wide-field imaging and high-resolution spectroscopy. One of its major goals is to further our understanding of Galactic positrons. COSI had a 46-day balloon flight in 2016 May–July from Wanaka, New Zealand, and here we report on the detection and spectral and spatial analyses of the 511 keV emission from those observations. To isolate the Galactic positron annihilation emission from instrumental background, we have developed a technique to separate celestial signals using the COMPTEL Data Space. With this method, we find a 7.2σ detection of the 511 keV line. We find that the spatial distribution is not consistent with a single point source, and it appears to be broader than what has previously been reported.

Unified Astronomy Thesaurus concepts: High altitude balloons (738); Gamma-ray lines (631); Gamma-ray telescopes (634); Spectroscopy (1558); Galactic center (565); Astronomy data modeling (1859)

1. Introduction

The 511 keV signature of electron–positron annihilation was first observed from the Galactic center (GC) region in the 1970s (Johnson et al. 1972; Haymes et al. 1975; Leventhal et al. 1978), but the source of these positrons is still not well understood. The 511 keV emission, which is the brightest persistent γ-ray line in the Galaxy, shows a strong concentration in the GC region with a low-surface brightness contribution from the Galactic disk: a distribution that is unlike anything seen in other wavelengths. The proposed birth sites of these Galactic positrons include the \( \beta^+ \) decay of stellar nucleosynthesis products (e.g., \( ^{26}\text{Al} \), \( ^{44}\text{Ti} \), and \( ^{56}\text{Ni} \); Milne et al. 1999; Prantzos et al. 2011; Crocker et al. 2017), pair production in microquasars, low-mass X-ray binaries, and millisecond pulsars (Prantzos 2006; Weidenspointner et al. 2008; Venter et al. 2015; Bartels et al. 2018), and even dark matter (Boehm & Ascasibar 2004). However, it is difficult to account for the observational constraints without tuning individual source parameters to extreme values.

Early spectral measurements of the emission found a slightly broadened line at 511 keV, and a low-energy continuum from the three-photon decay of ortho-positronium (o-Ps), a short-lived intermediate bound state between a positron and electron (Mohorovicic 1934; Deutsch 1951). Significant progress in our understanding of Galactic positrons has been made through spectral studies with the spectrometer SPI (Vedrenne et al. 2003) on board ESA’s INTEGRAL satellite (Winkler et al. 2003). Using one year of public SPI data, Jean et al. (2006) and Churazov et al. (2005) performed independent spectral studies of the GC region and found that the annihilation of positrons occurs predominately in warm neutral and partly ionized gas phases in the Galaxy. The 511 keV line shape and the o-Ps continuum flux imply that the annihilating positrons have kinetic energies at the electronvolt (eV) scale. At higher energies, positrons can annihilate in flight to produce a continuous high-energy spectrum; Beacom & Yüksel (2006) and Sizun et al. (2006) estimated that Galactic positrons cannot have initial energies higher than a few megaelectronvolt (MeV) from upper limits of the emission above 511 keV as measured by COMPTEL. The positrons must lose energy and slow down after production, and it is therefore expected that positrons propagate some distance from their production sites to where they annihilate. More recently, Siegert et al. (2016) have analyzed more than 10 years of SPI data and have confirmed earlier results in the spectral domain; however, the authors questioned whether the annihilation conditions, and thus the spectral signatures, are identical throughout the Galaxy.

The imaging analysis, on the other hand, has been less conclusive. Initial images of the positron annihilation signature were obtained by the Oriented Scintillation Spectrometer Experiment (OSSE) on board the Compton Gamma-Ray Observatory (CGRO), launched in 1991. By combining OSSE data with scanning observations from the Transient Gamma-Ray Spectrometer (TGRS) and the Solar Maximum Mission (SMM), Purcell et al. (1997) produced maps of the emission that showed three distinct features: (1) a central bulge, (2) emission along the Galactic disk, and (3) a positive latitude enhancement. This confirmed earlier measurements that detected an enhancement in the GC region and was the first observational evidence of 511 keV emission consistent with the plane of the Galaxy. The positive enhancement, which became known as the “annihilation fountain” (Dermer & Skibo 1997),
was not seen in OSSE images of the o-Ps continuum (Milne et al. 2001) and is now believed to be an imaging artifact.

Recent attempts to constrain the spatial distribution have been made with SPI observations. Because SPI is a coded-mask imaging telescope, analysis of diffuse emission has relied on a model fitting approach that makes SPI insensitive to weak gradients and large-scale structures much larger than the 16° field of view (FOV). The proposed spatial models remain entirely empirical. The first SPI all-sky map of the 511 keV emission (Knödlseder et al. 2005), which used a Richardson-Lucy deconvolution technique (Richardson 1972), showed a strong emission feature toward the Galactic bulge. Bouchet et al. (2010) analyzed six years of SPI data and found a possible shift of the 511 keV central bulge emission toward negative longitudes and no significant detection of a point-source contribution, and they reported on a possible halo emission geometry. Skinner et al. (2014) and Siegert et al. (2016) have performed more recent studies of the spatial distribution, and both describe the 511 keV emission in the Milky Way with four empirical 2D Gaussian functions: a narrow and broad bulge with 5°.9 and 20°.5 full width at half-maximum (FWHM), respectively, a point-source component consistent with Sgr A*, and a disk component. The reported extent of the disk emission is drastically different in these two recent studies, resulting in a poorly constrained positron annihilation rate in the Galaxy.

After almost five decades of scientific investigation, there are still major questions about Galactic positrons. The 511 keV emission from the Galactic disk can potentially be explained by nucleosynthesis products; however, there is no conclusion as to the source of positrons in the Galactic bulge region. The spatial morphology of the emission has not been well constrained, and it is not clear if the 511 keV emission should trace the distribution of positron sources or if there really is a significant positron propagation (Higdon et al. 2009; Jean et al. 2009; Alexis et al. 2014). In addition, there is the question of whether the emission is truly diffuse, as could be expected from gas in the Galaxy, or if there is a large population of unresolved point sources that makes the emission appear smooth. Both theoretical advancements in the understanding of positron interactions, the constituents of the interstellar medium, and Galactic magnetic fields, and a more accurate image of the 511 keV emission are needed to further advance in this topic. A direct-imaging telescope with a wide FOV would be able to determine the true spatial morphology, conclusively determine the extent of the disk emission, and measure the true annihilation rate from different regions of the Galaxy.

The Compton Spectrometer and Imager (COSI) is a telescope that has been developed with the goal of furthering our understanding of Galactic positrons. With its wide FOV and Compton-imaging capabilities, COSI, described in Section 2, can shed light on these open questions, especially in regards to morphology. In this paper, we report on the detection of the 511 keV GC emission with COSI during its 2016 balloon flight from Wanaka, New Zealand, overviewed in Section 3. This is the first detection and characterization of Galactic positron annihilation with a Compton telescope. Because other telescope technologies rely on distinct background estimation techniques and thus suffer from different systematics, the COSI measurements provide a unique diagnostic compared to the coded-mask imager SPI and the collimated OSSE. To extract the spectral and spatial signature of Galactic positron annihilation, we have developed a technique to estimate the environmental and instrumental background with the COMPTEL Data Space, described in Section 4. We present a characterization of the 511 keV line shape and o-Ps continuum fraction, as well as the flux of the 511 keV line, as detailed in Sections 5.1 and 5.2. In Section 5.3 we present a measurement of the spatial distribution of the Galactic bulge emission with COSI. A discussion of the results presented here is found in Section 6, and Section 7 is the conclusion of this study.

2. The Compton Spectrometer and Imager

COSI is a soft γ-ray (0.2–5 MeV) telescope designed to fly on NASA’s new 18 million cubic-foot Super Pressure Balloon (SPB) platform. COSI had a successful 46-day balloon flight in 2016 May–July (Kierans et al. 2016), and here we present the analysis of the Galactic positron annihilation signature as detected during that flight.

The heart of COSI is composed of 12 cross-strip, high-purity germanium detectors (GeDs; Amman et al. 2007). Each detector is 8 cm × 8 cm × 1.5 cm, where 37 strip electrodes deposited orthogonally on each side give the detectors internal position sensitivity with a 3D voxel size of 1.5 mm³ (Lowell et al. 2016). The use of GeDs gives COSI a high spectral resolution of 0.6% FWHM at 662 keV.

The 12 detectors are stacked in a 2 × 2 × 3 configuration in an aluminum cryostat and have a total active volume of 972 cm³. Cesium iodide scintillators surround the cryostat on the four sides and bottom to act as an anticoincidence shield to veto background radiation, predominantly from Earth’s albedo, and constrain the FOV to ~π sr. The COSI cryostat is fixed on top of a nonpointing, zenith-oriented gondola frame and operates as a free-floating survey instrument.

The COSI instrument has notable heritage. Prior to the 2016 flight, the same instrument was flown as an SPB Mission of Opportunity in 2014 from McMurdo Station, Antarctica; unfortunately, the balloon developed a leak and the flight only lasted 43 hr. The precursor instrument to COSI, the Nuclear Compton Telescope, saw three previous launches. For a description of the COSI instrument and its history, see Bandstra et al. (2011) and Kierans et al. (2016), and reference Lowell et al. (2017a, 2017b) for GRB science results from the 2016 COSI flight.

2.1. Compton Telescope Basics

Taking advantage of the dominant interaction mechanism at MeV energies, Compton telescopes use the interaction position and energy deposits in a sequence of Compton scatterings to determine the initial photon’s energy and source sky position (von Ballmoos et al. 1989; Boggs & Jean 2000). In a compact Compton telescope such as COSI, the distance between interactions is too small for time-of-flight methods, and thus the correct temporal order of scatters is determined through Compton kinematic reconstruction (Boggs & Jean 2000), which uses redundant information in the geometry and kinematics of the scatters to find the mostly likely path of the photon.

Each event in a Compton telescope is recorded as a measurement of the position and energy of interactions in the detector volume. After Compton event reconstruction, the main parameters for an event are reduced to the total energy
deposited and the geometric angles of the scattered photon in
the initial interaction (further discussed in Section 4). These
descriptors are used to constrain the initial photon direction to a
projected circle on the sky, often called the event circle. When
multiple photons from the same source interact in the detector,
the resulting event circles will overlap at the source sky
position and iterative deconvolution techniques can be used to
create an image.

The angular resolution of a Compton telescope is described
by the angular resolution measure (ARM). The ARM is the
smallest angular distance between a known source location and
the event circle for each photon. The distribution of all ARM
values from a sample of Compton events represents the
effective width of the point-spread function of a Compton
telecope. Consequently, the FWHM of the ARM distribution
defines the achievable angular resolution after event
reconstruction.

2.1.1. Compton Telescope Event Selections

The source detection significance of a Compton telescope
can be improved by rejecting lower quality events through
proper selections. The event selections aim to optimize the
signal-to-noise ratio; however, stricter selections will limit the
effective area. The selections used in this analysis, and their
general effect, are listed below and summarized in Table 1.

| Parameter                        | Allowed Range |
|----------------------------------|---------------|
| Altitude                         | \( \geq 27,000 \) m |
| Origin selection                 | 16° (if applicable) |
| Photon energy                    | 506–516 keV (if applicable) |
| Number of interactions           | 2–7 |
| Compton scatter angle            | 15°–55° |
| Distance between first 2
interactions                      | \( >0.5 \) cm |
| Distance between any interaction  | \( >0.3 \) cm |
| Earth horizon cut                | Reject if any part of event circle is below horizon |

Note. The origin selection is used only for the spectral
subtraction (Section 4.1), and the photon energy cut is only used for the CDS-ARM
subtraction (Section 4.2).

4. The Earth horizon cut (EHC) rejects any event whose
Compton event circle overlaps with the horizon. This is
the most rigorous method to reduce the background from
albedo radiation during flight.

5. An origin cut can be made on a location in image space
with a given radius. Only Compton events that overlap
with this origin selection will be kept.

2.2. Analysis Package

The COSI collaboration employs the Medium Energy
Gamma-ray Library (MEGAlib; Zoglauer et al. 2006) for its
primary data analysis pipeline. MEGAlib is a set of software
tools that specializes in Compton telescope data analysis:
applying instrument calibrations, performing Compton recon-
struction, and implementing image reconstruction. MEGAlib
also has tools for accurate instrument simulations based on
GEANT4 (Agostinelli et al. 2003), in which a detailed
description of the measured detector performance can be
applied to Monte Carlo simulations. For a description of the
COSI analysis pipeline and a thorough comparison between
simulations and laboratory measurements taken prior to the
2016 campaign, see Sleator et al. (2019).

3. Observations

COSI was launched from Wanaka, New Zealand (45° S,169° E), on 2016 May 17 (23:35 05/16/16 UTC) on-board
NASA’s SPB platform. The flight was terminated after 46 days,
and the instrument landed 200 km northwest of Arequipa, Peru,
on 2016 July 2 (19:54 07/02/16 UTC; 16° S, 72° W). The
trajectory of the instrument covered a range of latitudes from
60° S to 6° S and included a total circumnavigation of the
Earth. The nominal float altitude was 33 km; however, large
altitude drops occurred at night during the latter half of the
flight due to anomalies in the balloon. Three of the twelve
GeDs had high-voltage-related issues during the flight: two
were nonoperational after 48 hr, and one failed 20 days into the
flight. The loss of these detectors decreased the effective area
by close to 50% for these observations; the COSI team has
since determined and corrected the high-voltage issues for
future flights. A more detailed description of the COSI 2016
flight can be found in Kierans et al. (2016).

Southern latitudes provide excellent exposure of the GC
region, which is necessary for Galactic 511 keV studies. From
the 2016 flight, COSI had a total of 1.6 Ms of exposure of the
GC region, considering times when the GC was within 40° of
COSI’s zenith. Figure 1 shows the full-flight exposure map
with prominent \( \gamma \)-ray sources labeled. Figure 2 shows the
elevation of the GC for the duration of the flight, where 90°
corresponds to COSI’s zenith and 0° represents the horizon.
This figure also indicates the times when the altitude of the
payload descended below 32 km, depicted in red. Unfortu-
nately, the GC was in COSI’s FOV only during the night hours,
when the altitude eventually began to drop due to the lower
atmospheric temperatures. At lower altitudes, there is more
attenuation of \( \gamma \)-rays in the atmosphere, which directly impacts
the observation. At the expected float altitude of 33 km, the
nominal transmission probability at 500 keV is 49%, but, for
example, at 27 km the transmission probability is only 18% at
zenith. At the nominal float altitude of 33 km, the average
transmission probability for a 500 keV source at the GC is
46%, where we have included the flight aspect information.
when the elevation of the GC is above 40°. This is reduced to an average of 30% transmission when accounting for the loss of altitude. The total GC exposure time when the altitude was above 33 km is then reduced to 610 ks.

One of the difficulties of MeV γ-ray astrophysics is the dominant background radiation. Figure 3 shows the total accumulated background spectrum from the flight. The majority of photons in this spectrum are from atmospheric emissions, i.e., γ-rays from cosmic-ray interactions in the atmosphere. Furthermore, when the instrument is bombarded with protons, neutrons, and other cosmic-ray particles in the upper atmosphere, nuclear reactions will be induced within the instrument material. Radioactive isotopes that have a half-life longer than the timing resolution of the detector, but shorter than the flight duration, will eventually decay and could appear as a Compton event. Some of the activation lines, which are mostly from germanium, are labeled in Figure 3. The 511 keV line has background contributions from both activation and atmospheric emissions, and the intensity of these background components predominately depends on the atmospheric depth, geomagnetic cutoff rigidity, and zenith angle (Ling et al. 1977).

To extract the Galactic positron annihilation spectrum, a precise description of the observed background radiation is required. A physical standalone background model is not able to capture all the observed dynamics during the flight. However, calculating the variations of the background as a function of Earth longitude and latitude, resulting in rigidity values, as well as taking into account the flight altitude at every instance in time results in large systematics, especially for the 511 keV background line. Therefore, a sophisticated technique to separate out the Galactic emission from the background has been developed. In particular, the recorded events are analyzed according to their expected appearance in the fundamental data space of Compton telescopes. This is detailed in Section 4.

For the analysis presented here, we use all 46 days of flight, excluding times when the background rates were high due to electron precipitation events (Millan & Thorne 2007; Kierans et al. 2016) and times when the altitude dropped below 27 km.

4. Analysis Method

The COMPTEL collaboration pioneered the analysis tools for Compton telescopes. In particular, they performed the majority of their analyses in a 3D data space, referred to here as the COMPTEL data space (CDS). We use the CDS background handling approach as introduced for the 26Al γ-ray line measurement with COMPTEL (Knödlseder et al. 1996). To perform an accurate estimate of the background for the 511 keV line in COSI data, we further developed this technique. This is the first instance that this method has been applied for a compact Compton telescope such as COSI and for Galactic positron annihilation analysis. A similar approach for analysis of continuum point sources detected by COSI is presented in Sleator (2019).

The three orthogonal axes of the CDS are defined by the polar and azimuthal angles, χ and ψ, respectively, of the first Compton scatter direction d1 in detector coordinates, and the Compton scatter angle φ of the first interaction. In Figure 4(a), a schematic illustrates the definition of the three CDS angles for a single event. The total energy of the γ-ray can be considered the fourth dimension of this data space. In contrast to the projected event circle in image-space, each Compton event is a point in the CDS at (χ, ψ, φ). The accumulation of Compton events from point-source emission in the instrument FOV, depicted by the yellow star at (χ0, ψ0) in Figure 4(a), populates the surface of a 3D cone in the CDS; see Figure 4(b). The CDS cone has its apex at the source position (χ0, ψ0) in detector polar coordinates because in the limit that φ → 0, d1 will point toward the source location. The opening angle of the cone is 90° because the Compton scatter angle and polar scatter direction increase at the same rate. For a point source, the surface of the cone is as thick as the angular resolution of the instrument, while extended sources, such as the Galactic 511 keV emission, produce a thicker cone and an extended apex.

For flight observations, we convert the χ and ψ dimensions of the CDS from detector coordinates into Galactic coordinates.
with known aspect information of COSI for every Compton event. With the CDS in Galactic coordinates, a source at the GC would put the apex of the CDS cone at the origin of the data space and the cone shape is transformed into a 2D plane relative to the $f$ and $\chi$-axes, see Figure 4(c). The azimuthal scatter direction $\psi$ in detector coordinates is now equal to the Klein–Nishina azimuthal scatter angle \cite{Klein1929}, which encodes the polarization of the incoming emission. However, the Galactic positron annihilation emission is not expected to be polarized, and therefore, we can integrate over the $\psi$ dimension with no loss of information. The CDS is then projected into a 2D plane defined by $\chi$ and $\phi$.

Ideally, a source at the GC in this 2D space is mapped to a line at $\chi = \phi$. The resulting 2D CDS representation of a simulated 511 keV point source observed at COSI's zenith is shown in Figure 5(a): we have made an energy selection of 506–516 keV to select on the fully absorbed events. Because of the finite energy and position resolution in our detectors and Doppler broadening \cite{Zoglauer2003}, there is a spread to this distribution. The deviation from the ideal $\chi = \phi$ line is equivalent to the ARM distribution, i.e., the effective point-spread function. We define the distance of each event from the $\chi = \phi$ line as $\chi - \phi$, as opposed to the closest distance to the line, given by $(\chi - \phi)/2$. We refer to this angular distance as the CDS-ARM. The CDS-ARM histogram of the on-axis point-source simulation is shown in Figure 5(b). The CDS-ARM is the radial distribution of events around the source position, and we use these terms interchangeably. If the source is extended, then the radial distribution will be broadened. The use of this reduced 2D CDS can be generalized for sources not at the GC by rotating any source location into the origin of the CDS; see Kierans \cite{Kierans2018} for details.

In general, we can define a region of interest, or source region SR, for these observations as an angular cut around the
GC, and therefore a cut around the $\chi = \phi$ line. In Figure 6 we illustrate this 2D CDS with the source region SR defined as an origin cut (see Section 2.1.1) of $\pm \Delta$ around the GC, and the background regions BRin and BRout as adjacent cuts.

The relative population of the background regions depends on $\phi$. For this analysis, we find that an origin cut of $\Delta = 16^o$ results in the highest signal-to-noise ratio. We also find that the significance of the detection is higher when only BRout is used. This is understood to be due to its geometrical differences in the background regions; BRin does not begin to be populated until $\phi \gtrsim \Delta$, as can be seen in Figure 6. Because smaller Compton scatter angles allow for a more accurate reconstruction, the BRout region is better suited for determining the background spectrum in the analysis presented here, where we select only the Compton scatter angles in the range $15^o$–$55^o$. Therefore, we only use BRout to estimate the background for this analysis.

### 4.1. Spectral Background Estimation Routine

Although the Compton scatter angle $\phi$ is strongly dependent on energy, in this analysis, we take advantage of the fact that the scatter angle direction $\chi$ is energy independent. For each Compton scatter angle $\phi$ bin, we fill the CDS and find the spectrum from the source in SR and the surrounding background region BR. To account for the fact that the source and background regions of the CDS are not evenly populated, we estimate an off-measurement by scaling the background region spectrum for an adjacent energy range that contains no source contribution: here we use 520–720 keV for the positron annihilation emission.

The following four-step process defines how the relevant background in COSI data is estimated in the CDS:

1. Fill the CDS with all events. For SR and BR separately, bin the Compton scatter angle in the CDS. The measurement statistics allows us to define $\phi$ bins as small as $1^o$. For an origin cut of $\Delta$, the spectrum for the region consistent with SR in $\phi$ bin $i$ is

   $$N^{SR}(\phi_i, E) = \sum_{\chi=\phi-i}^{\phi+i} n(\chi, \phi, E),$$

   where $n(\chi, \phi, E)$ is the number of counts in the $(\chi, \phi, E)$ bin of the CDS. These are the on-source spectra. The $\phi$-dependent spectra for the outer background region BRout in bin $i$ are

   $$N^{BR}(\phi_i, E) = \sum_{\chi=\phi+i}^{\phi+3\Delta} n(\chi, \phi, E).$$

2. Find the scaling factor for each background spectrum $N^{BR}(\phi_i, E)$ so that the number of counts in a higher energy range, 520–720 keV for these studies, equals that in $N^{SR}(\phi_i, E)$ within the same energy band. The scaling factor, $F_{\phi_i}$, for each Compton scatter angle bin then is

   $$F_{\phi_i} = \frac{N^{SR}(\phi_i, E[520 < E < 720])}{N^{BR}(\phi_i, E[520 < E < 720]).}$$

3. For each $\phi$ bin $i$, scale the background region spectrum $N^{BR}(\phi_i, E)$ by $F_{\phi_i}$ to obtain a background estimate,

   $$B^{SR}(\phi_i, E) = F_{\phi_i} N^{BR}(\phi_i, E),$$

   i.e., an estimate for an off-measurement.

4. With our on-source measurements $N^{SR}(\phi_i, E)$ from Step 1 and our background estimate $B^{SR}(\phi_i, E)$ from Step 3, we can find the source spectrum by summing the remaining counts in each $\phi$ bin,

   $$S(E) = \sum_i [N^{SR}(\phi_i, E) - B^{SR}(\phi_i, E)].$$

The CDS background estimation routine is illustrated in Figures 7 and 8. Figure 7 shows the flight SR spectrum in red for two different Compton scatter ranges: $\phi = [20^o, 21^o]$ and $\phi = [40^o, 41^o]$. The difference seen in these two spectral shapes results from the $\phi$ energy dependence of Compton scattering and clearly demonstrates the need to perform background estimation as a function of $\phi$. The background spectrum from BR is plotted in blue after rescaling. For each Compton scatter range, there is a very good match between the source region spectrum and the scaled background region spectrum, as shown in the residuals of the plots.

By using the energy range from 520 to 720 keV to scale the background $\phi$-dependent spectra, we are relying on the energy independence of $\chi$. Figure 8 shows the $\chi$ distribution from background simulations for two different energy ranges above and below the 511 keV line emission: 300–500 keV is shown in green, and 520–720 keV is shown in black. Simulation data are used because the positron annihilation spectrum is known to have the $\alpha$-Ps continuum below 511 keV and therefore the flight data should show statistical differences between the two energy intervals. The $\chi$-distributions have been normalized, and we confirmed that there is no statistical difference between the two distributions with chi-square statistical tests.

Overlaid on the $\chi$-histograms in Figure 8 are the locations of the source region and the background regions, highlighted in...
red and blue, respectively. For each \( f \) bin, we know that the polar scatter angles that are consistent with the source region satisfy \( cf < D \). The \( \chi \) values that are consistent with the source region are shaded in red, while the \( \chi \) values that are consistent with the two background regions are shaded in blue. As discussed in Section 4, we only use \( BR_{\text{out}} \) for this analysis, but the \( \chi \) values that are consistent with \( BR_{\text{in}} \) are also shaded in this plot for clarification. The total number of counts within the red SR of the 520–720 keV \( \chi \)-distribution in Figure 8 is by definition equal to the integrated spectrum of the SR within 520–720 keV in Figure 7. This is also true for the \( BR \).

4.2. Spatial Background Estimation Routine

We can determine the radial distribution of the emission by performing a CDS-ARM analysis. Analogous to the routine described in Section 4.1, we wish to define a CDS-ARM off-measurement to recover the angular distribution of the celestial signal. To do this, we need to find an appropriate estimate of the background distribution.

Obtaining the CDS-ARM distribution of the Galactic positron annihilation emission is a direct measure of the radial extent of the source around the GC; if the emission originates from a point source, we would expect to recover a CDS-ARM distribution with an FWHM \( \sim 6^\circ \), equivalent to COSI’s angular resolution, as shown in Figure 5(b). If the emission has an inherent width, however, the measured CDS-ARM will be a convolution of the instrument point-spread function and the spatial distribution of the source.

The CDS-ARM background estimation procedure relies on the results from the spectral estimation and is a four-step process:

1. Find a separate CDS-ARM distribution for the two different energy ranges: the line interval \( (506 < E < 516 \text{ keV}) \) and the higher energy range \( (520 < E < 720 \text{ keV}) \).
\(\phi\)-dependent CDS-ARM distribution in the 511 keV line interval is given by \((\chi - \phi)\) for each \(\phi\) in bin \(i\): 

\[N^{511}(\phi, \chi - \phi).\]

This is our on-source measurement. The CDS-ARM distribution for the higher energy (HE) interval is \(N^{16}(\phi, \chi - \phi)\).

2. Use the scaled background spectrum \(B^{SR}(\phi, E)\) from the third step in the spectrum estimation routine to determine the normalization factor for the higher energy CDS-ARM in each bin \(i\):

\[A_{\phi} = \frac{B^{SR}(\phi, E)[506 < E < 516]}{B^{SR}(\phi, E)[520 < E < 720]},\]

(6)

3. For each \(\phi\) bin \(i\), scale the high-energy interval CDS-ARM distribution by \(A_{\phi}\) to obtain an estimate for the background distribution,

\[B^{511}(\phi, \chi - \phi) = A_{\phi}N^{16}(\phi, \chi - \phi),\]

(7)

i.e., an estimate for an off-measurement.

4. With our on-source measurements \(N^{511}(\phi, \chi - \phi)\) from Step 1 and our background distribution estimate \(B^{511}(\phi, \chi - \phi)\) from Step 3, we can find the radial distribution of the source by summing the remaining counts in each \(\phi\) bin:

\[S(\chi - \phi) = \sum_{i}[N^{511}(\phi, \chi - \phi) - B^{511}(\phi, \chi - \phi)].\]

(8)

Figure 9 shows the CDS-ARM distribution from a full-flight background simulation (see Kierans 2018 for details) for events with Compton scatter angle \(\phi = [16^\circ, 17^\circ]\) shown in panel (a), and events with \(\phi = [59^\circ, 60^\circ]\) shown in panel (b). The CDS-ARM distribution for the line interval 506–516 keV is shown in red. The distribution from the higher energy range, 520–720 keV, has been scaled using the background spectra \(B^{SR}(\phi, E)\), and is shown in blue. This scaled higher energy CDS-ARM serves as our estimated radial distribution of the background and closely matches the line interval distribution.

4.3. Background Estimation Method Validation

We developed a detailed background simulation for the full COSI flight, including the atmospheric contribution as well as instrument activation, that closely matches the measured data. With simulations of GC sources, we were able to recover the simulated flux, with the correct line width and spatial distribution. See Kierans (2018) for a detailed description of the method validation.

5. Results

5.1. Positron Annihilation Spectrum

Figure 10 shows our final measured spectrum for a 16° origin cut around the GC after applying the CDS background estimation routine described in Section 4.1. The significance of the Galactic 511 keV line is 7.2\(\sigma\) (calculated with an F-test; Snedecor & Cochran 1991). The event selections for this analysis are listed in Table 1.

As discussed in Section 1, the positron annihilation emission from the Galaxy is characterized by two spectral signatures: the annihilation line at 511 keV, and the \(o\)-Ps continuum below 511 keV. A possible contribution from the diffuse Galactic \(\gamma\)-ray continuum is strongly suppressed by this method. We therefore describe the spectrum by combining a Gaussian and \(o\)-Ps spectral component, \(F_{oPs}(E)\) as defined in Ore & Powell (1949), to give a four-parameter spectral fit function:

\[F(E) = A \exp \left(\frac{-(E - \mu)^2}{2\sigma^2}\right) + BF_{oPs}(E),\]

(9)

where \(A, B, \mu, \) and \(\sigma\) are the free parameters of the fit. \(A\) and \(B\) are amplitude-scaling factors for each spectral component, and \(\mu\) and \(\sigma\) are the Gaussian mean and width, respectively. \(F_{oPs}(E)\) has been convolved with the COSI instrument response prior to the fit. From the relative flux of the \(o\)-Ps continuum and the 511 keV line, denoted by \(I_{511}/I_{oPs}\), we calculate the positronium fraction (Prantzos et al. 2011):

\[f_{Ps} = \frac{8I_{511}/I_{oPs}}{9 + 6I_{511}/I_{oPs}}.\]

(10)

The resulting fit parameters are listed in Table 2.

The line was found with a centroid at 511.8 ± 0.3 keV with a width of \(\sigma = 2.5 \pm 0.3\) keV. The integrated background spectrum over the whole flight gives an annihilation line
The detection significance is 7.2σ detection.

Table 2
Fit Parameters for the COSI 2016 Flight Positron Annihilation Spectrum Shown in Figure 10

| Parameter       | Value                        |
|-----------------|------------------------------|
| Gaussian Fit    |                              |
| μ               | 511.8 ± 0.3 keV              |
| σ               | 2.5 ± 0.3 keV                |
| A               | 403 ± 57 cts keV⁻¹          |
| o-Ps Fit        |                              |
| B               | 12 ± 4 cts keV⁻¹             |
| $\chi^2$/dof    | 193.0/196                    |

Note. The fit is made over the energy range 450–550 keV. The reduced $\chi^2$ of 0.99 with 196 degrees of freedom (dof) implies an adequate fit to the spectrum. The derived parameters are the integrated 511 keV line counts, $I_{511}$, as well as the o-Ps counts ($I_\gamma$; area under the curve) and the positronium fraction.

5.2. Measured Flux

To convert the measured counts into a source flux, we use simulations to estimate the effective area, $A_{\text{eff}}$, of COSI at 511 keV. We simulate a Galactic 511 keV source based on the Skinner model (Skinner et al. 2014), with 10 times the expected Galactic flux to increase statistics. For these simulations, we use the COSI flight aspect information and take into account the drops in altitude to calculate the correct exposure and attenuation in the atmosphere. The flux is then calculated to be

$$\text{Flux} = \frac{N_{\text{det}}}{A_{\text{eff}} \times \text{time}} = \frac{2560 \pm 300 \text{ cts}}{(8775 \text{cts}) \times (0.0133 \gamma \text{ cm}^{-2} \text{s}^{-1} \times 3.08 \times 10^6 \text{s})} = (3.9 \pm 0.4) \times 10^{-3} \gamma \text{ cm}^{-2} \text{s}^{-1}. \quad (11)$$

The exposure time from the full flight is $3.08 \times 10^6$ s, ignoring times of very low altitude. From full-flight simulations we find 8775 cts between 506 and 516 keV from the 16° region around the GC, assuming a flux of 0.0133 γ cm⁻² s⁻¹. These numbers allow us to calculate an effective area, written out above with the numbers from the simulation, to find the measured flux of $(3.9 \pm 0.4) \times 10^{-3} \gamma \text{ cm}^{-2} \text{s}^{-1}$ from the COSI observations. The error is statistical and does not include all systematics. For comparison, Siegert et al. (2016) report a total Galactic 511 keV line flux of $(2.74 \pm 0.03) \times 10^{-3} \gamma \text{ cm}^{-2} \text{s}^{-1}$ with SPI measurements, and Purcell et al. (1997) find a line flux of $(2.25 \pm 0.07) \times 10^{-3} \gamma \text{ cm}^{-2} \text{s}^{-1}$ by combining OSSE, SMM, and TGRS data.

5.3. Radial Distribution of the 511 keV Sky

COSI provides a novel investigation of the 511 keV spatial distribution. As discussed in Section 1, coded-mask telescopes such as SPI rely on a model fitting approach to determine the morphology of the Galactic positron annihilation emission and suffer from an inability to detect diffuse emission with strong gradients, and thus have limitations. Furthermore, collimated instruments such as OSSE use on/off pointings with a detector that has no inherent imaging capabilities. Not only is the imaging model dependent, but these telescope types favor certain angular scales (e.g., FOV of the collimator, FOV and pitch of the coded mask). A Compton telescope such as COSI does not favor a particular spatial frequency and allows for a more direct measurement of the extent of the Galactic emission because Compton telescopes obtain spatial information from every photon.

Figure 11 shows the measured radial distribution for the 511 keV line with a 40° pointing selection on the GC. This CDS-ARM distribution is fit with a single Gaussian and the measured FWHM of $33° \pm 2°$. The parameters from the Gaussian fit of the CDS-ARM distribution are shown in Table 3. A 40° pointing selection was used for this analysis.
because it was found to decrease the uncertainties of the measured distribution; when no pointing selection is used, the measured FWHM is $32^\circ \pm 4^\circ$.

As described in Section 4, the CDS-ARM distribution is the angular distance of each 511 keV Compton event from the GC. Therefore, this 1D distribution shows the radial extent of emission around the GC. Unfortunately, it is not able to separate out any difference in longitude and latitude or possible asymmetries. However, work is currently underway to produce a full sky image from the COSI 2016 flight data (T. Siegert et al. 2020, in preparation).

We note that through detailed simulations, we have concluded that we are only sensitive to the bulge emission with the current data set and techniques and are not able to detect a disk component; therefore, we compare our measured distribution with the simulated CDS-ARM distribution of the Skinner model bulge emission only, shown in blue. The COSI data shows a distribution that is significantly larger. Likewise, the measured distribution from combined OSSE, SMM, and TGRS data has also been found to be a much narrower profile around the GC than the radial distribution reported here (Purcell et al. 1997; Kinzer et al. 2001).

The Skinner model bulge distribution in Figure 11 has been scaled so that the area under the curve is the same as the flight data CDS-ARM distribution. This visually shows the difference in widths of the Skinner model bulge distribution and the detected spatial distribution at 511 keV. To test the difference between these two histograms, we perform a chi-squared test, which gives a $P$-value = 0.001, and therefore there is a $3 \sigma$ statistical significance between the COSI distribution and the Skinner bulge distribution.

The radial distributions shown in Figure 11 include the COSI instrument response, which can be subtracted in quadrature to determine the true emission around the GC. The inherent COSI angular resolution of $6^\circ$ at 511 keV is small relative to the width of the measured CDS-ARM distribution, therefore the reported width of the 511 keV Galactic emission is $32^\circ \pm 2^\circ$.

### 6. Discussion

The spectral results from the 2016 COSI flight show a measured 511 keV line at $511.8 \pm 0.3$ keV with $\sigma = 1.7 \pm 0.4$ keV from a 16$^\circ$ region around the GC. This corresponds to a measured flux of $(3.9 \pm 0.4) \times 10^{-3} \gamma$ cm$^{-2}$ s$^{-1}$. We measure the o-Ps continuum emission with $5110 \pm 1700$ total counts in the distribution, which corresponds to a $3 \sigma$ detection. From the ratio of the 511 keV line and the o-Ps flux, we find a positronium fraction of $f_{Ps} = 0.76 \pm 0.12$. This line flux and o-Ps continuum are within $\sim 3 \sigma$ of previously reported values from SPI measurements.

We find a slightly enhanced 511 keV flux that is 1.4 times higher than the total Galactic flux reported in Siegert et al. (2016) from SPI data and 1.7 times the flux reported for combined OSSE, SMM, and TGRS observations (Purcell et al. 1997). Ever since the first measurements of the 511 keV emission in the 1970s, determining the true flux has proven to be a challenge, with instruments with a wider FOV always recording a higher flux because the nature of the source is diffuse (see Figure 4 of Purcell et al. 1997). Furthermore, the flux results from SPI and OSSE, SMM, and TGRS have relied on an assumed spatial model. Nonetheless, we must consider the systematics that might result in an overestimated flux, particularly because the backgrounds at these energies are known to be heavily influenced by even small variations of the balloon environment. We performed detailed background simulations and a thorough validation of our analysis method for Galactic source models (see Kierans 2018 for details). The simulation results substantiate that we can determine the correct spectral shapes and that the $f_{Ps}$ is preserved through the background estimation technique described here with simulated data.

We test our method at different origin cuts in the sky that we expect to be void of positron annihilation as a further check. Figure 12 shows the resulting spectrum when the source location is chosen to be at $(120^\circ, -60^\circ)$ in Galactic coordinates. The nearly flat spectrum further confirms the legitimacy of our routine.

Although systematics are known to be high for Galactic 511 keV measurements, it is useful to consider what these spectral results could imply. One possible explanation for a higher flux is that the true spatial distribution does not agree with the distribution modeled for the SPI observations. For example, a larger disk contribution in the measurement would result in a larger number of events that are consistent with the inner region of the Galaxy, and therefore our simulation of the flight-averaged effective area using the Skinner model (Section 5.2) would result in a falsely high flux. However, this scenario does not offer an explanation for the low $f_{Ps}$.

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**Table 3**

| Parameter | Value |
|-----------|-------|
| Gaussian Fit | $\mu$ fixed at 0 |
| | $\sigma$ 14.0 $\pm$ 0.7 |
| | $A$ 89 $\pm$ 0.6 cts/deg |
| $\chi^2$/dof | 52/1/52 |
| FWHM | $33^\circ \pm 2^\circ$ |

*Note.* The distribution is fit with a single Gaussian because the statistics are insufficient to warrant more parameters.
Figure 12. CDS background-subtracted spectrum of flight data with Galactic coordinates (120°, −60°) chosen to be the source location. The flat spectrum further confirms that the systematics in the CDS subtraction are minor.

The unusually low reported value of $f_{p_{\alpha}}$, although only a 3σ significance, could be a signature of a previously undetected emission component with a smaller FWHM. From the measured line shape and a positronium fraction close to 1, analysis of SPI data has concluded that the annihilation predominantly occurs in warm and neutral phases of the interstellar medium (ISM; Churazov et al. 2005; Jean et al. 2006). An $f_{p_{\alpha}} < 1$ could be due to annihilation in a dusty warm phase of the ISM, which predicts a narrow 511 keV line and a suppressed $f_{p_{\alpha}}$ (Zurek 1985; Guessoum et al. 2005). However, with our statistics and systematics, further investigation is necessary before any conclusions can be reached from these measurements.

The measured radial distribution of the 511 keV line around the GC shows a Gaussian shape with an FWHM of 33° ± 2° (convolved with the instrument response). The proposed models from Skinner et al. (2014) and Siegert et al. (2016) have a Galactic bulge distribution defined by three components (Section 1), and when convolved with the COSI instrument response, the width of this distribution is 15°:0; therefore, we measure a distribution that is twice as broad.

The large extended shape of the COSI detected CDS-ARM distribution is intriguing. Siegert et al. (2016) use the same bulge description as Skinner et al. (2014) for their spectral studies, but report an alternative, yet equally significant, model in the appendix. This alternative model describes the bulge emission by two elongated components, with a longitudinal extent of the broad bulge up to FWHM ~ 55°. Bouchet et al. (2010) also report a halo morphology that is consistent with SPI data; with this extended component, the 511 keV flux was found to be $2.9 \times 10^{-3} \, \text{cm}^{-2} \, \text{s}^{-1}$, which is closer to the flux reported here. Furthermore, Skinner et al. (2013) performed the analysis with 10 yr of SPI data combined with archival data from OSSE, SMM, and TGRS to conclude that the absence of an extended halo would be inconsistent with the OSSE, SMM, and TGRS data set. The COSI results seem to agree more with the halo morphology; however, more data are needed to make a strong conclusion about the spatial distribution.

A connection between the potentially overestimated flux in the spectral estimation and the broad spatial distribution must also be considered. These measurements are indeed related because the background spectral subtraction determines the scaling factors of the background CDS-ARM distribution. If the excess counts in the detected 511 keV line are from a poorly modeled background component, then it is most likely that the background component would have a spatial distribution similar to the FOV of the instrument; however, this would give an FWHM >50°, which is much larger than the distribution that we measure and therefore seems improbable.

7. Conclusions

We have reported the first detection of the positron annihilation signal from the Galaxy with a compact Compton telescope, and to perform this analysis, we have developed an accurate background estimation technique that is valid for sources of line emission.

We have found a 7.2σ detection of the 511 keV line from the GC region, and a 3.0σ detection of the o-Ps continuum after 46 days of flight. The relative ratio of the 511 keV line and o-Ps continuum results in a low measurement of $f_{p_{\alpha}} = 0.76 ± 0.12$. Through this analysis, we found the radial distribution of the 511 keV emission around the GC to be described by a Gaussian with FWHM of $32° ± 2°$.

Although our analysis techniques are still being improved, the results from this study of Galactic positron annihilation are intriguing. The flux measurements, although with known systematics, could hint at a morphology that is not seen in SPI observations. The measured angular distribution is broader than the emission models presented by the SPI collaboration and is similar to what is expected from a halo model. The results discussed here show the power of Compton telescopes and the CDS analysis, and the need for more data is clear.

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