PROCEEDINGS OF SCIENCE

Observations of the Galactic Diffuse Continuum Emission from the 2016 COSI Balloon Flight

Christopher M. Karwin,[a,b,*] **Thomas Siegert,**[c] **Jacqueline Beechert,**[d] **John A. Tomsick,**[d] **Troy A. Porter,**[e] **Michela Negro,**[b] **Carolyn Kierans,**[b] **Marco Ajello,**[f] **Israel Martinez Castellanos,**[b,g] **Albert Shih,**[b] **Andreas Zoglauer**[d] **and Steven E. Boggs**[h] **for the COSI collaboration**

[a] *NASA Postdoctoral Program Fellow*
[b] *NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA*
[c] *Julius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Institut für Theoretische Physik und Astrophysik, Lehrstuhl für Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany*
[d] *Space Sciences Laboratory, UC Berkeley, 7 Gauss Way, Berkeley, CA 94720, USA*
[e] *W.W. Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA*
[f] *Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA*
[g] *Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA*
[h] *Department of Astronomy & Astrophysics, UC San Diego, 9500 Gilman Drive, La Jolla CA 92093, USA*

E-mail: christopher.m.karwin@nasa.gov

In this work we report measurements of the Galactic diffuse continuum emission (GDCE) observed towards the inner Galaxy during the 2016 COSI Balloon flight, which in the COSI energy band (0.2 – 5 MeV) is primarily generated from inverse Compton radiation. Within uncertainties we find overall good agreement with previous measurements from INTEGRAL/SPI and COMPTEL. Based on these initial findings, we discuss the potential for further probing the GDCE with the 2016 COSI balloon data, as well as prospects for the upcoming satellite mission.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)623

1. Introduction

The Galactic plane is a bright source of diffuse γ-ray emission. At energies below ~100 MeV the Galactic diffuse continuum emission (GDCE) is dominated by inverse Compton (IC) radiation, produced by cosmic ray (CR) electrons up-scattering low-energy photons of the interstellar radiation field (ISRF), which consists of UV-to-far-IR photons (from stellar emission and the scattering, absorption, and re-emission by dust), as well as photons from the cosmic microwave background [1]. The GDCE is also expected to contain subdominant contributions from Bremsstrahlung radiation, generated by CR electrons interacting with the Coulomb fields of the ambient gas, as well as from positron annihilation via positronium formation [2]. Observations of the GDCE in the MeV band thus provide a unique probe into the nature of both primary and secondary CR electrons. More specifically, the observations provide crucial information about the (energy-dependent) electron spectrum throughout the Galaxy, which in turn has implications for the electron source density, injection, and propagation. One key aspect of this is identifying the different source classes of CR electrons, which has remained a longstanding open issue in astrophysics [3]. Moreover, probing the GDCE in the MeV band is especially important, since γ rays at these energies correspond to a region of the electron spectrum for which no CR data is available, due to solar modulation [4, 5]. Instead, the local interstellar electron spectrum below ~10 GeV must be estimated by interpolation and/or CR propagation models. In contrast to the MeV band, the GDCE observed at high energies by the *Fermi* Large Area Telescope (*Fermi*-LAT) is dominated by hadronic interactions (mostly π^0-decay from CR protons interacting with the ambient gas), which makes probing CR electrons much more difficult with the LAT.

Overall, there are still numerous open questions pertaining to the fundamental nature of CR electrons in the Galaxy and their associated diffuse emission, and this warrants further investigation from new and independent probes. One such probe now on the horizon is the Compton Spectrometer and Imager (COSI), a Small Explorer satellite mission recently selected by NASA and scheduled to launch in 2027 [6, 7]. In 2016 COSI was flown as a balloon-borne experiment onboard NASA's Super Pressure Balloon platform, and had a successful 46-day flight, launching from Wanaka, New Zealand, and landing in Peru [8]. COSI primarily detects photons between 0.2 – 5 MeV via Compton scattering, and it functions as a spectrometer, wide-field imager, and polarimeter. More details about COSI's main science goals, the instrument, and the 2016 balloon flight can be found in [6–8], and references therein.

2. Analysis

Data for the 2016 COSI balloon flight is taken from [9], which analyzed the Galactic ^{26}Al nuclear decay line at 1.809 MeV. Although focused on the detection of ^{26}Al, a continuum signal towards the inner Galaxy was also found in that work. We convert the observed count rate to flux by determining COSI's response to the GDCE, including atmospheric attenuation. The GDCE is modeled using the CR propagation code GALPROP[1] (v57) [10, 11]. We use the latest state-of-the-art models from the most recent release of the GALPROP code, described in detail in [12]. This entails a set of six different models originally developed in [13], corresponding to three CR source

[1] https://galprop.stanford.edu/

distributions (SA0, SA50, and SA100) and two different models of the ISRF, R12 [14] and F98 [15]. We choose the SA100-F98 model as our representative case. In addition to our representative model, we also use two additional GALPROP models from [16], in which updated measurements of the GDCE towards the inner Galaxy were recently made with INTEGRAL/SPI. Specifically, we use the baseline model from that work [17], as well as the model that best-matched the data. COSI's response to the GDCE is simulated using the Medium-Energy Gamma-ray Astronomy library (MEGAlib) software package[2], a standard tool in MeV astronomy [18]. Simulations are ran for the full 46-day COSI balloon flight, and they closely mimic the real time-dependence of the instrument's pointing on the sky. For running the simulations we employ the COSI simulation pipeline[3], which is available in COSItools[4] (currently being developed for the COSI mission).

The observed count rate per energy bin from [9] is converted to flux using

$$F = \frac{\left(\frac{N_{\mathrm{obs}}}{t\times\Delta E}\right)}{\epsilon_{\mathrm{atm}} \times A_{\mathrm{eff}} \times \Delta\Omega}, \tag{1}$$

The effective area (A_{eff}) for a given energy bin is calculated from the MEGAlib simulations using the formulation

$$A_{\mathrm{eff}} = \frac{N_{\mathrm{det}}}{N_{\mathrm{sim}}} \times A_{\mathrm{sp}}, \tag{2}$$

where N_{det} and N_{sim} are the detected and simulated counts, respectively, and A_{sp} is a reference area in the simulations equal to 11310 cm^2. The number of simulated counts in a given energy bin is calculated as

$$N_{\mathrm{sim}} = \bar{F}_{\mathrm{reg}} \times t \times A_{\mathrm{sp}} \times \Delta\Omega \times \Delta E, \tag{3}$$

where $\bar{F}_{\mathrm{reg}}$ is the average model flux over the region of the sky covered by the observations (in units of ph cm^{-2} s^{-1} sr^{-1} MeV^{-1}), t is the total exposure time, $\Delta\Omega$ is the corresponding area of the sky, and ΔE is the width of the given energy bin. Our signal region is spanned by $|l| \leq 30°$ and $|b| \leq 10°$, plus a Compton broadening of $\phi_{\mathrm{max}} = 35°$ in all directions, which results in a sky region of $\Delta\Omega = 130° \times 90° = 3.56$ sr. The term ϵ_{atm} in Eq. 1 represents the atmospheric response. A full analysis of the atmospheric response for γ rays observed with balloon-borne detectors was recently made in [19]. We use results from that work to correct the spectrum of the GDCE for atmospheric attenuation, which includes both transmitted and scattered photons.

3. Results

In Figure 1 we show the resulting flux obtained by converting the emission observed in [9], as described in the previous section. For comparison, we also plot similar measurements from INTEGRAL/SPI [2, 16] and COMPTEL [3, 20]. As can be seen, the COSI observations are in overall good agreement with previous measurements. Thus the emission detected in [9] can most likely be attributed to the GDCE, and the results presented in Figure 1 provide the first estimate of the observed flux during the 2016 COSI balloon flight.

[2] https://megalibtoolkit.com/home.html
[3] https://github.com/cositools/cosi-data-challenges
[4] https://github.com/cositools

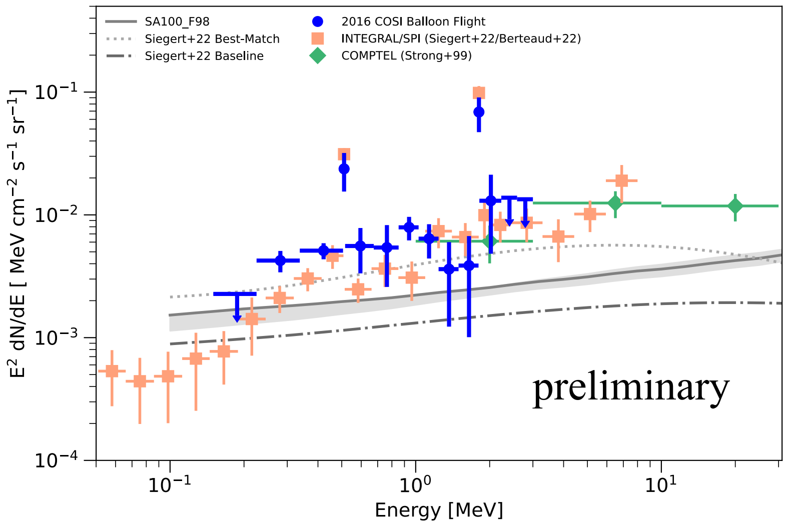

Figure 1: Observed flux towards the inner Galaxy during the 2016 COSI balloon flight. The blue data points are for COSI, and the error bars are 1σ statistical only. The salmon data points are for INTEGRAL/SPI, and the green data points are for COMPTEL, with the error bars on both measurements including statistical and systematic uncertainty. The grey curves show predictions for our three primary GALPROP models, as specified in the legend. The grey band shows the full range spanned by the six GALPROP models from [12], which includes the SA100-F98 model.

4. Conclusion

In this work we have determined the flux from the GDCE observed towards the inner Galaxy during the 2016 COSI balloon flight, finding good agreement with previous measurements from INTEGRAL/SPI and COMPTEL. Our measurements are based on the continuum emission initially detected in [7], which was focused on the detection of ^{26}Al. We stress that the full range of systematic uncertainties associated with the background subtraction have not yet been accounted for. Complete analysis details will be provided in a forthcoming publication [21]. With the current data from the COSI balloon flight we do not expect to have the sensitivity needed to make significant advances in our understanding of the GDCE. However, the COSI satellite mission should mark a giant leap forward in this regard. This will be the result of COSI's large field of view and improved sensitivity, as well as advancements in the modeling of the GDCE and data analysis tools (i.e. cosipy[5], currently under development). The COSI satellite mission should enable measurements of a highly precise spectrum over the entire sky, including the inner Galaxy. Such measurements will likely play a major role in disentangling the different components of the emission, including searches for new physics (e.g. [2, 22]), and they will be intimately connected with other wavelengths, including radio, GeV, and possibly TeV. The measurements will also help to map out the diffuse line emission in the Galaxy, including the 0.511 MeV line from electron-positron annihilation and associated ortho-positronium continuum. This is due to the strong correlation that can arise when analyzing the GDCE and line emission. Additionally, it is well known that there exists an excess in the observed flux towards the inner Galaxy with respect to the GALPROP predictions by a factor of $\sim 2-3$ (as

[5]https://github.com/cositools/cosipy

can be seen in Figure 1), and the COSI observations will help to probe the nature of this excess. Finally, by measuring the truly diffuse emission with unprecedented sensitivity in the MeV band, COSI will likely lead to new insights regarding the sources of CR electrons in the Galaxy.

Acknowledgements

CMK's research was supported by an appointment to the NASA Postdoctoral Program at NASA Goddard Space Flight Center, administered by Oak Ridge Associated Universities under contract with NASA.

References

[1] T.A. Porter, I.V. Moskalenko, A.W. Strong, E. Orlando and L. Bouchet, *Inverse Compton Origin of the Hard X-Ray and Soft Gamma-Ray Emission from the Galactic Ridge*, *ApJ* **682** (2008) 400 [0804.1774].

[2] J. Berteaud, F. Calore, J. Iguaz, P.D. Serpico and T. Siegert, *Strong constraints on Primordial Black Hole Dark Matter from 16 years of INTEGRAL/SPI Observations*, *PRD* **106** (2022) 023030 [2202.07483].

[3] A.W. Strong, K. Bennett, H. Bloemen, R. Diehl, W. Hermsen, D. Morris et al., *Diffuse Continuum Gamma Rays from the Galaxy Observed by COMPTEL.*, *AAP* **292** (1994) 82.

[4] M.J. Boschini, S. Della Torre, M. Gervasi, D. Grandi, G. Jóhannesson, G. La Vacca et al., *HelMod in the Works: From Direct Observations to the Local Interstellar Spectrum of Cosmic-Ray Electrons*, *ApJ* **854** (2018) 94 [1801.04059].

[5] E. Orlando, *Imprints of Cosmic Rays in Multifrequency Observations of the Interstellar Emission*, *MNRAS* **475** (2018) 2724 [1712.07127].

[6] J. Tomsick, A. Zoglauer, C. Sleator, H. Lazar, J. Beechert, S. Boggs et al., *The Compton Spectrometer and Imager*, in *Bulletin of the American Astronomical Society*, vol. 51, p. 98, Sept., 2019 [1908.04334].

[7] J. Beechert, H. Lazar, S.E. Boggs, T.J. Brandt, Y.-C. Chang, C.-Y. Chu et al., *Calibrations of the Compton Spectrometer and Imager*, *Nuclear Instruments and Methods in Physics Research A* **1031** (2022) 166510 [2203.00695].

[8] C.A. Kierans et al., *The 2016 Super Pressure Balloon flight of the Compton Spectrometer and Imager*, *PoS* **INTEGRAL2016** (2016) 075 [1701.05558].

[9] J. Beechert et al., *Measurement of Galactic 26Al with the Compton Spectrometer and Imager*, *ApJ* **928** (2022) 119 [2202.11713].

[10] I.V. Moskalenko and A.W. Strong, *Production and Propagation of Cosmic Ray Positrons and Electrons*, *Astrophys. J.* **493** (1998) 694 [astro-ph/9710124].

[11] A.W. Strong and I.V. Moskalenko, *Propagation of Cosmic-Ray Nucleons in the Galaxy*, *Astrophys. J.* **509** (1998) 212 [astro-ph/9807150].

[12] T.A. Porter, G. Johannesson and I.V. Moskalenko, *The GALPROP Cosmic-ray Propagation and Non-thermal Emissions Framework: Release v57*, *arXiv e-prints* (2021) arXiv:2112.12745 [2112.12745].

[13] T.A. Porter, G. Johannesson and I.V. Moskalenko, *High-energy Gamma Rays from the Milky Way: Three-dimensional Spatial Models for the Cosmic-Ray and Radiation Field Densities in the Interstellar Medium*, *Astrophys. J.* **846** (2017) 23pp.

[14] T.P. Robitaille, E. Churchwell, R.A. Benjamin, B.A. Whitney, K. Wood, B.L. Babler et al., *A self-consistent model of Galactic stellar and dust infrared emission and the abundance of polycyclic aromatic hydrocarbons*, *AAP* **545** (2012) A39 [1208.4606].

[15] H.T. Freudenreich, *A COBE Model of the Galactic Bar and Disk*, *ApJ* **492** (1998) 495 [astro-ph/9707340].

[16] T. Siegert, J. Berteaud, F. Calore, P.D. Serpico and C. Weinberger, *Diffuse Galactic Emission Spectrum Between 0.5 and 8.0 MeV*, *AAP* **660** (2022) A130 [2202.04574].

[17] D. Bisschoff, M.S. Potgieter and O.P.M. Aslam, *New Very Local Interstellar Spectra for Electrons, Positrons, Protons, and Light Cosmic Ray Nuclei*, *ApJ* **878** (2019) 59 [1902.10438].

[18] A. Zoglauer, R. Andritschke and F. Schopper, *MEGAlib The Medium Energy Gamma-ray Astronomy Library*, *NAR* **50** (2006) 629.

[19] C.M. Karwin et al., *Atmospheric Response for Gamma-Ray Observations with Balloon-Borne Experiments*, *prepared for submission to ApJ* (2023) .

[20] A.W. Strong, H. Bloemen, R. Diehl, W. Hermsen and V. Schönfelder, *COMPTEL Skymapping: a New Approach Using Parallel Computing*, *Astrophysical Letters and Communications* **39** (1999) 209 [astro-ph/9811211].

[21] C.M. Karwin et al., *Probing the Galactic Diffuse Continuum Emission with COSI*, *prepared for submission to ApJ* (2023) .

[22] A. Caputo, M. Negro, M. Regis and M. Taoso, *Dark matter prospects with COSI: ALPs, PBHs and sub-GeV dark matter*, *JCAP* **2023** (2023) 006 [2210.09310].