

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} Andreas Zoglauer^d and Steven E. Boggs^h for the COSI collaboration

^aNASA Postdoctoral Program Fellow

^bNASA Goddard Space Flight Center,
Greenbelt, MD, 20771, USA

^cJulius-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

^dSpace Sciences Laboratory, UC Berkeley,
7 Gauss Way, Berkeley, CA 94720, USA

^eW.W. Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University,
Stanford, CA 94305, USA

^fDepartment of Physics and Astronomy, Clemson University,
Clemson, SC 29634, USA

^gDepartment of Astronomy, University of Maryland, College Park, Maryland 20742, USA

^hDepartment 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.

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*Speaker

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 GALPROP¹ (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 package², 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 pipeline³, which is available in COSItools⁴ (currently being developed for the COSI mission).

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

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

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

$$A_{\text{eff}} = \frac{N_{\text{det}}}{N_{\text{sim}}} \times A_{\text{sp}}, \quad (2)$$

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 cm². The number of simulated counts in a given energy bin is calculated as

$$N_{\text{sim}} = \bar{F}_{\text{reg}} \times t \times A_{\text{sp}} \times \Delta \Omega \times \Delta E, \quad (3)$$

where \bar{F}_{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 $|l| \leq 30^\circ$ and $|b| \leq 10^\circ$, plus a Compton broadening of $\phi_{\text{max}} = 35^\circ$ in all directions, which results in a sky region of $\Delta \Omega = 130^\circ \times 90^\circ = 3.56$ 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>

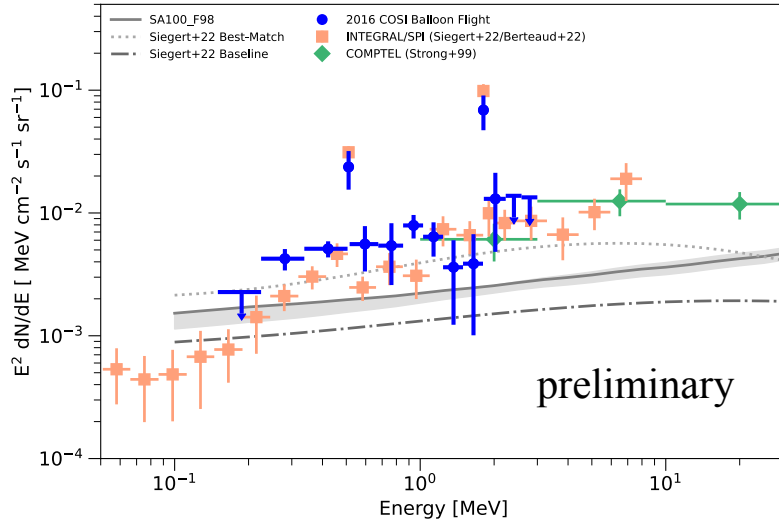


Figure 1: Observed flux towards the inner Galaxy during the 2016 COSI balloon flight. The blue data points are for COSI, and the error bars are 1σ statistical only. The salmon data points are for INTEGRAL/SPI, and the green data points are for COMPTEL, with the error bars on both measurements including 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.

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