

Pitch-angle Anisotropy, Magnetic Focusing, and Scattering of 4 TeV Cosmic Rays in the Local Inter-stellar Medium

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Abstract

We use anisotropy data for 4 TeV cosmic rays to study pitch-angle focusing and diffusion due to the interstellar magnetic field/turbulence. We infer the pitch-angle distribution (PAD) in the local interstellar medium (LISM). The pitch-angle diffusion coefficient is asymmetric, suggesting magnetic focusing. A model with these effects fits the PAD.

The Experiment

The data we used was produced by the Tibet AS γ experiment, which took place in the Yangbajing International Cosmic Ray Observatory, located at geographic coordinates 90.53°E longitude, 30.11°N latitude, at an altitude of 4300 m above sea level (The Tibet Collaboration, 2013; Amenomori et al., 1992). It has accumulated a high number of TeV cosmic ray events during the decades it was active. This led to the construction of a skymap of TeV cosmic ray anisotropy with sensitivity better than 10^{-4} in relative intensity (Amenomori et al., 2006). We use the 4 TeV data collected by the Tibet AS γ experiment (Amenomori et al., 2006). Figure 2 shows a map of relative intensity as a function of right ascension (longitude) and declination (latitude) in J2000 celestial coordinates. The angular cadence of data points is $2^\circ \times 2^\circ$, but the intensity is averaged within an angular distance of 5° from the center of each pixel.

Methodology

The Liouville mapping method (Zhang et al., 2014, 2020; Maalal & Zhang, 2024) is a technique meant to map the flux measurements at Earth back to the LISM. It is based on the Liouville theorem, which states that the phase space density (or distribution function) $f(\mathbf{r}, \mathbf{p})$ is conserved along particle trajectories. $f(\mathbf{r}, \mathbf{p})$ is also Lorentz invariant. Given a model of heliospheric fields (such as the Multi-scale Fluid-Kinetic Simulation Suite of the University of Alabama in Huntsville (Pogorelov et al., 2015, 2017), it is possible to use the Liouville theorem and a Lorentz transformation to map the distribution function at Earth $f(\mathbf{r}_0, \mathbf{p}_0)$ to/from $f(\mathbf{r}, \mathbf{p})$ in the LISM plasma reference frame.

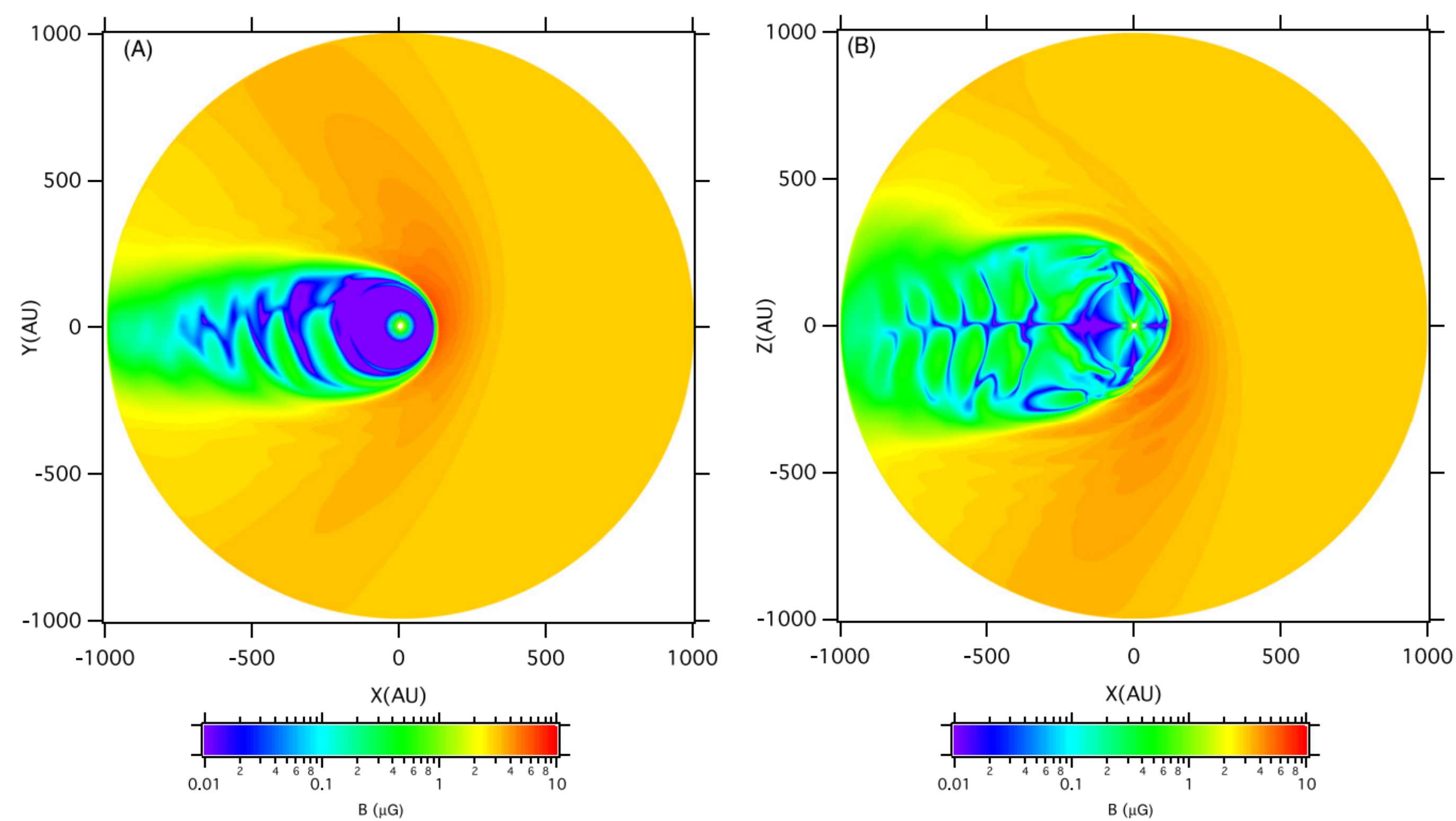


Figure 1. Magnitude of the magnetic field in (A) the solar equatorial plane, and (B) the meridional plane (Zhang et al., 2014).

The relative intensity measured at Earth in terms of the interstellar position and momenta is:

$$I(\theta, \phi) = p_0^2 f(\mathbf{x}(\theta, \phi), \mathbf{p}(\theta, \phi)) \quad (1)$$

where p_0 is the magnitude of the momentum at Earth. To emulate the latitudinal normalization of the data, we write (Maalal & Zhang, 2024, 2025):

$$\mathcal{I}(\theta, \phi) = \frac{I(\theta, \phi)}{\frac{1}{2\pi} \int_0^{2\pi} I(\theta, \phi) d\phi}, \quad (2)$$

$I(\theta, \phi)$ is the true relative intensity. In the previous equation:

$$I(\theta, \phi) = [1 + A_1 P_1(\mu) + A_2 P_2(\mu) + \dots + A_n P_n(\mu) + G_x R_x + G_y R_y] \left(\frac{p}{p_0}\right)^{-\gamma} \quad (3)$$

where A_n with $n = 1, \dots, N$ and $G_{x,y}$ are fitting parameters. An appropriate relative intensity map needs to be globally normalized to 1. From our renormalized intensity I_{rn} and the gradient values $G_{x,y}$ from our fits, we can calculate the PAD as such:

$$PAD = I_{rn}(p/p_0)^\gamma - (G_x R_x + G_y R_y) \quad (4)$$

To extract physical information about the LISM from the PAD, we solve the Fokker-Planck equation under the assumptions of weak magnetic focusing, and fit to the data.

$$\partial_\mu [D_{\mu\mu} \partial_\mu F(\mu)] - \frac{(1 - \mu^2)v}{2L} \partial_\mu F(\mu) = -\Phi(\mu), \quad (5)$$

where $-\Phi(\mu)$ is a diffusion source term produced by the gradient and time-derivative of the flux, $L = -(\partial_z \ln B_0)^{-1}$ is the magnetic focusing length, and $F(\mu)$ is identified with the PAD.

Conclusions

- The pitch-angle diffusion coefficient is anisotropic, and has the form

$$D_{\mu\mu}^{(S)} = -\frac{v\partial_z F}{2}(1 - \mu^2) \left[\eta \cos(2\pi\mu/\omega) + \gamma \right]. \quad (6)$$

- We find $L \approx 17.8\kappa_{29}$ pc if the cosmic ray diffusion coefficient in the LISM is $\sim 10^{29}$ cm²/s.
- The gradient parallel to the magnetic field has a length of roughly $1.72\kappa_{29}$ kpc.
- The temporal variation of cosmic ray intensity is negligible: less than $7.08 \times 10^{-7}/\kappa_{29}$ year⁻¹.

Plots

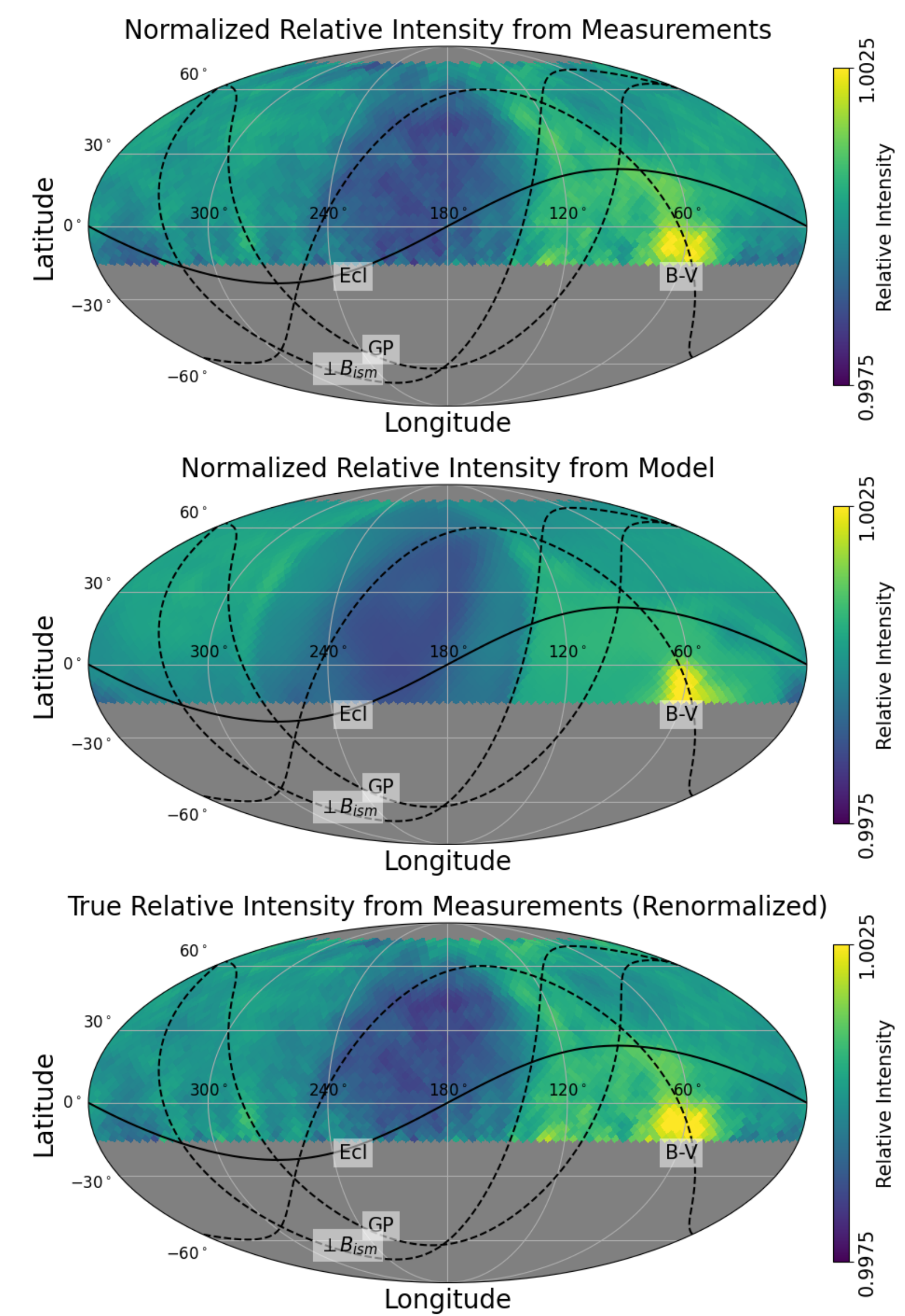


Figure 2. (Top) Anisotropy skymap from the Tibet AS γ experiment. (Middle) Nonlinear model fit truncated to 7th order. (Bottom) Renormalized data map (Maalal & Zhang, 2025).

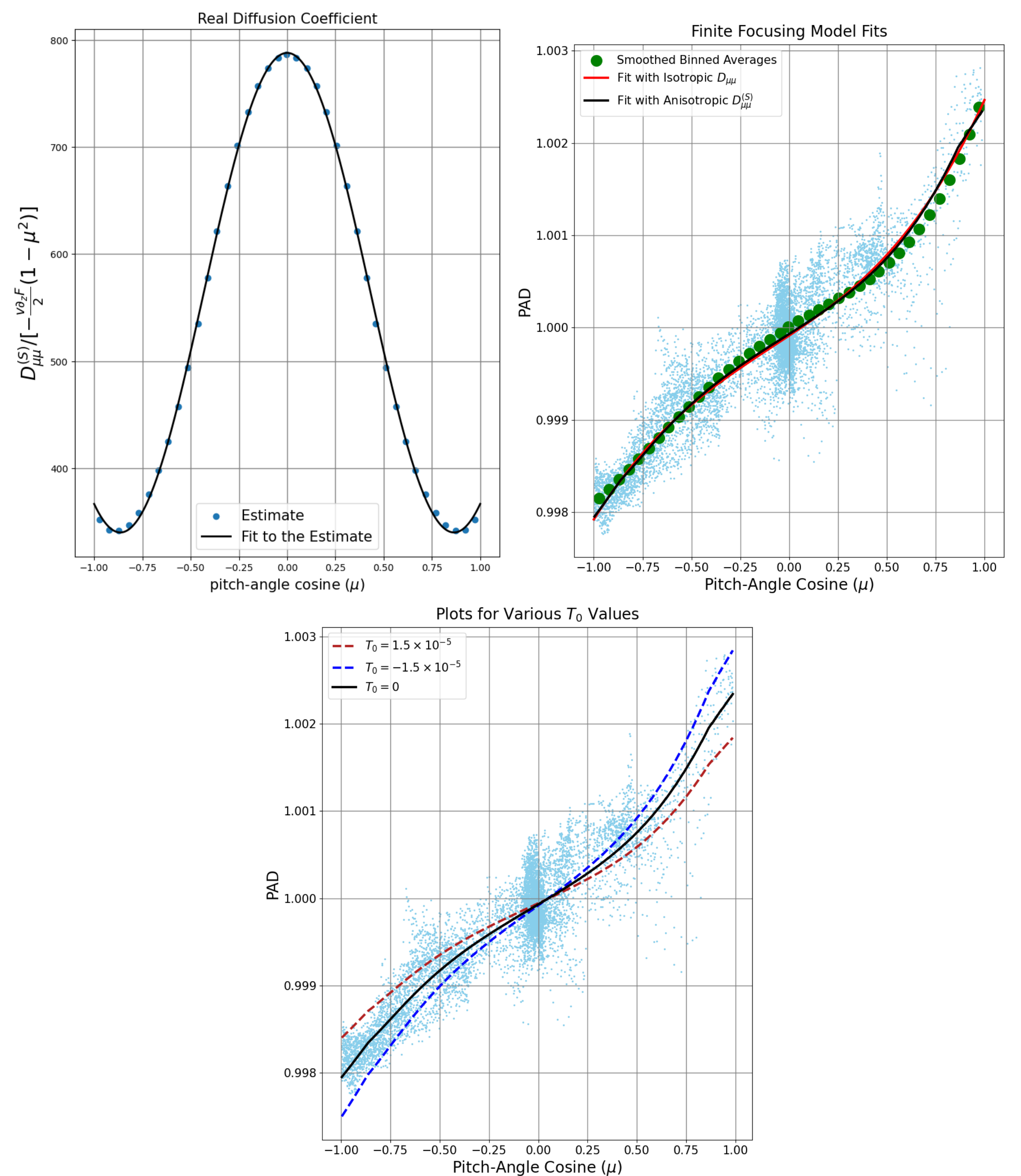


Figure 3. (Top Left) Diffusion coefficient $D_{\mu\mu}^{(S)}$ as a function of μ . (Top Right) Output of the diffusion models. (Bottom) Curves corresponding to different $T_0 = \partial_t F|_{\mu=0}$ values.

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