Non-parametric determination of H and He IS fluxes from TOA cosmic-ray data

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Abstract: *Top-of-atmosphere (TOA) cosmic-ray (CR) fluxes from satellites and balloon-borne experiments are snapshots of the solar activity imprinted on the interstellar (IS) fluxes. Given a series of snapshots, the unknown IS flux shape and the level of modulation (for each snapshot) can be recovered. Using H and He TOA measurements, we perform a non-parametric fit (using spline functions) of the IS fluxes and modulation levels for each data taking period. We rely on a Markov Chain Monte Carlo (MCMC) engine to extract the PDF and correlations (hence the credible intervals) of the sought parameters.*

1. Motivation

H and He IS fluxes are the most abundant species in the cosmic radiation and play in important role in the Galaxy ecology. They are responsible for:

- At low-energy: ISM and molecular clouds ionisation, LiBeB and nuclear g-ray production (e.g., Indriolo *et al.*, 2009);
- At high-energy: secondary production of γ-rays, neutrinos, antiprotons, and positrons (e.g., Strong *et al.*, 2007).

All these observables underline the need to have as accurate a description as possible for the H and He IS fluxes over a wide energy range.

2. Methodology

A standard approach is to rely on TOA data and fit simultaneously the IS flux and solar modulation parameters. In this work:

- Solar modulation model: in this first step, we use the simple Force-Field approximation (e.g., Caballero-Lopez & Moraal, 2004)

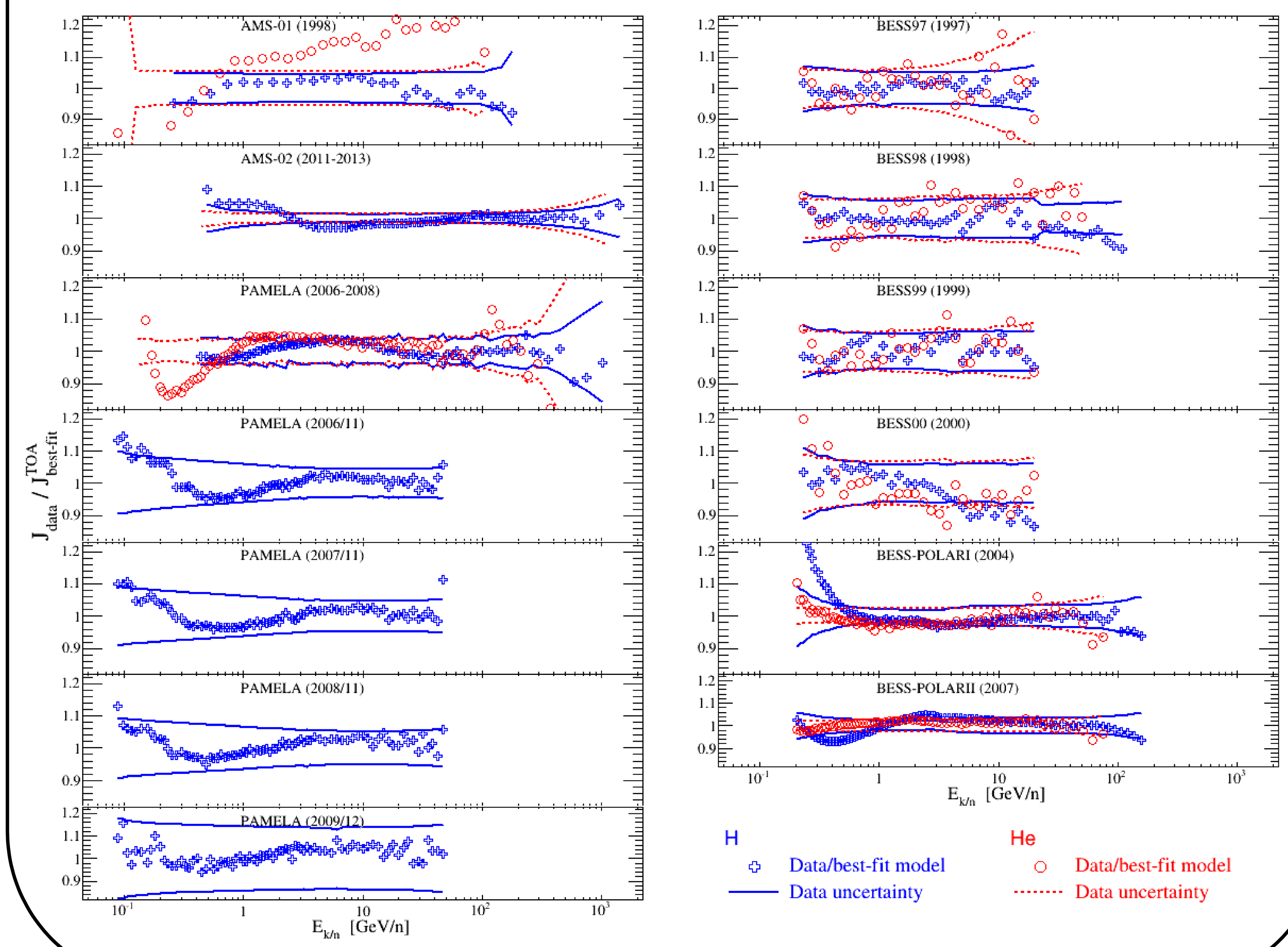
  → Single free parameter f(t) for each TOA dataset

- IS flux: flexible spline function (piecewise-defined by polynomial functions connecting at knots) to achieve non-parametric determination of the H and He fluxes. Smoothness is guaranteed by continuity of spline and n-1 derivatives

  → Spline of order n=3
  → 6 knots (for H and He) at 1, 7, 50, 100, 400, and 800 GV

3. Data selection (TOA)

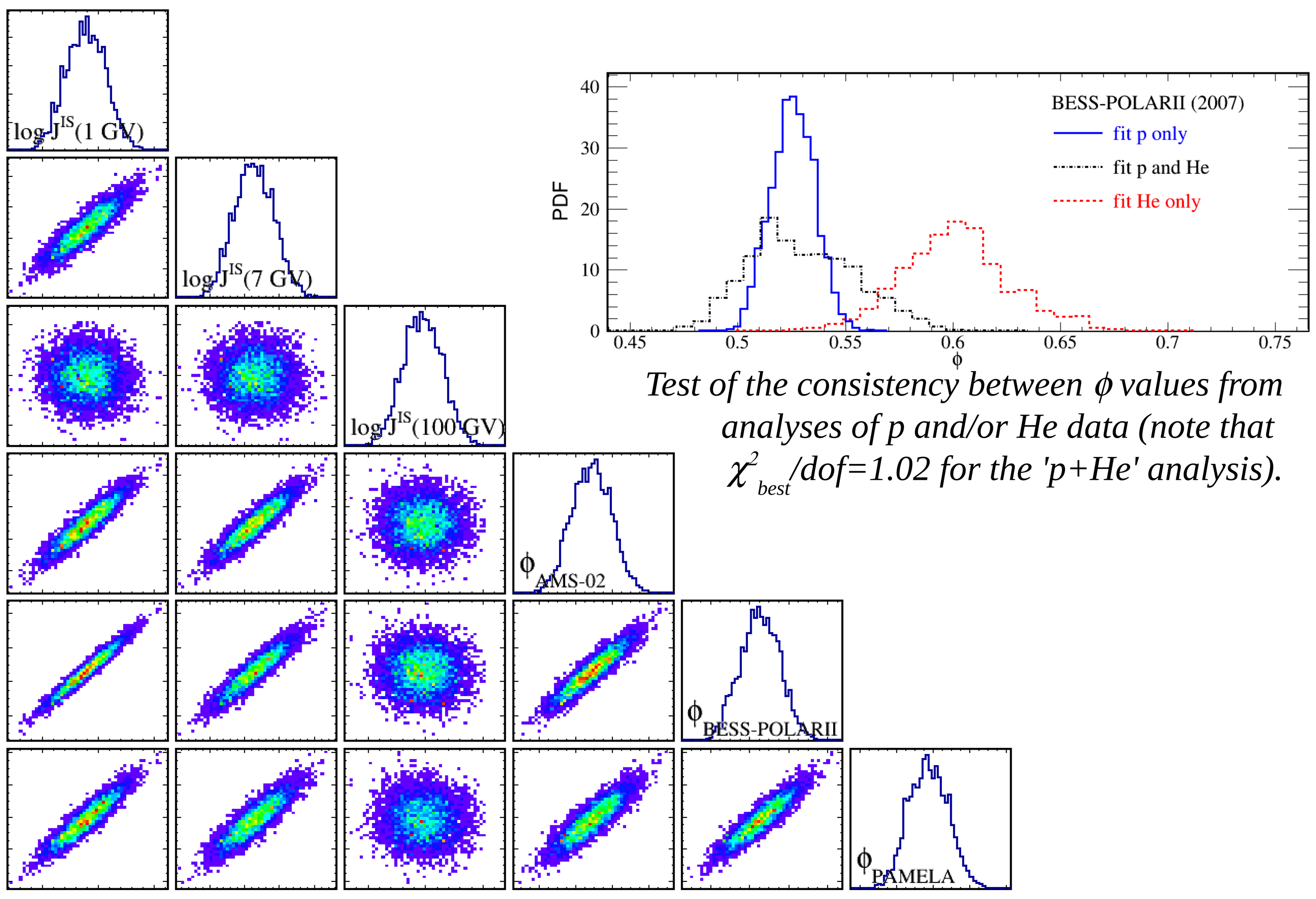
- H and He data from Cosmic-ray data base (Maurin *et al.*, 2014)
  → CRDB: http://lpsc.in2p3.fr/crdb
- Inconsistent datasets rejected (χ^2 analysis on all data)
  → Cut on 'distance' (of data from modulated best-fit flux)



4. MCMC analysis

We employ an Markov Chain Monte Carlo (MCMC) algorithm to determine the probability density functions. The MCMC is based on the Bayes theorem linking the multidimensional PDF of the parameters to the likelihood function of the model and the prior on each parameter:

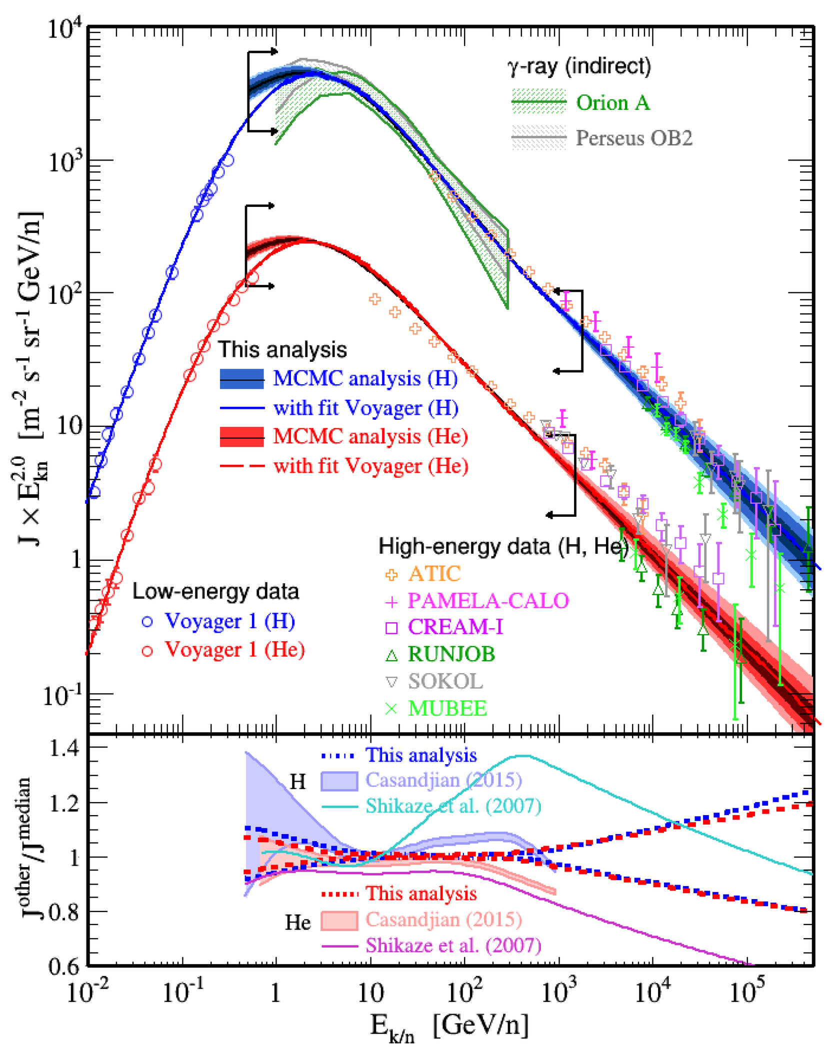
→ MCMC = GreAT (Putze et Derome, 2014): http://lpsc.in2p3.fr/great
→ Allow to determine correlations, and credible intervals for ϕ and IS flux knots



Test of the consistency between ϕ values from analyses of p and/or He data (note that χ^2_{best}/dof=1.02 for the 'p+He' analysis).

PDF (diagonal) and 2D correlations (off-diagonal) plots for 3 selected knots and 3 high-statistics datasets: knots above 100 GV show no correlation with any other parameter (these parameter values are driven by data uncertainties).

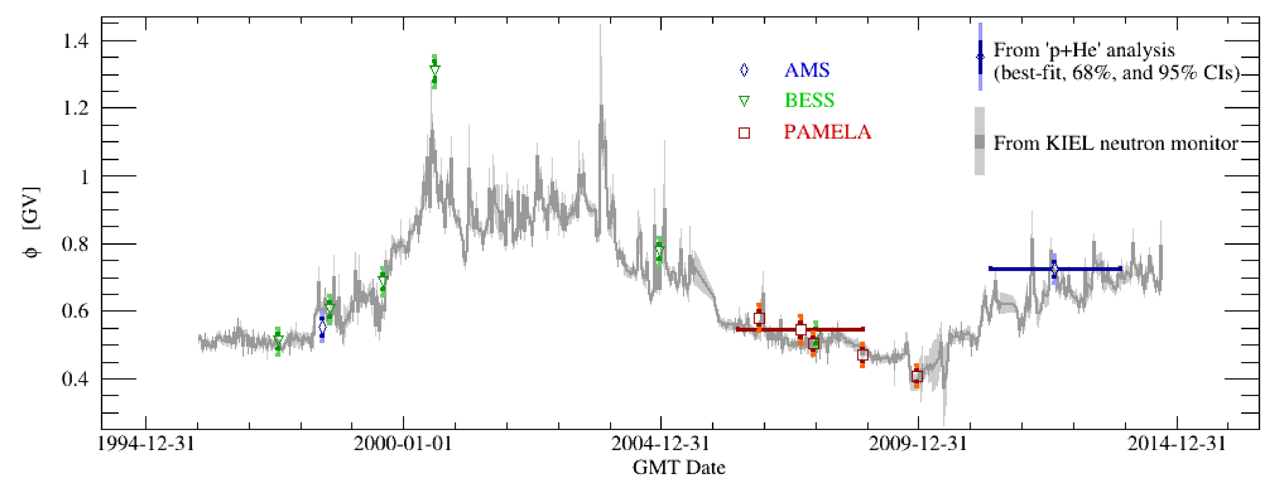
5. IS flux: uncertainties and comparisons



→ Blue (p) and red (He) shaded areas: 68%, 95%, and 99% CLs (from darker to lighter) from the 'p+He" analysis

- γ-ray derived limits from local giant molecular clouds using Fermi-LAT data (Yang *et al.* 2014) ;
- Low-energy Voyager 1 measurements (Stone *et al.* 2013);
- High-energy data.

- *Casandjian (2015)*: likelihood analysis of Fermi-LAT γ-ray emissivity and PAMELA/AMS p+He+e^++e^- data;
- *Shikaze et al. (2007)*: χ^2 analysis on BESS data.



Solar modulation level from TOA data (this analysis) and reconstructed from Kiel neutron monitor data (Ghelfi et al., in prep.)

Conclusions : *We have revisited the determination of IS fluxes and solar modulation parameters from TOA data only. We took advantage of recent high-statistics data, a non-parametric fit of the IS fluxes, and an MCMC algorithm to extract the PDF, CIs, and correlation between the parameters. The Force-Field approximation provides a good description of the modulated fluxes at Earth. The situation may change with AMS-02, which has the capability and the statistics to provide monthly, weekly, or even daily average p and He fluxes. More realistic modulation models will also be tested in a future study.*