The GALPROP program for cosmic-ray propagation: new developments

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Abstract

The cosmic-ray propagation code GALPROP has been generalized to include fragmentation networks of arbitrary complexity. The code can now provide an alternative to leaky-box calculations for full isotopic abundance calculations and has the advantage of including the spatial dimension which is essential for radioactive nuclei. Preliminary predictions for sub-Fe/Fe, ^{10}Be/ ^{9}Be, ^{26}Al/ ^{27}Al, ^{36}Cl/ Cl, and ^{54}Mn/ Mn are presented in anticipation of new experimental isotopic data.

1 Introduction:

The GALPROP program (Strong and Moskalenko 1998, Moskalenko and Strong 1998, Strong et al. 1999) performs cosmic-ray propagation calculations for nuclei, electrons and positrons and computes γ-ray and synchrotron emission in the same framework. The 3D spatial approach with a realistic distribution of interstellar gas distinguishes it from leaky-box calculations. Originally we considered that the complexity of the spatial model would preclude using cosmic-ray reaction networks with more than a few species, and our results so far have hence been obtained using a simplifying 'weighted cross sections' method. However we have now been able to generalize the scheme to include reaction networks of arbitrary complexity. The scheme can hence potentially compete with leaky-box calculations for computation of isotopic abundances, while retaining the spatial component essential for radioactive nuclei, electrons and gamma rays. Even for stable nuclei it has the advantage of a physically-based propagation scheme with a spatial distribution of sources rather than an *ad hoc* path length distribution. It also facilitates tests of reacceleration. Here we give a progress report on the new extension of the method and present some illustrative results. The technique should be of interest for the interpretation of new measurements such as those becoming available from ACE and ISOMAX.

2 Method:

GALPROP solves the Galactic CR propagation equation numerically on a grid in 3D with cylindrical symmetry. In the original simplified approach for nuclei we propagated first the primaries, then the source function for each secondary was computed and then the secondaries were propagated. Multiple progenitors and tertiary etc. reactions were handled by weighting the cross-sections according to the observed abundances, which was clearly a compromise solution.

The new extended scheme instead handles the reaction network explicitly, as follows:

1. Propagate all primary species from an assumed set of source abundances;
2. Compute the resulting spallation source function for all species;
3. Propagate all species using the sum of primary and spallation sources;
4. Iterate steps 2 and 3 until converged.

After the second iteration the result is already accurate for the pure secondary component, after the third iteration it is accurate for tertiaries, and so on. Hence in practice only 3 or 4 such iterations are necessary for a complete solution of the network. The method is more time-consuming than the simple approach since many more species are included and because of the several iterations required.

3 Results:

We have applied the method to a network of 87 nuclei from protons to Ni, including explicitly all stable species and radioactive species with half-life more than 10^5 years. The network of channels for decayed cross-

sections is based on Nuclear Data Sheets. Isotopic cross sections are based on measured values where available, up to and including Webber et al. (1998). For cases where measurements at enough energies exist we interpolate a smooth function. Otherwise we use the Webber et al. (1990) cross-section code, renormalizing to measurements where they exist. The interstellar He abundance is taken as 0.11 by number. Source abundances are from DuVernois and Thayer (1996), with solar isotopic ratios within a given element. Propagation parameters for this model with reacceleration are: halo size $z_h = 4$ kpc, $v_A = 20$ km s^{-1}, diffusion coeffient $D = D_0 \beta (p/p_0)^{\frac{1}{3}}$, where $D_0 = 6.75 \times 10^{28}$ cm^2 s^{-1}, $p_0 = 3$ GeV. The diffusion coefficient, adjusted to fit B/C, differs slighly from that used in the original work for the same z_h (Strong et al. 1998: $D_0 = 6 \times 10^{28}$ cm^2 s^{-1}), reflecting the more detailed treatment and updated cross sections.

Fig. 1 shows computed fluxes of all the included isotopes at 2 GeV/nucleon. This result is illustrative of the method but not to be taken as predictions for evaluation purposes.

Fig. 2 shows B/C and sub-Fe/Fe. This model with reacceleration reproduces the sub-Fe data reasonably well considering that the model was adjusted only to fit B/C. The deviation from the observed sub-Fe/Fe shape is however noticeable, as discussed by Webber (1997). Figs. 3 and 4 show the radioactive isotope ratios ^{10}Be/ ^{9}Be, ^{26}Al/ ^{27}Al, ^{36}Cl/ Cl, and ^{54}Mn/ Mn (using an estimated ^{54}Mn halflife of 6.3×10^5 years, Wuosmaa et al. 1998). Modulation is for nominal values of the modulation parameter but this has little effect on the comparison due to the small energy dependence of these 4 ratios in the 100–1000 MeV/nucleon range. In Strong and Moskalenko (1998) we obtained a range 4 kpc$< z_h <$12 kpc for the halo height; in the present improved model the ^{10}Be/ ^{9}Be, ^{26}Al/ ^{27}Al predictions are consistent with this. A complete grid of models will be generated in future to obtain new limits. Our ^{36}Cl/ Cl and ^{54}Mn/ Mn predictions are preliminary and do not yet provide significant constraints.

4 Conclusions:

The extension of GALPROP to complete networks of nuclei has been accomplished, but further work is needed especially on the cross-sections before the method can be used for detailed evaluation. As usual the software will be made available on the WWW at http://www.gamma.mpe–garching.mpg.de/∼aws/aws.html

References

Binns, W.R., et al. 1988, ApJ 324, 1106
Connell, J.J. 1998, ApJ 501, L59
Connell, J.J. et al. 1998, ApJ 509, L97
DuVernois, M.A. 1997, ApJ 481, 241
DuVernois, M.A. & Thayer, M.A. 1996, ApJ 465, 982
Engelmann, J.J., et al. 1990, A&A 233, 96
Leske, R.A. 1993, ApJ 405, 567
Lukasiak, A., et al. 1994a, ApJ 423, 426
Lukasiak, A., et al. 1994b, ApJ 430, L69
Lukasiak, A. et al. 1995, Proc. 24th ICRC (Roma) 2, 576
Moskalenko, I.V., & Strong, A.W. 1998, ApJ 493, 694
Simpson, J.A., & Connell, J.J. 1998, ApJ 497, L85
Strong, A.W., & Moskalenko, I.V. 1998, ApJ 509, 212
Strong, A.W., & Moskalenko, I.V., & Reimer, O. 1999, submitted (astro–ph/9811296)
(see also these proceedings OG 2.4.03)
Webber, W.R., Kish, J.C., & Schrier, D.A., 1990, Phys. Rev. C 41, 566
Webber, W.R., et al. 1996, ApJ 457, 435
Webber, W.R., 1997, Spa. Sci. Rev. 81, 107
Webber, W.R., et al. 1998, ApJ 508, 940; *ibid.*, p.949
Wuosmaa, A.H., et al. 1998, Phys. Rev. Lett. 80, 2085

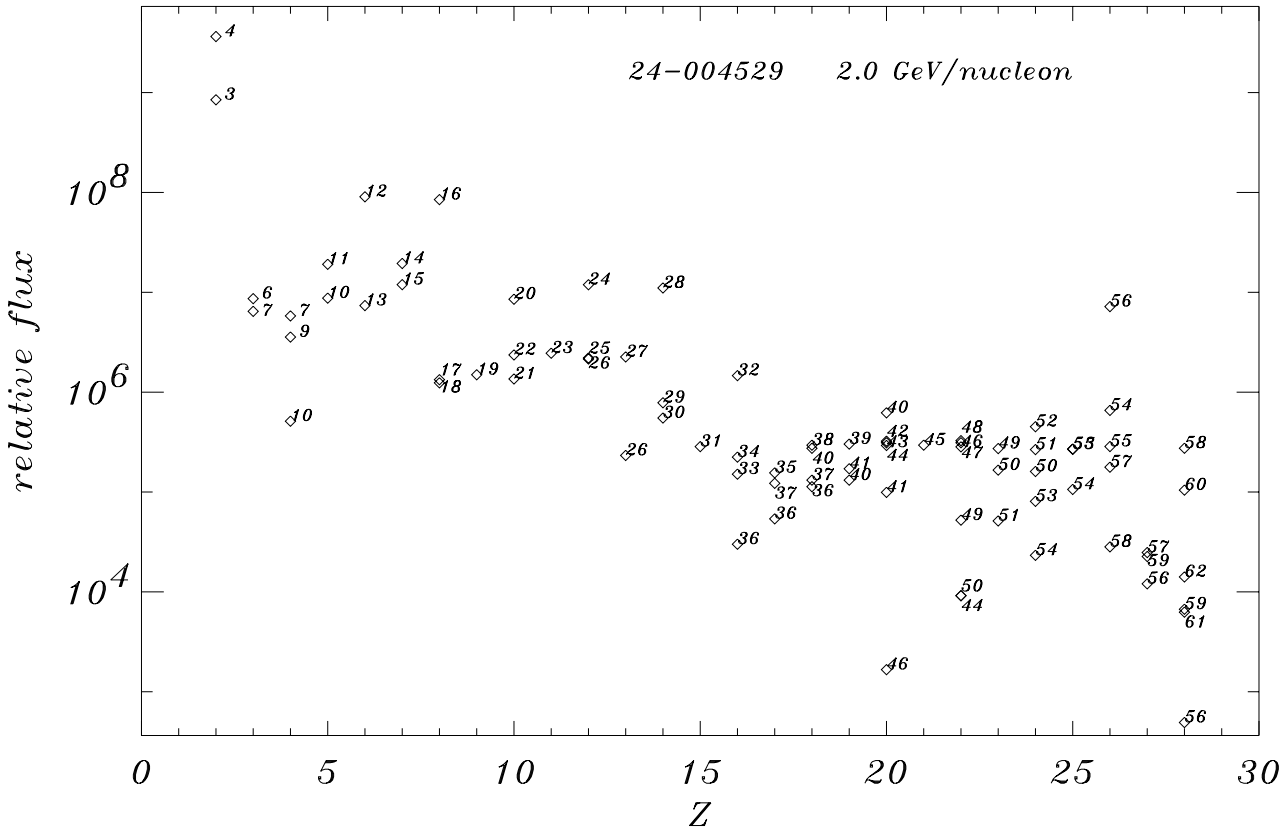

Figure 1: Model isotopic fluxes at 2 GeV/nucleon as function of Z; individual A values are marked. NB: This plot is illustrative of the method but not to be taken as predictions for evaluation purposes.

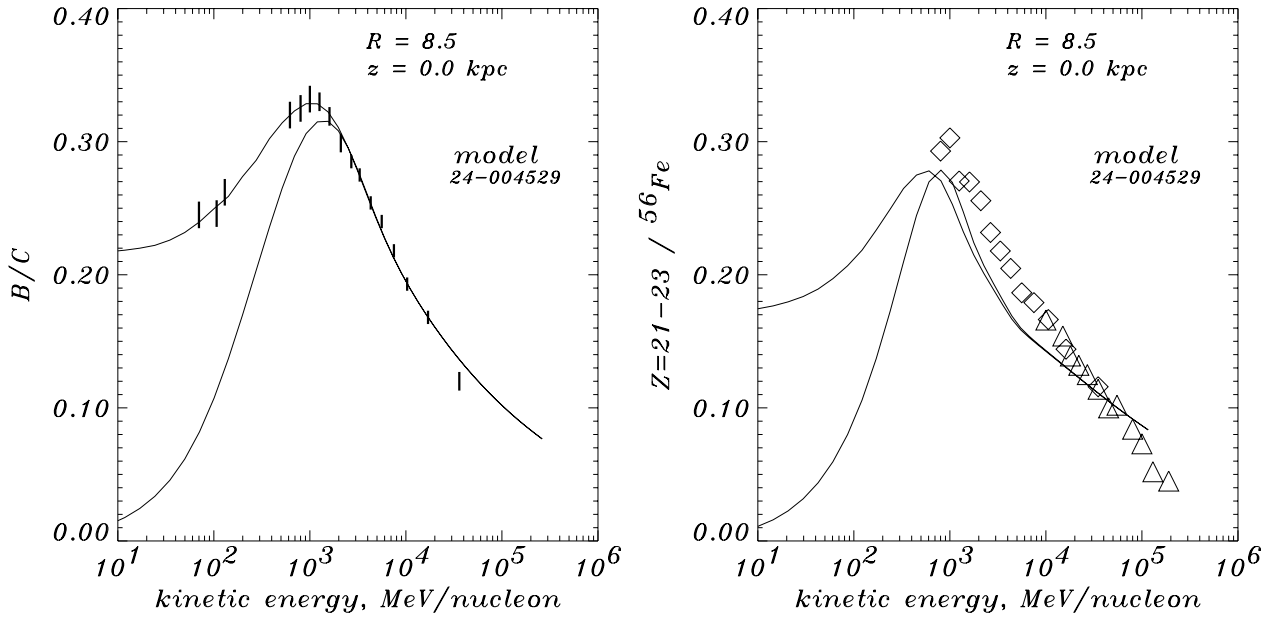

Figure 2: *Left*: B/C interstellar and modulated to 500 MV for diffusive reacceleration model with z_h = 4 kpc. Data compilation: Webber et al. (1996). *Right*: The same for sub-Fe/Fe $(Z = 21 - 23/{}^{56}\mathrm{Fe})$. Data: ◇ – Engelmann et al. (1990), △ – Binns et al. (1988).

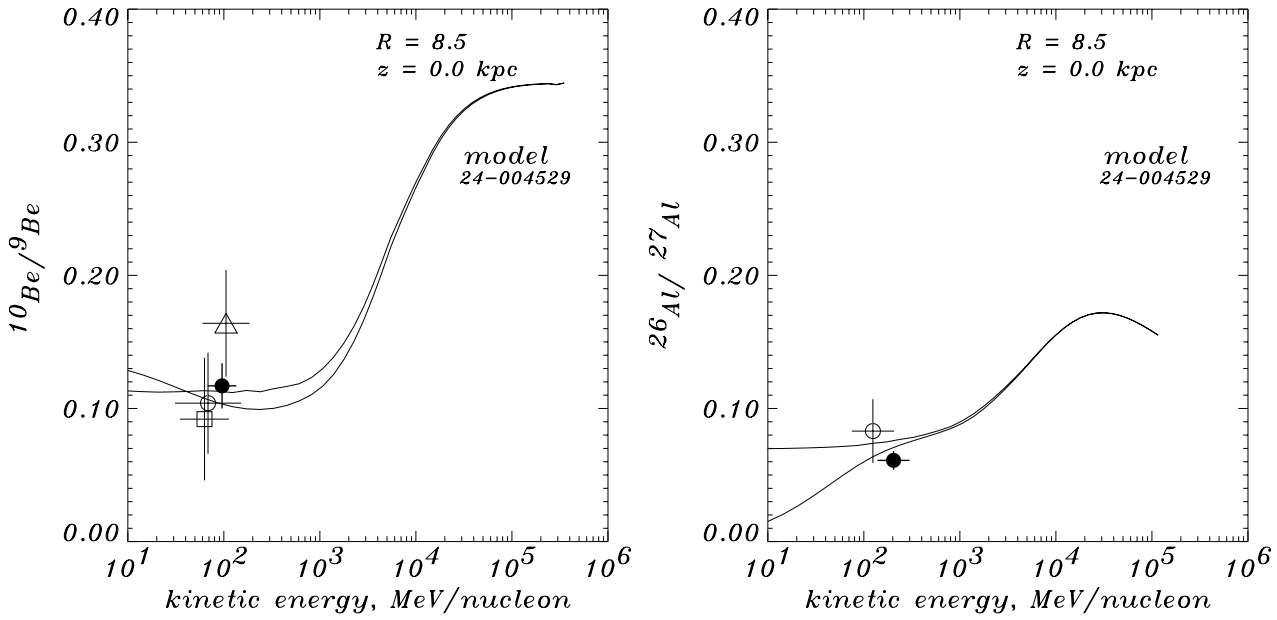

Figure 3: Model interstellar and modulated (500 MV) ratios. *Left*: ^{10}Be/ ^{9}Be. Data from Lukasiak et al. (1994a) (□ – Voyager–1,2, ○ – IMP–7/8, △ – ISEE–3) and Connell (1998) (● – Ulysses). *Right*: ^{26}Al/ ^{27}Al. Data: ○ – Lukasiak et al. (1994b), ● – Simpson and Connell (1998). Note that the data points shown are at the measured (not interstellar) energies.

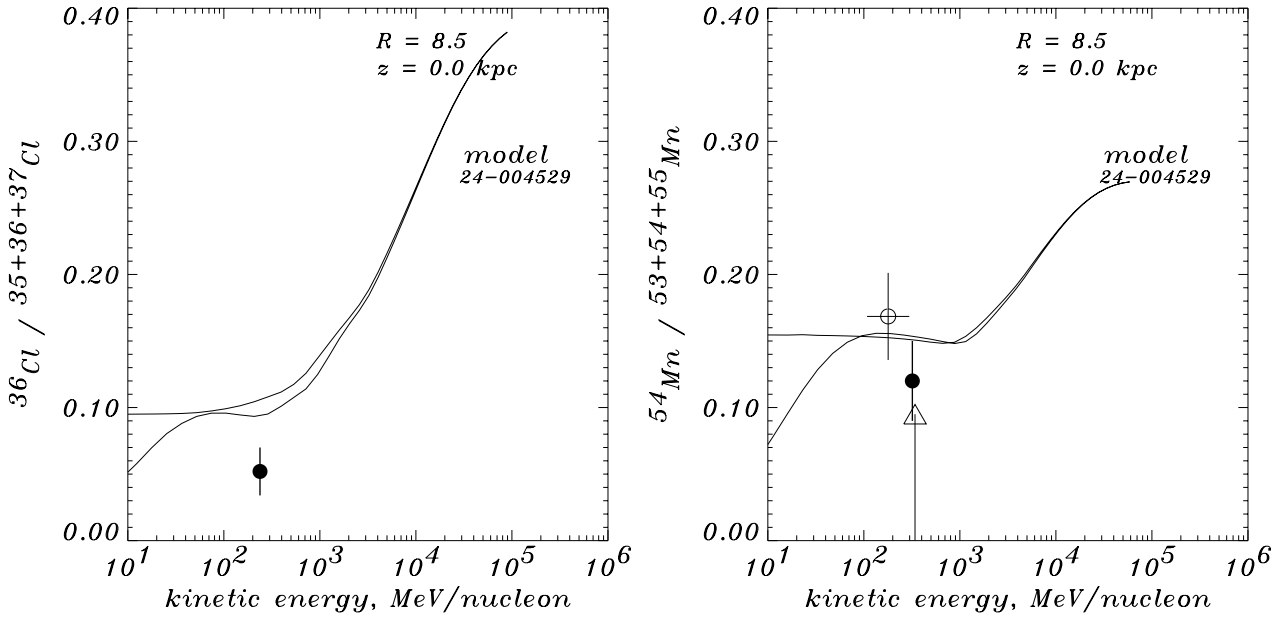

Figure 4: Model interstellar and modulated (500 MV) ratios. *Left*: ^{36}Cl/ Cl. Data: Connell et al. (1998); *Right*: ^{54}Mn/ Mn. Data: ● – Duvernois (1997), ○ – Lukasiak et al. (1995), △ – Leske (1993).