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How well do we understand the properties of Galactic Cosmic Ray acceleration and propagation? A critical view.

Paolo Lipari[a,*]

[a] *INFN Sezione Roma "Sapienza", P. A.Moro 2, 00185 Roma, Italy*
E-mail: paolo.lipari@roma1.infn.it

The Galactic cosmic ray (CR) fluxes observed in the vicinity of the Earth encode the space and time averaged properties of their sources and are also shaped by the effects of their propagation in the Galaxy. A combined study of the spectra of different particle types (protons, primary and secondary nuclei, electrons, positrons and antiprotons) is essential to determine the roles of the source and of propagation in the formation of the fluxes. Several authors are now claiming that these combined studies have essentially solved the problem, and that the properties of CR propagation, and the source spectra for all particle types are now well determined in a broad energy range, with significant uncertainties only at high energy. In this contribution we analyse critically these results, and conclude that the problem of determining in good approximation the average CR source spectra (and therefore also the main properties of CR propagation) remains open, with very large uncertainties. Solving this problem has profound implications for the properties of the Galactic CR accelerators (that have not yet been firmly identified) and for our understanding of the Milky Way magnetic structure. Future observations, especially of electrons and positrons in the multi–TeV range and of unstable isotopes like beryllium in the few GeV range should soon allow to solve the problem.

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The shapes of the Cosmic Ray spectra for different particles

The spectra of CRs of different types *at the Earth* have been measured with detectors in space and at the ground. Fig. 1 shows an incomplete summary of the available data. Understanding the origin of the different shapes for the spectra of different particles is a fundamental problem for CR astrophysics. Before entering this discussion, it is important to note the CR spectra in other points of the Galaxy remains poorly known. A large class of models predicts that the spectra of p and nuclei have the same shape (with different normalizations) in most of the Galactic volume, with the exception of the regions near active (in the present or recent past) sources, (while the spectra of $e^{\pm}$ become softer away from the Galactic equator). Other models however predict spectra that have a much larger space dependence. The CR space distributions are encoded in the γ–ray and ν diffuse fluxes. The γ–ray measurements by the FERMI telescope and ground based detectors [5] do not see very large deviations from the standard predictions but also give some intriguing indications that the CR spectra are harder near the center of the Galaxy. Clarifying this question (with improved models of the Milky Way structure, and more data in a broader energy range) is of crucial importance [6].

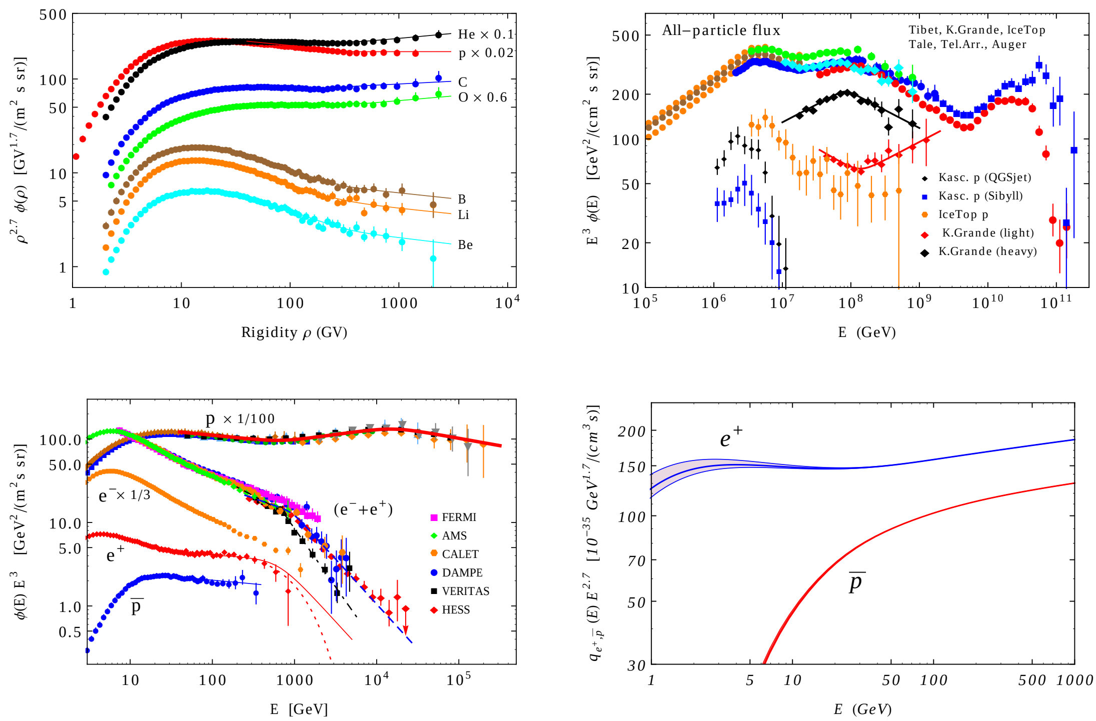

Figure 1: Top left panel: rigidity spectra of protons and nuclei (He, Li, Be, B, C, O) obtained by the AMS02 detector [1]. Bottom left panel: spectra in kinetic energy of p, $e^{\mp}$, $(e^- + e^-)$ and $\overline{p}$. The highest energy measurements for $(e^+ + e^-)$ have been obtained by Cherenkov telescopes [2] at the ground. The thick line is a fit to the p data from [3]. Top right panel: measurements of the all–particle CR spectra at high energy by EAS. Also shown are estimates of the fluxes of protons and of the "light" (p + helium) and "heavy" components. Bottom right panel: rate of creation of e^+ and $\overline{p}$ as secondaries in the interactions of the CR spectra observed at the Earth with the local interstellar gas from [4].

Secondary Nuclei (Li, Be, B)

The concept that the composition of the CR spectra encodes information on the confinement time of CR in the Galaxy, has been understood for many decades, and the special role of the light elements (Li, Be, B) has been recognized and studied since the 1940's [7]. Fig. 1 (top–left panel) shows that the light nuclei (very rare in ordinary matter) have "surprisingly" large abundances in the CR flux. At rigidity $\rho \simeq$ 5–10 GV the ratios B/C, Li/C and Be/C are of order 0.3, 0.2, 0.1 respectively, and at higher rigidity the spectra of secondary nuclei are significantly softer than those of carbon and oxygen, with a difference in spectral index of order $\Delta\alpha \simeq$ 0.4–0.5. These results are the "corner stone" of what has become the "standard interpretation" of cosmic ray data.

For a first order understanding of the problem one can consider a flux of primary nuclei (for example ^{12}C) that traverses a column density X. What emerges is a flux of the primary nuclei reduced by absorption, accompanied by fluxes of secondary nuclei (^{6}Li, ^{7}Li, ^{9}Be,^{10}Be, ...) created in fragmentation interactions, in good approximation with a constant energy per nucleon. If the relevant nuclear cross sections are known, it is straightforward to reconstruct the grammage X from the observed secondary/primary ratios. In the limit of small X (for the general case of primary P and secondary S) the ratio takes the simple form: $\phi_S/\phi_P \simeq X \; \sigma_{P\to S}/m_p$ linear in X. Summing over all primary nuclei contributions, and using the known values of the cross sections (of order of 30–70 mbarn and weakly dependent on energy) it is elementary to infer a grammage of order 10 g/cm^2 at $\rho \approx 10$ GV, that decreases with rigidity approximately as a power law. Assuming that the grammage is integrated during propagation in interstellar space, the value of X can be mapped into the product $T_{\rm age}\,\langle n_{\rm ism}\rangle$ of the residence time and the average density of the propagation medium.

The problem of connecting the observations of the light nuclei spectra to CR propagation has been the object of many studies, that also include some modeling of CR propagation. This is because particles (of a fixed type and energy) that reach the Earth do not cross a unique X, but a distribution of values, and the secondary/primary ratio depends not only on the average but also on the (model dependent) shape of the distribution. For example, the HEAO–3 team [8] used a "leaky box"framework to estimates the grammage as: $\langle X\rangle \simeq 14.0\,\beta\,(\rho/\rho_0)^{-0.60}$ for rigidities $\rho > \rho_0 = 4.4$ GV and a constant value for $\rho < \rho_0$. Several new studies have been recently performed [9] after the release of the AMS02 data, using better descriptions of the nuclear cross sections and more sophisticated models for Galactic propagation, and obtain results that are in reasonable good (if not perfect) agreement with previous studies (and with each other). The study of Evoli, Aloisio and Blasi [9] is the only one that estimates explicitely a grammage with results that are essentially identical to those of HEAO–3 ($\langle X\rangle \simeq 8.4$ g/cm^2 at $\rho > 10$ GV, and a rigidity dependence $\propto \rho^{-0.63}$). Other works parametrize the ratios secondary/primary in terms of CR propagation parameters. For all models in [9] the main effect that controls propagation is diffusion [10], modeled with an isotropic diffusion coefficient, assumed constant in a confinement volume of simple geometry. The three main CR propagation parameters are then: H the half–height of the magnetic halo, D_0 the diffusion coefficient at a reference rigidity and the exponent δ of its ρ dependence. Other effects, such as advection and reaccelaration can be included (but are not required). In the fits, the ratio H/D_0 is better constrained than the individual parameters because, in first approximation, it determines the grammage [the CR escape time is of order $T \simeq H^2/(2\,D)$, and the average density scales as H^{-1}].

One criticism for the models in [9] is that they make use of parameters (such as H and D_0)

that can only be considered as "effective" (there is obviously no sharp boundary to the Galactic confinement volume), and it would be preferable to describe the propagation in terms of quantities that have an intrinsic, model independent, meaning. A more fundamental problem is that the models are constructed starting from the *assumption* that Li, Be and B are created in interstellar space, excluding a priori the possibility that a significant fraction (or most) of the light nuclei are formed inside or in the vicinity of the CR sources, an hypothesis extensively discussed in the framework of the "Nested Leaky Box Model" by Cowsik and collaborators [11]. If this crucial "interstellar grammage" assumption is not correct, all the conclusions on CR propagation are not valid.

Beryllium–10

Measurements of the isotopic composition of beryllium allow in principle to directly measure the residence time of CR in the Galaxy. Beryllium nuclei have three isotopes: ^{7}Be and ^{9}Be are stable, while ^{10}Be is unstable with halftime $T_{1/2} \simeq 1.387 \pm 0.012$ Myr. Using the measured fluxes of primary nuclei and the relevant cross sections it is possible to compute the isotopic composition of beryllium at production. During propagation the unstable nuclei can decay, and the ^{10}Be flux is reduced (with respect to the stable isotopes) by a factor $\langle P_{\rm surv}(E)\rangle$ that encodes the age distribution.

Some measurements of the berylllium isotopic composition suggest a CR residence time shorter than what is inferred by the standard analysis of secondary nuclei production. As an illustration, the ISOMAX detector [12] has measured a ratio ^{10}Be/^{9}Be $= 0.195 \pm 0.036 \pm 0.039$ for nuclei in the energy range $E_0 = [0.26, 1.03]$ GeV. This result can be compared to a prediction (constructed assuming that all isotopes are stable) of order 0.61. This implies an average survival probability for the ^{10}Be nuclei of order 0.32. For a unique residence time t_0 (when $\langle P_{\rm surv}\rangle = e^{-t_0/T_{\rm dec}}$) this corresponds to $t_0 \simeq 2.9 \pm 1.0$ Myr. For a broad age distribution the average residence time becomes larger (of order 5 Myr for a leaky box model, and 10 Myr for standard diffusion models). The highest energy measurements of the beryllium isotopic composition have been obtained by the SMILI detector [12] and have been interpreted estimating a mean lifetime shorter than 6 Myr (at 97.5 C.L.). Recently Evoli et al. [13] have argued that the AMS02 measurement of the energy dependence of the measured ratio $\phi_{\rm Be}/\phi_{\rm B}$ (where the numerator includes the contribution of ^{10}Be) is sufficient to infer a longer average age for CR nuclei. We find however that uncertainties in the fragmentation cross section are too large to reach a firm conclusion.

Electron and Positron propagation

The rate of energy loss for $e^\mp$ is several orders of magnitude higher than for protons, and nuclei, and correspond to the loss time $T_{\rm loss}(E) \approx 310\ [\langle \rho_E\rangle\, E]^{-1}$ Myr, where E (in GeV) is the $e^\mp$energy, and $\langle \rho_E\rangle$ (in eV/cm^3) is the average energy density in magnetic field and radiation (for Compton scatterings in the Thomson regime). Energy losses are the dominant effect on propagation, when $T_{\rm age} > T_{\rm loss}$, and are of negligible importance in the opposite case. Since $T_{\rm loss}$ decreases $\propto E^{-1}$, while $T_{\rm age}$ very likely changes more slowly, one expects to find in the $e^\mp$ spectra two energy ranges separated by the critical energy E^*, with energy losses important only for $E > E^*$. The shapes of the $e^\mp$ spectra are model dependent, but a robust prediction is that at the critical energy E^* the $e^\mp$ spectra should have a *softening feature*. This allows to determine experimentally E^* and to obtain an estimate the CR residence time at this energy, because $T_{\rm age}(E^*) = T_{\rm loss}(E^*)$. From the shape of the e^+ and e^- spectra (see Fig. 1) one can see that there are two possibilities for E^*.

(A) The critical energy is $E^* \lesssim 3$ GeV, with the softening "hidden" in the energy range where the spectra are curved and also shaped by solar modulations. In this case the CR age is of order $T_{\rm age}(E^*) \approx 100\ [E^*/(3\ {\rm GeV})]^{-1}$ Myr). (B) The alternative is to identify the spectral structures visible in the e^+ and the $(e^- + e^+)$ spectra at $E \sim 1$ TeV with the energy loss threshold. In this case with $T_{\rm age}$ at 1 TeV is of order 0.5–1 Myr. Solution (A) is consistent with the "standard interpretation" for secondary nuclei. Solution (B) requires that the grammage inferred by the study of light nuclei spectra is integrated inside or near the CR accelerators.

Positrons and antiprotons

The only certain mechanism for the production of CR e^+ and $\overline{p}$ is secondary production in the interactions of CR protons and nuclei. This mechanism (assuming for the primary interacting particles the spectra observed at the Earth) generates secondary spectra that for $E \gtrsim 30$ GeV, are in good approximation power laws with the same spectral index of the all–nucleon flux with a ratio $e^+/\overline{p}$ of order 1.8 ± 0.5 [4]. At lower energy the ratio $e^+/\overline{p}$ grows because the production of $\overline{p}$ at small E is suppressed for simple kinematics reasons. According to the "standard interpretation" for the abundances of light nuclei, the source spectra of $\overline{p}$ and e^+ should be softened by large propagation effects. The $\overline{p}$ by a factor of order $\rho^{-\delta}$ (the rigidity dependence of the B/C ratio), and the positron flux by a factor changing even more rapidly with energy, controlled by energy losses. With this assumptions secondary production is inconsistent with the hard spectrum of the e^+ data, and in serious tension with the $\overline{p}$ flux (that is also too hard),. The observed ratio $e^+/\overline{p}$ in the energy range 1–300 GeV is consistent with being equal to the one predicted by the secondary mechanism production. This result can be interpreted [4] assuming that secondary production is indeed the dominant mechanism for the production of antiparticles *and* that – in this energy range – propagation effects distort the spectra of e^+ and $\overline{p}$ in the same way (with a propagation distortions smaller than what is predicted by the standard interpretation of the light nuclei abundances). The equality of the $e^+/\overline{p}$ ratios at production and for the observed flux can be explained in the standard picture as a simple "coincidence". This requires "fine–tuning" the source spectra to cancel with sufficient accuracy the effects of the different propagation effects.

At sufficiently high energy the rate of energy loss for positrons will become the dominant effect in propagation, and the spectrum will have a break. The AMS detector has observed a softening of the e^+ spectrum that has been fitted as an exponential cutoff $\phi(E) \propto E^{-\alpha}\ e^{-E/E_s}$ with a "cutoff energy" $E_s = 810^{+310}_{-180}$ GeV (dashed red line in the bottom left panel of Fig. 1). An exponential cutoff cannot be generated by energy loss effects, and must have a different origin, however the softening in the e^+ spectrum is also consistent with a "break" between two power laws (solid line in the figure) that is shape predicted for feature formed by energy losses. The measurements of the spectrum of the sum $(e^- + e^+)$ obtained by calorimeter detector on satellites and by Cherenkov detectors at ground level also show a marked softening for $E \approx 1$ TeV. The measurements are not in perfect agreement with each other, but the softening feature seems to be better described by a broken power law (with a spectral index of order 3.9–4.0 for $E \gtrsim 1$ TeV), than by an exponential cutoff. These results imply that both the $e^\mp$ spectra have softenings at approximately the same energy of order 1 TeV. It is very important to determine if the breaks have the same origin or not.

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Accelerator source spectra

In the study of Galactic CRs it is natural to decompose the problem in two parts: the source spectra and the propagation effects. Most works start constructing a model for CR propagation that can then be used to infer the properties of the source spectra from the observations. It is however also possible to study directly the CR sources. The observation have in fact revealed that several classes of astrophysical objects contain populations of relativistic charged particles, that generate emissions of photons and neutrinos. Measurements of these emissions can be used to obtain information on CRs inside (or near) the sources, and this information can then be used to estimate the contribution of different classes of sources to the injection of Galactic cosmic rays, and the shape of the source spectra. An important question is if the source spectrum is generated by a single class of objects, or if several different classes can contribute (for example SNR and Pulsars for e^-).

The CR source spectra are usually modeled as (and are consistent with) a simple power law form: $Q_j(E) \propto E^{-\alpha_j}$, where $Q_j(E)$ is the time averaged, source spectrum of particle j, that can be considered as stationary. Many authors have discussed the shape of the source spectra and and the values of the exponents α_j. It is well known that first order diffusive Fermi acceleration predicts a universal power–law spectral shape for the accelerated particles with exponent $\alpha \simeq 2 + \varepsilon$, with ε positive and vanishing in the limit of strong shocks.

Young Supernova Remnants (SNR) are generally considered the best candidate as the dominant source of Galactic CRs. Fig. 2 shows the best fits to the γ–ray fluxes from young SNR in the Milky Way measured by the FERMI telescope [14]. The interpretation of these results, and the identification of the contributions of the hadronic and leptonic mechanisms to the emission is is not easy. In any case, the SNR observations show that SN are capable to convert a large amount of energy into relativistic charged particles, the shape of the emission spectra have however a broad range of (in general curved) different shapes, in conflict with models based on the idea of a universal acceleration spectrum [15] that predicted a simple power law spectra for all sources. The SNR observations are in fact equivalent of a set of "snapshots" taken at different times of objects that are also very likely far from identical, also because the explosions can happen in different environments, Reconstructing from this very incomplete information the total contribution of SNR to the injection of CR protons or electrons is therefore model dependent and a challenging task, and it is possible that the different spectral shapes observed for SNR is the result of observing objects in different states of evolution, and the theoretically preferred form is recovered integrating over time.

A (rather "radical") alternative is to make the hypothesis that the approximately power law form of the source spectrum emerges from the sum of the spectra of individual sources that are not of equal shape. The power–law form of source spectra becomes then the manifestation of the statistical properties of the ensemble of the sources. An example of how a spectrum with approximately power–law form can be obtained by the combination of spectra of different (log–normal) shape is illustrate in the right–panel of Fig. 2. Power–laws are common in many fields (physics, biology, economics, social sciences) describing the distributions of a variety of phenomena such as the size of earthquakes, moon craters, towns and cities or forest fires. The origin of these distributions has been the object of much debate, and perhaps the power–law form of cosmic ray spectra has a similar origin to power–law dependence of other phenomena. (for more discussion on these speculations see [16]). More studies of astrophysical sources could shed light on this problem.

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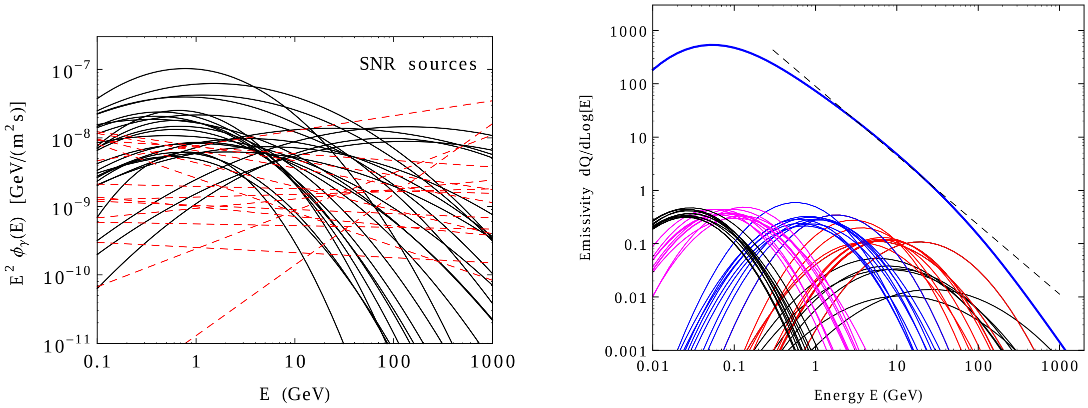

Figure 2: Left panel: spectra of all sources in the 4FGL catalog that classified as supernova remnants. The solid (black) lines are sources fitted with the log–parabola form, the dashed (red) lines are sources fitted with a simple power–law form (from [16]). Right panel: Example of how a power law spectrum can be obtained as the sum of curved spectra of individual sources that have a broad range of shapes The total spectrum (thick line) is obtained with a Monte Carlo calculation for an ensemble of $N_s = 10^4$ sources emitting log–parabola spectra with luminosity correlated with the hardness. The thin solid lines show the spectra of ten sources that give the highest contributions to the total emission at $E = 0.01$, 0.1, 1, 10 and 100 GeV. The dashed line is a power law with an exponent $\alpha = 2.3$. (see discussion in [16]).

Conclusions

The "standard interpretation" of the abundances of light, secondary nuclei, (that assumes that production inside or near the CR accelerators is neglible) points to a long CR residence time of order 100 Myr for rigidity of few GV, that decreases quite rapidly ($\propto \rho^{-\delta}$) with $\delta \approx 0.4$–0.6. This estimate implies that energy losses are the dominant effect in the propagation of $e^{\mp}$ for $E \gtrsim$ few GeV. The observed hard spectrum of CR positrons requires then the existence of a non–standard source. Before considering as "established" these results one should address a number of questions that remain open. For example: (1) Some measurements of the Beryllium–10 unstable isotope suggest a much shorter CR residence time. (2) The signatures of energy losses in the spectra of both and e^+ and e^- have not been clearly identified [1]. (3) The existence of the required new source of relativistic positrons remains an unproved hypothesis. (4) The spectrum of $\overline{p}$ is in tension with the predictions, that prefer a softer spectrum. (5) A physical mechanism has to be found for the sharp break in the e^- spectrum at $E \simeq 1$ TeV. (6) Electrons with $E \gtrsim 1$ TeV are predicted to arrive from very few near sources, but these sources have not been identified.

An alternative "scenario" is suggested by the observation that the $e^+/\overline{p}$ ratio, for $E \lesssim 1$ TeV, is consistent with the hypothesis of a common secondary origin assuming equal propagation effects for $p/\overline{p}$ and $e^{\pm}$ in this energy range. Since the *rate* of energy losses are known, this is possible only if the CR residence time is sufficiently short. Energy losses are then the origin of the breaks in the $e^{\pm}$ spectra at $E \approx 1$ TeV. A critical prediction (in some tension with AMS02 observations) is that the softenings of the $e^{\pm}$ spectra have the same origin and must have similar structure. A shorter CR residence time implies faster space propagation, and therefore high energy $e^{\pm}$ can reach the

[1]The identification of a signature of Compton losses in the Klein–Nishina regime in the e^- spectrum as been discussed by some authors [17]. The crucial problem however is the identification of the signature of the dominant contributions.

Earth from a larger volume, so that the existence of discrete e^- accelerator should remain hidden at $E \approx 1$ TeV and become apparent only at higher energy. The large abundances of secondary nuclei imply their creation in or near the accelerators (but a detailed model for this has not yet been constructed), Important implications of this scenario are a slower rigidity dependence of the CR residence time, higher power for the CR accelerators and softer source spectra (with quite different spectral shapes for the injection of e^- and p).

The point of view held here is that the problem can be solved with additional observations, and both the scenarios outlined above can be falsified. An exponential cutoff for the e^+ spectrum would impose the rejection of the alternative scenario, while a short residence time for beryllium–10 would be in conflict with the standard one.

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