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Truths universally acknowledged? Reflections on some common notions in cosmic rays

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Abstract

Some common ideas which are often taken as known or self-evident are put in question: the detection (or not) of the gamma-ray ‘pion bump’, the importance of CR diffusive reacceleration, and the energy range of extragalactic cosmic rays.

Keywords:
, cosmic rays, gamma rays

1. Truths?

The title of this talk is taken from the opening line of a classic of English literature[1]. A number of common notions in the cosmic-ray (CR) literature seem to me to be questionable or at least worth a critical look. These include the detection of the gamma-ray ‘pion bump’, the importance of CR diffusive reacceleration, and the energy range of extragalactic CR. These are taken in turn[2].

In addition progress on an new heritage MeV gamma-ray astronomy initiative is reported.

2. The pion-bump in SNR gamma-ray spectra: a cautionary tale

Many supernova remnants (SNR) have been studied in gamma rays, with excellent spectral information from both satellite and Cherenkov instruments. Frequently the phrase ‘pion bump’ or ’pion peak’ is used, referring to the maximum in the π^o-decay spectrum from hadronic interactions, and cited as ‘proof’ of hadronic CR in SNR. However this is very misleading: the peak is at one-half of the π^o mass, i.e. 67.5 MeV, and the (differential) gamma-ray energy spectrum is in fact symmetrical on a log-energy scale independent of the proton (and Helium) spectra which determine the π^o spectrum. This is a simple consequences of the istropic decay in the π^o rest frame and the Lorentz transformation. A detailed analysis can be found in the book by Floyd Stecker[3]. The peak energy is however below the limit reached by Fermi-LAT in current analyses, which is about 100 MeV; to really see the peak would need a spectral measurement extending below the maximum, say to 40 MeV at least. The AGILE intstrument has spectra extending to slightly lower energies but the same argument applies.

Why then is the pion bump often invoked? it seems that it is because the spectrum is normally presented with a factor E^2 to reflect the energy distribution and improve the readability of the data (which is quite in order and standard practice). Then the spectra do indeed often show a peak around 1 GeV, and this seems often

[1]Jane Austen, Pride and Prejudice: “It is a truth universally acknowledged, that a man in possession of a fortune must be in search of a wife.”

[2]More topics were covered in the talk but not icluded in these proceedings

[3]Cosmic Gamma Rays, available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710015288.pdf, see Chapters 1-6 and 5-2.

thought to be (hearing people's comments) the shifted pion bump to higher energies due to the E^2 factor. However if the peak is not in the raw differential flux spectrum, multiplying by this factor cannot make it appear! The observed peak is in fact usually due to the fact that the gamma-ray spectrum reflects a proton spectrum with a break in the several GeV range.

To illustrate this explicitly, I took two sample SNR spectra from the literature (W44: [1, 2] W49B:[3]) and removed the E^2 factor[4]. Clearly there is no pion bump visible since it lies below the minimum energy measured.

Of course the proper procedure is to make explicit models of the hadronic and leptonic emission, and there are many examples where this is done, but the interpretation is necessarily model-dependent. An example where the combination of gamma-ray and synchrotron data favours a mainly leptonic model is RCW 86 [4]. The 'smoking gun' pion bump will have to await extension of Fermi-LAT analysis to lower energies, which is indeed foreseen in the new 'Pass 8' event analysis (although this is difficult because of the broad angular response at low energies), and future experiments (e.g. COSI, eAstrogam) which extend into the low MeV range.

3. Diffusive Reacceleration: how important is it?

The CR secondary-to-primary ratio, in particular B/C, shows a peak in energy at a few GeV. In older times this was modelled with an ad-hoc break in the grammage or diffusion coefficient, but a physical origin has been proposed as the diffusion in momentum which is expected at some level if the scattering entities for spatial diffusion are also moving. This is referred to as diffusive reacceleration (DR). For a detailed account see [5], and the paper by Luke Drury in these proceedings. See also [6] where a simple derivation of the approximate relation between spatial and momentum diffusion coefficients at momentum p: $D_{xx}D_{pp} \approx p^2V_a^2/9$ (where V_a is the Alfvén speed) as well as the full formulae are given. While DR can give a good fit to B/C and other secondary-to-primary ratios, and allows a more Kolmogorov-like exponent (1/3) in the $D_{xx}(p)$ law, and hence helps to avoid too large anisotropy when extrapolated to higher energies, the question arises whether is really occurs at the level required for this to work. We used both analytical and numerical (GALPROP) methods to estimate the energy injection from DR for typical

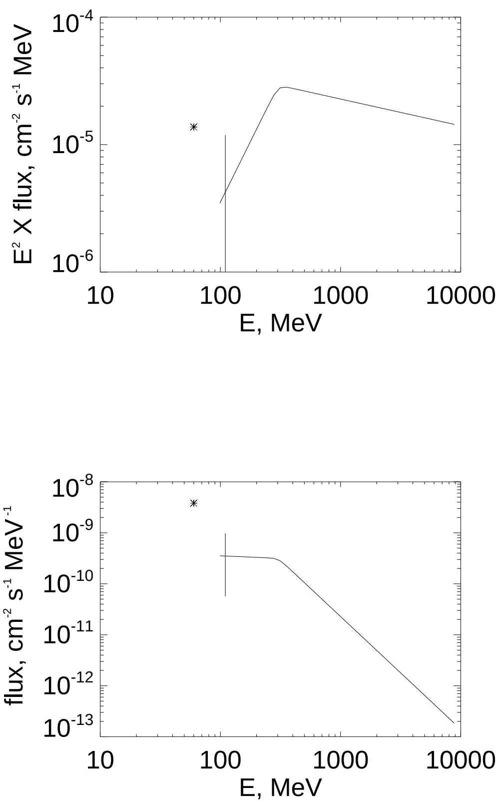
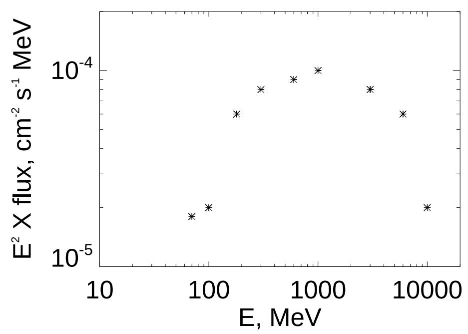


Figure 1: SNR W49B spectrum adapted from [3]. Top: with E^2 factor, lower: without E^2 factor. Units: MeV^2 cm^{-2} s^{-1} MeV s^{-1}, cm^{-2} s^{-1} MeV s^{-1} respectively. The asterisk is an upper limit (from AGILE). The pion peak would be centred on 67.5 MeV which is clearly not covered by these data.

[4]The numerical values are approximate from reading the published figures, but suffice for this illustrative presentation.



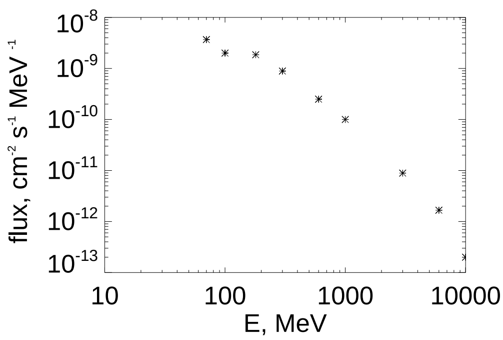


Figure 2: SNR W44 spectrum adapted from [1, 2] Top: with E^2 factor, lower: without E^2 factor. Units: as in Figure 1.

values of the parameter $V_a \approx 30$ km s^{-1} required by B/C, and found that 30-50% of the total energy of CR then actually comes from the ISM via DR, and not from the usual sources such as SNR! This refers to energies around a few GeV where most of the CR energy is concentrated.

An example of the proton spectrum without and with DR at typical levels required to fit B/C is shown in Fig 3. This was computed with the GALPROP CR-propagation programme[5].

So while not excluded, our conclusion is that DR should not be invoked just because it gives a good fit to CR data, but should be considered critically along with other possible origins for the shape of B/C. These include convection via a Galactic wind, which produces an energy-independent term in the propgagation equation and hence dominates at low energies where diffusion becomes small under the usual momentum-dependent law $D_{xx}(p) = \beta p^{\delta}$ where $\delta = 0.3 - 0.5$. Note that in any case the velocity term in the secondary-production rate means that B/C decreases below 1 GeV as β = v/c < 1, (although this may be partly cancelled by the velocity term in $D_{xx}(p)$) and that the observed B/C has the rather uncertain effect of solar modulation as well.

While DR should occur at some level on physical grounds, it probably does not suffice to explain B/C; in any case experimental checks using other CR indicators would be valuable. Up to now we were unable to think of any critical tests however. Meanwhile other mechanisms like convection should be considered at least on equal terms with DR.

4. Extragalactic CR: how far down in energy?

In a paper in 1972 Brecher and Burbidge [8] proposed that all (hadronic) CR[6] are extragalactic (EG) and fill the universe at the same level as in the Galaxy. The classical disproof of this conjecture was that the hadronic pion-decay gamma-ray background on intergalactic gas would exceed the observations. Also the density of CR in the Galaxy seems vary with position [9], which would also argue against this idea. However now 40 years later we have far better data and we ought to check up on the current situtation. The intergalactic gas density is about 10^{-7} H atoms cm^{-3} from Big-Bang nucleosynthesis theory, and using measured Galactic gamma-ray

[5] Latest version available from https://sourceforge.net/projects/galprop

[6] energy losses on the CMB exclude this for the leptonic component

emissivities [10, 7] e.g. at 1 GeV: 2 10^{-24} MeV^2 sr^{-1} s^{-1} MeV^{-1} H-atom^{-1}, we find (multiplying by the Hubble distance $\approx 10^{28}$ cm) a diffuse background 2 10^{-3} MeV^2 cm^{-2} sr^{-1} s^{-1} MeV^{-1} compared to the observed intergalactic gamma-ray background IGRB (defined as the background excluding resolved extragalactic sources) 6 10^{-4} MeV^2 cm^{-2} sr^{-1} s^{-1} MeV^{-1} [11], so the resulting background is still too high but strangely close. Of course the IGRB is thought to be dominated by AGN and any residual diffuse flux much lower, so the excess is certainly robust and the universal CR theory is still excluded.

Regarding the Galactic CR variations, the derivation of the Galactic CR density is fraught with uncertainty due to the difficulty of getting reliable densities of atomic and molecular hydrogen, including the so-called dark gas not traced by CO. So this is not a watertight argument again universal CR. More solid is the relatively low interstellar flux from the LMC [12] and M31 [13], less than expected if CR fill the universe.

Although there is evidence for hadronic production in SNR, this is not yet completely proved, as discussed in section 2.

While it is unlikely that the universe is uniformly filled with CR, an extragalactic origin above say 1 TeV is certainy not excluded by any data. The IGRB has not been measured at these energies and there does not seem much prospect of doing so at present.

Most extragalactic CR models e.g. [14, 15] invoke a quite hard CR spectrum e.g. E^{-2} to avoid having a substantial EG component at lower energies, and EGCR are assumed to cut in above 10^{15} eV. Instead a $E^{-2.5}$ law would give a few percent EGCR/GCR at 1 TeV and be consistent with available constraints. Of course this would have to be investigated in the context of composition studies, secondary production etc. But it does appear that restricting EGCR to above 10^{15} eV is a preconceived notion, again perhaps a truth universally accepted but not necessarily so.

The pair cascades induced by UHECR on the cosmological radiation fields are a current hot topic [16, 17] because of their contribution to the extragalactic gamma-ray background, and it is interesting that apart from constraining models, there might be the prospect of eventually actually detecting this gamma-ray background among the other components, as first discussed by [18].

5. The MeV gamma-ray sky

As an additional topic I mention recent ongoing work on the MeV gamma-ray sky. For cosmic ray studies,

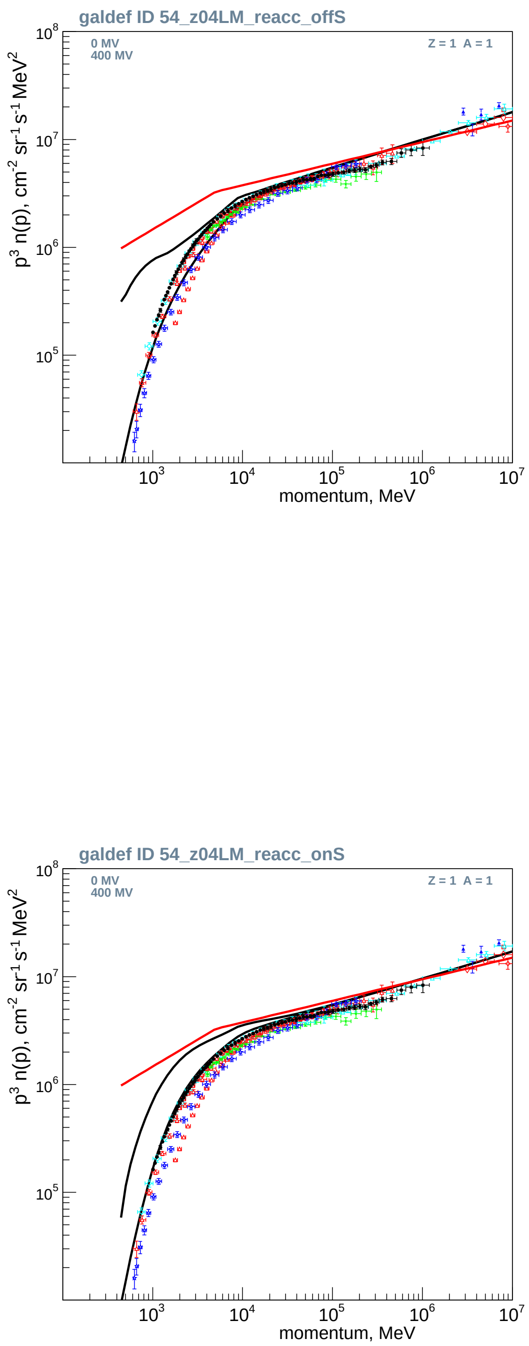


Figure 3: CR proton momentum spectra without (upper) and with (lower) DR, for $V_a \approx 30$ km s^{-1}. Black lines: interstellar and modulated spectra, red line: spectrum derived from gamma-ray emissivities [7], data points: direct measurements, for details see [7].

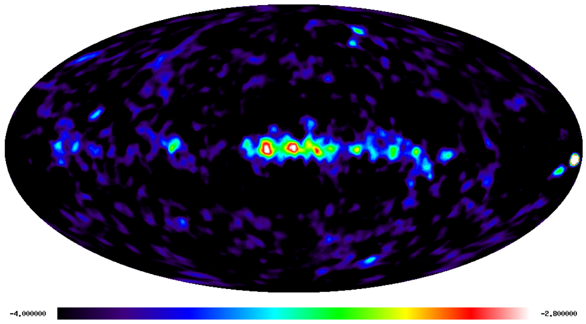


Figure 4: COMPTEL all-sky image 10-30 MeV. Galactic coordinates centred on l=b=0. Intensity in $cm^{-2}\ sr^{-1} s^{-1}$.

continuum MeV gamma rays are sensitive to electron bremsstrahlung and inverse Compton emission, as well as extending below the pion bump to complete the spectrum as discussion in Section 2.

As is well known, there is a lack of new missions in the MeV range, while Fermi-LAT and AGILE have provided a very detailed view in the range above 100 MeV. Fermi-LAT may extend down to 30 MeV in the future with new data processing techniques but the angular resolution and sensitivity are limited. We have a few thousand GeV sources but only about 30 in the 1-30 MeV range from GRO/COMPTEL. New missions like eAstrogam are being proposed and the ballon experiment COSI has flown, but meanwhile an ongoing effort to exploit the heritage COMPTEL data is underway at MPE and MPA in Garching.

The double-Compton telescope COMPTEL flew on the NASA CGRO satellite from 1991 to 2000, and is still the basis of most of our knowledge about the 1-30 MeV sky (while INTEGRAL/SPI provides more details on high-resolution line spectroscopy). Several developments are in progress: new event processing techniques improve the background rejection, and new energy ranges are defined to avoid background lines. The original maximum-entropy skymapping method used for the existing published skymaps [19] has been updated to use current state-of-the art convolution on the sphere and the HealPix sky projection, and adapted to modern parallel processing hardware.

As an example Fig 4 shows an all-sky image in the 10-30 MeV range generated with the new analysis. The Galactic plane and the well-known sources are visible.

More advanced analysis techniques using Information Field Theory[20] are under development.

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