Galactic Cosmic Rays (Direct) Theory and Interpretation

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A genuinely “seminal” book. Marked the change of cosmic ray physics from the poor relative of particle physics to a branch of modern astrophysics.
Key points of GS64

- Cosmic rays are essentially a Galactic phenomenon - not solar and not cosmological.
- The CR properties observed at the solar system are representative for the bulk of the disc.
- Propagation is essentially spatial diffusion in an extended magnetised CR halo surrounding the gas disc.
- Energetics point firmly to supernovae as the power source ("literally leaps off the page" to quote GS)
- Pointed to potential of gamma-ray and neutrino astronomy over fifty years ago!
Still largely true (we think)....

Energetically dominant component of the cosmic rays at about a GeV/nucleon are certainly Galactic - UHE probably extra-Galactic, but transition uncertain though probably in EeV region - see talk by Andrew Taylor.

The GCR do fill the Galactic disc rather uniformly and isotropically - surprisingly so in fact.

Transport has a strong diffusion component, but is probably more complicated than GS model.

Energy argument has not changed much and is still a compelling argument for Supernovae as ultimate power source.
Distribution in the Galaxy

GS had only radio synchrotron data, but pointed to potential of gamma-ray and neutrino astronomy.

Fermi-LAT and earlier gamma-ray satellites clearly show entire Galactic disc filled with cosmic rays similar to those observed locally.

Slight radial gradient and lower values in Magellanic clouds consistent with Galactic origin for GeV-PeV component.
\[ p + A \rightarrow \pi^0 + \ldots \rightarrow \gamma + \gamma \]

**Figure 5**

Sky maps of (a) the \( \gamma \)-ray intensity recorded by Fermi-LAT above 1 GeV in six years of observations (http://fermi.gsfc.nasa.gov/ssc/) and of (b) the dust optical depth measured at 353 GHz from the Planck and IRAS surveys (Planck Collab. et al. 2014b). Both maps broadly trace the same total gas column densities, weighted by the ambient cosmic-ray density in \( \gamma \) rays and by the ambient dust-to-gas mass ratio and starlight heating rate in the dust map. They exhibit striking similarities in details of the gas features. The \( \gamma \)-ray map also contains numerous point sources and faint non-gas-related diffuse components.

I. Grenier, J. Black and A. Strong: Annual Reviews Astronomy and Astrophysics 2015. 53

Also various Fermi-LAT talks at this conference
What nobody expected - the Fermi “bubbles”

Clearly points to some episode of nuclear activity in the past in our own Galaxy.
Distribution of GCRs

Do permeate entire Galaxy.

Local values appear “representative” for most of the disc.

Do not really understand why distribution is so flat in outer Galaxy - Large halo? enhanced radial transport? Propagation models?

The Galactic centre is clearly “special” and appears to have been active in the past.
Anisotropy

Remarkably low at all energies!

Isotropisation by magnetic fields is obvious cause, but details complex.

Now very good data from Icecube, Argo-YBJ, EAS-TOP, Tibet-ASG etc at PeV energies (one man’s background is another man’s signal!).
Older data on magnitude of dipole anisotropy - of order $10^{-3}$ to $10^{-4}$ with no strong energy dependence.

Figure 21. Pictorial view of the CR TeV sky obtained by merging data from the ARGO.YBJ and the IceCube experiments. ARGO-YBJ covered the declination range $-20^\circ - 80^\circ$, whereas the IceCube experiment observed the sky below $\delta = -65^\circ$. The image has illustrative purposes, as the median energy and the angular scale for which data were optimized are different for the experiments.
Small-scale structure was initially a bit surprising, but now I think understood (e.g. Giacinti and Kirk, arXiv: 1702.01001) and can in principle be used as probe of the local ISM and heliospheric magnetic field structure (see talk by Ming Zhang).

Large scale structure possibly hints at interesting local sources, e.g. Vela SNR (see e.g. Ahlers, arXiv:1605.06446).

Low level of anisotropy remains a strong constraint for propagation models and argues for a large halo at high energies as in dynamical outflow propagation models.
Power

How much power is required to maintain the observed GCR population? Conventional estimate is about $10^{41}$ erg/s or $10^{34}$ W.

- GS64: $0.3 \times 10^{34}$ W
- Galprop (Strong et al, 2010): $(0.7 \pm 0.1) \times 10^{34}$ W
- Drury, Markiewicz and Völk (1989): $< 3 \times 10^{34}$ W
Basic Power Estimate

Local energy density and “grammage” for mildly relativistic CRs are both very well constrained by observations at a few GeV/nucleon.

Gives a more or less model independent estimate of the cosmic ray power needed to maintain a steady state cosmic ray population in the Galaxy within simple propagation models where particles do not change their energy significantly.

\[ g = \frac{\tau c M}{V} \]

Confinement time

Target mass

Grammage

Confinement volume

Energy density

Luminosity

\[ L_{CR} = \frac{\mathcal{E}_{CR} V}{\tau} \]
\[ L_{\text{CR}} \approx \mathcal{E}_{\text{CR}} \frac{cM}{g} \]

\[ \mathcal{E}_{\text{CR}} \approx 1.0 \text{ eV cm}^{-3} \]

\[ M \approx 5 \times 10^9 M_\odot \]

\[ g \approx 5 \text{ g cm}^{-2} \]

\[ \implies L_{\text{CR}} \approx 10^{41} \text{ erg s}^{-1} = 10^{34} \text{W} \]

NB does not depend on $^{10}\text{Be}$ age etc.
Aside on propagation

Traditional “leaky box” has fixed volume and energy dependent escape time - can be seen as approximation to physical GS diffusion model.

At phenomenological level, can equally consider volume to be energy dependent (expanding leaky box) - can be shown to approximate dynamical outflow and diffusion model (e.g. Recchia et al and references therein, arXiv:1703.04490).
Two questions

At high energies how hard is the true injection spectrum? High estimate of DMV results from assuming hard injection spectrum $\propto E^{-2}$ and strong leakage and/or large volume at high energies (favoured by DSA theory).

At low energies how much energy is contributed by second order Fermi if using re-acceleration term to fit B/C at low energies (as in Galprop)?
Reacceleration Power

Must be diffusion in momentum as well as in space if scattering is not magneto-static.

On very general grounds expect the two diffusion coefficients to be related by \((V_A = \text{Alfvén speed})\)

\[
D_{pp}D_{xx} \approx \frac{1}{9} p^2 V_A^2
\]

Used in Galprop and similar propagation codes and helps to fit low-energy B/C ratios (but same effect can be obtained by advection in outflow).
Using the “standard” values from Galprop and the local ISM proton spectrum from Voyager we estimate the reacceleration power to be

\[ P_R \lesssim 5 \times 10^{33} \text{ W} \]

or possibly as much as half the cosmic ray luminosity of the Galaxy - personally do not find this believable!
Summary of energetics

Can safely assume \( 0.3 \times 10^{34} \text{ W} < L_{\text{GCR}} < 3 \times 10^{34} \text{ W} \)

As much as half of this comes from reacceleration if standard Galprop fitting used!

As is well known \( P_{\text{SNe}} \approx 10^{35} \text{ W} \)

Apart from GC no other plausible source of enough energy although pulsar winds and OB winds may contribute at 10% level.

Solar wind definitely accelerates GCR by pushing them out of the heliosphere, but total power in solar wind is only \( 3 \times 10^{20} \text{ W} \) so even for all M stars in Galaxy only get \( 3 \times 10^{31} \text{ W} \)
So most plausible source of bulk of energy is SNe.

Adiabatic losses imply not in explosion itself.

Mediated through shocks and/or turbulence driven by SNRs in the ISM.

\[ P_{\text{SNe}} \approx 10^{35} \text{ W} \]

\[ L_{\text{GCR}} \approx 10^{34} \text{ W} \]
The Galactic Centre

Eddington luminosity of GC supermassive black hole is

\[
1.26 \times 10^{31} \left( \frac{M}{M_\odot} \right) \text{ W} \approx 5 \times 10^{37} \text{ W}
\]

Clearly extremely sub-luminous at the moment, but evidence of time variability.

Could easily make a significant contribution.

Recent evidence from H.E.S.S. is very exciting in this regard - first Galactic Pevatron detected!

arXiv:1603.07730
New and exciting discoveries!

At time of GS and until a few years ago paradigm was that all primary nuclei had the same power law spectrum below the “knee” at about 3PeV.

Now clear from Pamela, AMS02 and CREAM that:

- H is distinctly softer than He (and heavier species).
- Both spectra show a hardening break at 200GV.
- Voyager has measured local interstellar spectra at low energies for first time!
Proton (top data set) and helium (bottom data set) fluxes measured by PAMELA in the rigidity range 1 GV to 1.2 TV. The pink shaded areas represent the estimated systematic uncertainty. The lines represent the fit with a single power law and the GALPROP and Zatsepin models.
From the AMS02 website

Figure 2. Measured proton flux as a function of rigidity.
Figure 3. Measured helium flux as a function of rigidity.
Figure 3 from Discrepant Hardening Observed in Cosmic-ray Elemental Spectra
In all particle energy spectrum, He appears to dominate H above 100 TeV, so knee in all particle spectrum at 3 PeV is probably a He knee, not a p knee! Reminiscent of old Grigorov claims (but detail seems wrong).

The break at 200 GV could be a propagation effect related to a transition from CR self-generated waves to general ISM turbulence - see e.g. Amato and Blasi arXiv:1704.05696 - however in this case should also see effect in secondary to primary ratios, and an enhanced break in secondary species such as Li. Also break seems a bit too sharp?
AMS02 B/C

Figure 4. Boron over Carbon ratio as a function of kinetic energy per nucleon.

From E Fiandrini

XIV International Conference on Topics in Astroparticle and Underground Physics (TAUP 2015) IOP Publishing
As shown on Thursday at this meeting
Fit of Lithium flux

Same model as the one used for proton and helium (double power law with smooth transition) between 45 GV and 3 TV:

\[
\Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^s
\]

→ Change of slope at the same range than for the one found for Proton and Helium.

AMS days, April 2015
The 200 (or 300) GeV spectral hardening

If a propagation effect, should be seen in secondary to primary data (not immediately obvious in AMS02 results as presented - PRL paper promised).

However Genolini et al argue that the AMS B/C data in fact already demand just such a break in the diffusion coefficient (arXiv:1706.09812)!

Worth noting that spectral hardening (concavity) is a generic feature of DSA so could be a source effect (but then why in both H and He?), but also exist plausible arguments for it being a propagation effect - how sharp is the break?
**Fig. 1.** Spectrum of protons measured by Voyager (blue empty circles), AMS-02 (black filled circles; Aguilar et al. 2015), PAMELA (green empty squares; Adriani 2011) and CREAM (blue filled squares; Yoon et al. 2011), compared with the prediction of our calculations (lines). The solid line is the flux at the Earth after the correction due to solar modulation, while the dashed line is the spectrum in the ISM.

R. Aloisio et al.: Nonlinear cosmic ray Galactic transport in the light of AMS-02 and Voyager data

A&A 583, A95 (2015)
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Relative abundances of the different species in the cosmic rays.

Complicated by spectral differences - not obvious for example how to compare electrons to protons, and now protons to alphas.

Usually taken to mean ratios of fluxes at a few Gev/n for the nuclear species.
From ACE News #83, 2004

The diagram shows the relative abundances of elements as a function of their atomic number (Z). The abundances are plotted on a logarithmic scale. The graph compares the solar system and GCR (Galactic Cosmic Rays) abundances. The elements labeled are H, He, C, Ne, Si, Ar, Ti, Fe, and Zn.
Need much the same nucleosynthetic mix as in solar system material - not all r-process for example. No one class of SNe.

Chemical abundances can not be fit with a one-parameter model. Need at least two parameters one of which is correlated with chemistry or outer electronic structure of un-stripped atom.

Telling us something about injection process at low energies - must favour heavy species and refractory elements.

FIP, volatility, dust chemistry etc.
Rauch et al, 2009 ApJ 697, 2083 COSMIC RAY ORIGIN IN OB ASSOCIATIONS AND PREFERENTIAL ACCELERATION OF REFRACTORY ELEMENTS: EVIDENCE FROM ABUNDANCES OF ELEMENTS $^{26}$Fe THROUGH $^{34}$Se
Latest Tiger results (Murphy et al, arXiv:1608.08183)

These results support a model of cosmic-ray origin in which the source material consists of a mixture of $19_{-6}^{+11}\%$ material from massive stars and $\sim 81\%$ normal interstellar medium (ISM) material with solar system abundances. The results also show a preferential acceleration of refractory elements (found in interstellar dust grains) by a factor of $\sim 4$ over volatile elements (found in interstellar gas) ordered by atomic mass (A). Both the refractory and volatile elements show a mass-dependent enhancement with similar slopes.
Chemical Enhancements in Shock-accelerated Particles: Ab-initio Simulations

Damiano Caprioli,¹,² Dennis T. Yi,² and Anatoly Spitkovsky²

FIG. 1: Normalized post-shock spectra for ion species with mass $A$ and charge $Z$ as in the legend, for a quasi-parallel ($\theta = 20^\circ$) shock with $M = 10$. The thermal peaks correspond to the Maxwellian distributions (color-matching dotted lines) expected if the temperature scaled with $A$ (see text for more details); the non-thermal tails have a maximum extent $\propto E/Z$ and a normalization enhanced as a function of $A/Z$. 
Isotopic and other hints

- $^{22}\text{Ne}$ suggests input from WR winds (Cassé and Paul, 1982)

- Live $^{60}\text{Fe}$ points to some freshly synthesised material, less than few million years old (Israel et al, APS 2016) while absence of $^{59}\text{Ni}$ (k-capture) suggests more than $10^5$ yr since nucleosynthesis.

- Actinide composition also hints at mixture of old and young material (Donnelly et al, 2012)
A recipe to make Galactic Cosmic rays

\[RX\]

- Standard well-mixed old ISM gas
- Refractory elements in ISM grains
- Some circumstellar wind material
- Traces of freshly synthesised material

Blend well and feed into the accelerator(s).
But what are the accelerators?

Best bet remains strong shocks associated with SNRs and DSA mechanism, perhaps with some second order Fermi associated with turbulence.

Galactic Centre may have contributed in the past, especially at the higher energies (intermittent Pevatron?).

Magnetic reconnection remains possible as an acceleration process, but hard to see how it could make the bulk of the GCR or explain composition and luminosity.

Pulsars probably contribute to the electron and positron components (Pamela excess?).
Not without problems though.

DSA produces particles behind the shock - that is inside the SNR - need a theory of escape as well.

Maximum energy is a problem (Lagage and Cesarsky) unless magnetic fields are amplified (Bell). Also need adequate power and not just maximum energy (problem for very early shocks and reverse shocks).

Theory favours distinctly harder production spectra than most propagation models allow - if too soft, no power at high energies to bootstrap the acceleration mechanism.
To explain different H and He spectra either need different source populations or different phases in the evolution of sources - important to see what other nuclear species do (looks as if they follow He).

Definitely need improved and dynamical propagation models - pure diffusion is going the way of the old leaky box - must include advection and wave excitation effects, realistic geometry etc.

No show stoppers that I can see, but lots of detail to fill in and exciting times!
On H/He see arXiv:1707.02744

Anomalies in Cosmic Ray Composition: Explanation Based on Mass to Charge Ratio

Adrian Hanusch (1), Tatyana Liseykina (1), Mikhail Malkov (2) ((1) Universität Rostock, Germany (2) University of California, San Diego, USA)

(Submitted on 10 Jul 2017)

and talk by Adrian this afternoon

Rather looks as if it is the proton spectra that are soft rather than all other species hard?

If so, probably related to the fact that the protons are the dynamically dominant species - in many ways the problem for shock acceleration is to suppress the proton injection.
Finally….

Have clear evidence from gamma-ray and X-ray observations for particle acceleration to 100 TeV or so in several shell-type SNRs (but not to PeV!)

Relative importance of electrons v protons not entirely clear, but acceleration is certain.

Magnetic field amplification also seems confirmed, and then strong indirect evidence for CR acceleration in SNRs (need dynamically significant CR pressure).
H.E.S.S. observations of RX J1713.7–3946 with improved angular and spectral resolution: Evidence for gamma-ray emission extending beyond the X-ray emitting shell

arXiv:1609.08671