What are the key problems in probing the CR origin?

How can astronomy help to solve the problems?

How can measurements of CR properties help the study of astrophysical phenomena and processes?

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Why Cosmic Rays (CRs) in Astronomy?

- Universe as the lab of particle and nuclear physics!
- CRs as an energetic component of the ISM: energy density $\sim 1$ eV/cm$^3$ + diffusion time $\rightarrow$ production rate of $\sim 10^{41}$ erg/s --- 10% the mechanical energy from all SNe.
- Only $\sim 2\%$ of the CR energy is released via $\gamma$-ray emission in the Galactic disk. Where is the rest of the energy?
- CRs represent a major form (but not well-studied) galactic feedback, regulating the formation and evolution of galaxies.

Energy spectrum of primary cosmic rays (Nagano 09)
Rough decomposition of the CR spectrum

- Galactic sources include pulsars and X-ray binaries, as well as SNRs.
- Extragalactic sources include AGNs, radio lobes, and GRBs.
- None of the components are well quantified!
- The cutoff at \(10^{20}\) eV is due to the GZK effect, the photo-disintegration, and/or the maximum energy that any acceleration can reach.
Why is it hard to determine the CR origin?

• CRs are mostly charged particles. Their bending in B-field, often poorly known, leads to the loss of the direction information.

\[ r_L = (1 \text{ Mpc}) Z^{-1} (E/10^{19}\text{eV})(B/1\mu\text{G})^{-1} \]
\[ = (0.1 \text{ kpc}) Z^{-1} (E/10^{15}\text{eV})(B/1\mu\text{G})^{-1} \]

• The interaction with the ISM/IGM (including the radiation field) changes the composition-dependent energy spectrum of CRs.

• Both acceleration and propagation of CRs are accompanied by the emission of photons and/or neutrinos and by non-linear heating and dynamic effects on the ISM/IGM.

The CR origin is a problem of the complex astrophysical interplay between CR and ambient medium!
Galactic CR origin: the SNR paradigm

Evidence for CR acceleration is compelling!
- Nonthermal X-ray $\rightarrow$ electron CRs up to $\sim 100$ TeV
- Charge exchange, as observed in the Hα-line emission at SNR shock $\rightarrow$ energetics of CR acceleration affecting the line widths of the narrow and broad Hα-line components.
Galactic CR origin: the SNR paradigm

- γ-ray imaging and spectra: $\pi_0$ decay signal in the 0.05-0.2 GeV range and radiation up to ~10 TeV (which is, however, far below the theoretically achievable ~1 PeV limit).

- On average, the inferred efficiency of CR acceleration reaches 5-10%.

Multiwavelength imagery (top) and gamma-ray spectra (bottom). Credit: NASA/DOE/Fermi LAT Collaboration, Chandra X-ray Observatory, ESA Herschel/XMM-Newton
Major questions about the SNR paradigm

1. What is the leptonic to hadronic CR energy ratio \((K_{ep})\)?
2. What is the intrinsic particle spectral shape of the DSA?
3. How high energy a particle can reach in a SNR?
4. How may the acceleration depend on the B-field orientation relative to the shock?

More systematic studies are needed, especially at photon energies < 1 GeV or > 100 TeV.

Are individual SNRs the dominant source of CRs?
Are superbubbles more important?

- > 85% of core-collapsed SNe take place inside superbubbles created by clusters of massive stars (Higdon & Lingenfelter 05).
- CRs can, in principle, be accelerated to higher energies: large-scales, highly turbulent, shocks from multiple SNe and fast stellar winds.
- Observed CR composition favors a mixture of massive star stellar winds and SN ejecta.

What is the exact mechanism for the CR acceleration? at which stage?
Are superbubbles more important?

Snowden et al. 1995,

Bartoli, B. et al. (14)

Qu et al. (12)
What is the origin of Fermi bubbles?

- Apparently related to starburst activity, single or multiple energy release events of the central SMBH. Could both starburst and AGN activities be important?
- These same activities may be responsible for the CR spectrum > the “knee” (e.g., Chernyshov et al. 14).
- There are smaller bubbles near the disk, but with softer spectra. Is this due to acceleration or propagation effect?
Are AGNs/radio galaxies responsible for high energy CRs?

- Powerful jets and outflows are the hallmark of AGNs.
- Observations of nonthermal radio and X-ray emission from jets and lobes.
- How high energy can CRs be accelerated in an AGN?
- Too few of requisite high luminosity AGNS are observed within the GZK distance of \( \sim 100 \) Mpc
How may the episodic nature of AGNs affect CR observations?

- For example, Sgr A* shows strong variability on various time scales.
- But in general, the episodic behavior of AGNs are hardly quantified on scales > 10 years.

Could strong variability of AGNs (on, say, $10^4$-$10^6$ yrs) explain the weak correlation of $> 10^{19}$ eV CRs with Cen A and with AGNs within ~ 100 Mpc in general?
How significant are other CR sources?

- A necessary, but not sufficient condition is the confinement of a particle in the acceleration region.
- CR acceleration involves the interplay of charged particles and EM field.
- Energy loss is invoked in both the acceleration and the escape from the region.

What are possible CR sources?
Large-scale accretion or merger shocks

- Radio observations show evidence for CR acceleration in galaxy clusters.
- Gamma-ray flux from Fermi gives the upper limit to the average CR-to-thermal energy ratio of 5% (Huber et al. 13).
- But CRs could be energetically important in certain regions.
- Ongoing radio-X-ray observations could potentially quantify the CR energy density there.

WSRT at 1.4 GHz image showing the north and south radio relics. ROSAT X-ray emission is shown by the red contours. (van Weeren et al. 2010)
Hypernova remnants: a potential UHECR source

- **IC 10** -- a dwarf irregular galaxy of the Local Group at D=0.7 Mpc (1"= 3.4 pc)
- **Nonthermal bubble**
  - discovered by Yang & Skillman (93)
  - ~184 pc diameter
  - HI shell \( V_{\text{exp}} \sim 15 \text{ km/s} \).
  - Centered at IC X-1 -- an X-ray binary with the primary \( M > 23 M_\odot \) and a WR companion.
  - Required energy \( > 10^{52} \text{ erg} \).
- **Most likely created by a hypernova (SN Ic) of the primary progenitor.**

Heesen et al. (14, 15)

For the hypernova scenario, see also X.-Y. Wang, et al. 2007, PRD, 76, 3009
Isolated pulsars and their CR outflow

- **B2224+65 as an example:**
  - Period = 0.68 s
  - $\dot{E}_s = 1.2 \times 10^{33}$ erg s$^{-1}$
  - $t_s \sim 1.1$ Myr
  - Distance $\sim 1$ kpc
  - Proper motion $\sim 900$ km/s
  - A bow shock nebula in Ha.
  - A linear X-ray feature stemming from the pulsar, $\sim 118^\circ$ offset from its proper motion direction (Johnson & Wang 2010).

- **Are such pulsars an important source of CRs ($\sim 10^2$ TeV leptons, at least)?**
It is the B-field that determines the path of CRs!

Example: large-scale isotropy of TeV CRs → co-rotation with the Galactic B field.

How to model B field (both organized and random components) in our Galaxy?

A possible approach is the modeling based on radio synchrotron emission, dispersion measurements of pulsars, and Faraday rotation measurements (FRM) of AGNs.
Measuring B-field in nearby galaxies

- FRM+soft X-ray $\rightarrow$ B\_org intensity distribution
- Radio polarization $\rightarrow$ B\_org orientation
- Radio emission + spectral distribution + flow dynamics $\rightarrow$ B\_tot + electron CR density distributions
- With these, one can model the outflow and/or diffusion of CRs.

Are galaxies CR calorimeters?

- Galaxies are typically calorimeters for lepton CRs, explaining the FIR-radio linear correlation and the radio spectral steepening with off-galactic disk distance.
- No significant energy loss is expected for hadronic CRs in galactic disks, except for nuclear starburst galaxies (Abdo et al. 10).
- But are galactic halos calorimeters for hadronic CRs?
- Could stacking of Fermi data of nearby galaxies be used to answer this question?
- Are galaxy clusters hadronic CR calorimeters?
How to explain the weak correlation (if any) of $\sim 10^{19}$ eV CRs with AGNs?

1. Is the mean on-time scale of AGNs smaller than CR travel time across the GZK distance ($\sim$ a few $\times 10^8$ years)?
   In this case, an overall correlation of the CRs with the local galaxy distribution should still be observable!

2. Is the IGM B-field $> 1$ nG?

3. Is $(B_h/1\mu G)(r_h/100$ kpc) $> 1$ for the magnetized Galactic halo.

4. Does bulk of the CRs originate in our Galaxy.
What is the nature of the \(~5\times10^{19}\) eV cutoff?

- Maximum possible energy of any CR acceleration?
  - The observed CR spectrum seems to be well fitted by a mixed composition, similar to Galactic CR spectrum.
  - This maximum-energy model may also explain the low level of directional correlation of UHECRs with nearby AGN (cancelation of the energy and charge dependences of \(r_L\)).

- Photo-disintegration of CR ions?
What is the nature of the \(~5 \times 10^{19}\) eV cutoff?

- **GZK effect?**
  - How to measure the IGM B field? Very difficult. But measurement of GeV halos (not detected so far) of variable TeV blazars may be the best hope.
  - Observations of the correlation of extragalactic neutrinos with AGNs may also be helpful.

Illustration: Alan Stonebraker
How may CRs affect the galaxy ecosystem and evolution?

1. Heat the ISM and suppress star formation.
2. Directly transport energy and drive outflows.
3. Seed B field in the early Universe.
4. Amplify B-field in the ISM/IGM.
5. Provide nonthermal pressure, balancing gravity and confining gas clouds.
Key questions raised here

1. What determines the CR properties (e.g., $K_{ep}$, $E_{max}$, spectral shape) in DSA?
2. Are superbubbles a more important source of CRs than individual SNRs?
3. How are ultra-high energy CRs produced (AGNs or something else)?
4. Are detected CRs a fair sample of the Galactic and extragalactic CR populations?
5. How can B field in various media be measured to understand the propagation of CRs?
6. How do CRs affect the galaxy ecosystem and evolution?