Molecular Cloud Ionization: Where are the Cosmic Rays?

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Outline

1. Cosmic Rays in a nutshell
2. Importance of low-energy cosmic rays
3. Bridging low and high energies
4. Concluding remarks
I. Cosmic Rays in a nutshell
AMS-02 (ISS, 2018)

Fluxes of Cosmic Rays (Observed)

Galactic

LHC

$10^{32} \times 10^{12}$

Probably galactic

Extragalactic ?

Auger

1 GeV-100 TeV

(Swordy 2001)

HansFest (03-08/09/18) 4
Solar Wind (magnetized)

Fluxes of Cosmic Rays

(Observed)

(Swordy 2001)
Various proposed "demodulated" low-energy CR spectra

... to explain:
- molecular cloud ionization ($\zeta$)
- LiBeB production

Indriolo+ 2009
2. Importance of low-energy cosmic rays in the Galaxy
Low-energy cosmic rays (LECR)

• Traditionally unknown spectrum and flux
  – solar modulation: $E_{\text{CR}} < 1 \text{ GeV/n}$
  – **But new**: "Local Interstellar Spectra": Voyager 1 (Cummings et al. 2016),
    + propagation, etc. (Orlando 2017, Tatischeff+ 2018...)

• Tracing the first steps of (shock) acceleration?
  – e.g., vicinity of SNRs

• **Important feedback effects** on (local) environment (e.g., molecular cloud chemistry; + electrons)

• Role in star formation (coupling "neutral" matter with ISM magnetic field)
  – => ionization rate $\zeta$, units $10^{-17} \text{ s}^{-1}$ ("Spitzer rate")

• => galactic distribution (from MC): **new Voyager I data do not explain the observed rates**!
Ionization rate measurements (see later): Diffuse vs. Dense Clouds

Diffuse clouds: $\zeta \approx 0.5-3 \times 10^{-16} \text{s}^{-1}$

Dense clouds: $\zeta \approx 0.1-5 \times 10^{-17} \text{s}^{-1}$
Voyager 1 @ 40!

- Launched Sep. 5, 1977
- Reached interstellar space (= beyond heliosphere) in Aug. 2012
- Engines re-started Dec. 1, 2017 to re-orient the antennas
- *Now at >140 au from the Sun!"
No steep low-energy (> 3 MeV) component!
3. Bridging low and high energies?
In the Galaxy: Search for low-energy CR (LECR) where evidence for elevated high-energy CR (HECR) flux

- **GeV-TeV CR**: $\gamma$-ray emission [$\gamma$ energy $\sim 10\%$ lower than parent CR]

  "HECR"

- **MeV-GeV CR**: ionization of the gas ($H_2^+, He^+, H^+, \ldots$)

  "LECR"

... by measuring and mapping the ionization rate $\zeta$ of selected "active" molecular clouds (e.g., with SNR) (fiducial value $\zeta_0 \sim 10^{-17}$ s$^{-1}$ for the Galaxy: "Spitzer" rate; ionization fraction $\sim 10^{-7}$)
Chemical reactions network: Molecules... and radicals

<table>
<thead>
<tr>
<th>#</th>
<th>Reaction</th>
<th>Reaction rates (cm³.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(#1)</td>
<td>$\text{CR} + \text{H}_2 \xrightarrow{\zeta} \text{H}_2^+ + e^-$</td>
<td>$\zeta$ (s⁻¹)</td>
</tr>
<tr>
<td>(#2)</td>
<td>$\text{H}_2^+ + \text{H}<em>2 \xrightarrow{k</em>{H_2^+}} \text{H}_3^+ + \text{H}$</td>
<td>$k_{H_2^+} = 2.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>(#3)</td>
<td>$\text{H}_2\text{D}^+ + \text{CO} \xrightarrow{k_D} \text{DCO}^+ + \text{H}_2$</td>
<td>$k_D = 5.37 \times 10^{-10}$</td>
</tr>
<tr>
<td>(#4)</td>
<td>$\text{H}_3^+ + \text{CO} \xrightarrow{k_H} \text{HCO}^+ + \text{H}_2$</td>
<td>$k_H = 1.61 \times 10^{-9}$</td>
</tr>
<tr>
<td>(#5)</td>
<td>$\text{H}_3^+ + \text{HD} \xrightarrow{k_f} \text{H}_2\text{D}^+ + \text{H}_2$</td>
<td>$k_f = 1.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>(#6)</td>
<td>$\text{DCO}^+ + \text{e}^- \xrightarrow{\beta'} \text{CO} + \text{D}$</td>
<td>$\beta' = 2.8 \times 10^{-7} (T/300)^{-0.69}$</td>
</tr>
<tr>
<td>(#7)</td>
<td>$\text{HCO}^+ + \text{e}^- \xrightarrow{\beta'} \text{CO} + \text{H}$</td>
<td>$\beta' = 2.8 \times 10^{-7} (T/300)^{-0.69}$</td>
</tr>
<tr>
<td>(#8)</td>
<td>$\text{H}_2\text{D}^+ + \text{e}^- \xrightarrow{k_e} \text{H} + \text{H} + \text{D}$</td>
<td>$k_e = 6.00 \times 10^{-8} (T/300)^{-0.50}$</td>
</tr>
<tr>
<td>(#9)</td>
<td>$\text{H}_3^+ + \text{e}^- \xrightarrow{\beta} \text{H} + \text{H} + \text{H}$</td>
<td>$\beta = 6.7 \times 10^{-8} (T/300)^{-0.69}$</td>
</tr>
<tr>
<td>(#10)</td>
<td>$\text{H} + \text{H} \xrightarrow{k'} \text{H}_2$</td>
<td>$k' = 4.95 \times 10^{-17} (T/300)^{0.50}$</td>
</tr>
<tr>
<td>(#11)</td>
<td>$\text{H} + \text{D} \xrightarrow{k''} \text{HD}$</td>
<td>$k'' = \sqrt{2} k'$</td>
</tr>
</tbody>
</table>

Additional reactions:

| (#12) | $\text{H}_2\text{D}^+ + \text{CO} \xrightarrow{k_D} \text{HCO}^+ + \text{H}_2$ | $k_D = 1.1 \times 10^{-9}$ |
| (#13) | $\text{CO}^+ + \text{HD} \xrightarrow{k_{CO^+}} \text{DCO}^+ + \text{H}$ | $k_{CO^+} = 7.5 \times 10^{-10}$ |
Massive star-forming regions as CR laboratories

Molecular clouds (+ HI)

$\pi^0 \gamma$-rays ($E_{CR} > 280$ MeV)

$H_3^+ \ldots$

Cosmic rays ($E_{CR} > 0.1 - 100$ MeV)

SN explosion (massive stars: $M_\star > 8 M_{\text{sun}}$)
Case study: W28
(~ galactic plane, not far from GC)

X-ray, "filled" SNR
CGRO and HESS γ-ray source

d ~ 2-3 kpc
D ≈ 20 pc
Age ~ 35-150,000 yrs
$W28 = SNR + SFR$, complex of GeV/TeV sources

d $\sim 1.9$ kpc
age $\sim 10^4$ yr
W28 spectral fitting ($\pi^0$): > GeV protons

(Nava & Gabici 2013)
IRAM 30-m observations of W28: near and far from the shock

<table>
<thead>
<tr>
<th>Species</th>
<th>Line</th>
</tr>
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<tbody>
<tr>
<td>H^{13}CO^+</td>
<td>(1-0)</td>
</tr>
<tr>
<td>C^{18}O</td>
<td>(1-0)</td>
</tr>
<tr>
<td>^{13}CO</td>
<td>(1-0)</td>
</tr>
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<td>(1-0)</td>
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16 pointings
Vaupré+2014
W28: Enhanced ionization ($x \sim 100$) downstream of the shock

$\Leftrightarrow$ enhancement of LECR

$\approx$ enhancement of \textit{local} HECR from $\pi^0$-decay $\gamma$-rays

$\gg$ enhancement of \textit{galactic} HECR from $\pi^0$-decay $\gamma$-rays
Where are the (low-energy) cosmic rays?

- Cummings et al. (2016) and Phan et al. (2018), taking into account the "local" interstellar LECR measurements ("Local Interstellar Spectrum", LIS: Voyager 1), have shown that if the LIS is identical throughout the Galaxy, it is impossible to explain the observed ionization rate of molecular clouds (≥ 1-2 orders of magnitude too low).

- Phan et al. (2018) proposed a new, detailed model for the penetration of LECR into molecular clouds (with advection, diffusion, energy losses, magnetic turbulence, etc.) and give the resulting (reduced) ionization rates (p + e).

- => invoke very-low energy "suprathermal" CR (< 3 MeV/n)?

- Counterexamples? See W28
Very low-energy cosmic rays ??

Cummings+ 2016
Voyager I, >3 MeV/n

AMS-02, >400 MeV/n

Fit: broken power-law CR spectrum (< 3 MeV – 100 GeV)
ISM ionization by GCR: fact. $>10$ too low!

LECR penetration limited by MHD effects in diffuse envelope

$A_V = 2.5$

(points are from Caselli et al. (1998) (blue filled circles), Williams et al. (1998) (blue empty triangle), Maret & Bergin (2007) (purple asterisk), and Indriolo & McCall (2012) (black filled squares are data points while yellow filled inverted triangles are upper limits).)

(Phan et al. 2018)
W28: Enhanced ionization ($\times \sim 100$) downstream of the shock

$\leftrightarrow$ enhancement of local LECR (= near SNR shock)

But ~ "Voyager value" far from the shock !?
4. Concluding remarks
• Origin of cosmic rays still a puzzle, in spite (or because) of recent advances

• For galactic cosmic rays, supernova remnants interacting with molecular clouds are a good laboratory for studying hadron acceleration
  – via γ-rays at high energies (down to ~ 280 MeV, π°-decay threshold)
  – via mm observations+astrochemistry at low energies (molecular cloud ionization)

• However, Voyager I results pose a new challenge: where are the low-energy cosmic rays necessary for ISM ionization?