Cosmic rays injected by runaway stars in open clusters

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Molecular clouds

Star forming regions

Very dense \(<n> \sim 10^2 \text{ cm}^{-3}\)

Very massive \(\sim 10^{5-6} \text{ Mo}\)

Host massive stars, YSOs, pulsars, SNRs, etc.
MCs as gamma-ray sources

Very dense  →  Perfect target for CRs
Locally accelerated or not

They are passive gamma-ray sources

$L \sim 10^{33} - 10^{35}$ erg/s

SNRs are thought to be the main producers of Galactic CRs (e.g., Hillas 2005)

But they are not the only sources …
Massive runaway stars

Runaway stars:
- $v > 30 \text{ km/s} > \text{supersonic}$
- Origin: SN in binary system/close encounters inside cluster
- 30-40% of the massive stars
- The wind sweeps the ISM
Non-thermal emission from the bowshocks of massive runaway stars

Radio: BD+43°3654
Synchrotron from relativistic e⁻

Bowshocks accelerate particles up to relativistic energies

IC scattering with IR photons

And maybe gamma-rays
Modeling bow-shocks and their emission

Relativistic particles are accelerated at the reverse adiabatic shock in the stellar wind.

\[ R_0 = \sqrt{\frac{\dot{M}_w V_w}{4\pi \rho a V_*^2}}. \]
Modeling bow-shocks and their emission

\[
\frac{\partial}{\partial E} \left[ \frac{dE}{dt} \right]_{\text{loss}} N(E) + \frac{N(E)}{t_{\text{esc}}} = Q(E),
\]
Spectral energy distributions for O4I and O9I stars

del Valle & Romero 2012, A&A
Runaway stars inject protons

Cluster ejects ~ 6 massive runaway stars
Fujii & Zwart 2011, Perets & Subr 2012

6 stars are ejected in random directions

<table>
<thead>
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<th>$V_*$ (km s$^{-1}$)</th>
<th>$\dot{M}<em>W$ ($M</em>\odot$ yr$^{-1}$)</th>
<th>$V_w$ (km s$^{-1}$)</th>
<th>Potencia</th>
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<td>$10^{-6}$</td>
<td>800</td>
<td>$4 \times 10^{32}$ erg s$^{-1}$</td>
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<td>30</td>
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<td>2200</td>
<td>$3 \times 10^{35}$ erg s$^{-1}$</td>
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**MC parameters**

Spherical cloud

- $R = 50$ pc
- $R_c = 0.5$ pc
- $M_{\text{total}} = 10^6 M_\odot$
- $n_0 = 10^4$ cm$^{-3}$

Larson 2003; Bodenheimer 2011

Boxy cloud

- $D_{10} = 10^{26}$ cm$^2$s$^{-1}$
- High density

- $n_H(R) = \frac{n_0}{1 + \left(\frac{R}{R_c}\right)^\alpha}$

Crutcher 1999

Berezinskii et al. 1990
Proton distribution

Diffusive transport equation

\[
\frac{\partial N_p}{\partial t} = D(E) \left[ \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \frac{\partial N_p}{\partial R} \right) + \frac{1}{R^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial N_p}{\partial \theta} \right) \right] - \frac{\partial}{\partial E} \left( P(R, \theta, E) N_p \right) + Q_p(R, \theta, E, t). 
\]

- Diffusive term
- Injection
- Radiative losses
  - ioniz + p-p
- with
  - \( \bar{r}_* = \bar{V}_* t \)

\( Q_p(R, \theta, E, t) = N_0 E^{-2} \delta^3(\bar{r} - \bar{r}_*) \)
Pair distribution

Transport equation with diffusion

\[
\frac{\partial N_e}{\partial t} = D(E) \left[ \frac{1}{R^2} \frac{\partial}{\partial R} \left( R^2 \frac{\partial N_e}{\partial R} \right) + \frac{1}{R^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial N_e}{\partial \theta} \right) \right]
- \frac{\partial}{\partial E} \left( P(R, \theta, E) N_e \right) + Q_e(R, \theta, E, t).
\]

Diffusion term

Injection

Radiative losses:
Synchrotron + relativistic
Bremsstrhalung + IC
Results
Non-thermal emission from massive runaway bowshocks

The $e^-$ radiate but the protons escape without losing energy

They are injected into the intra-cluster medium

Massive runaway stars ejected from clusters in GMCs
Proton and pair distributions

\[ E = 10^4 \text{ GeV} \]

\[ E = 10 \text{ GeV} \]

\[ \log N_p [\text{erg}^{-1} \text{cm}^{-2}] \]

\[ \log N_e [\text{erg}^{-1} \text{cm}^{-2}] \]

\[ x (\text{pc}) \]

\[ y (\text{pc}) \]

\[ \text{time} = 0.00 \text{ Myr} \]
Emissivity at 1 keV and 10 GeV
Emissivity maps

10 background
1.0 background
0.1 background

$E = 10 \text{ GeV}$

0.1 Myr
0.2 Myr
0.4 Myr

0.6 Myr
0.8 Myr
1 Myr

$\log Q \left[ \text{erg}^{-1} \text{ cm}^{-2} \text{s}^{-1} \right]$
SED: whole cloud and core
What’s next?

Evolved MC: different density distribution

Include effects of turbulence through diffusion in momentum space

\[
\frac{1}{4\pi p^2} \frac{\partial}{\partial p} \left( 4\pi p^2 D_{pp} \frac{\partial f}{\partial p} \right)
\]
Runaway pulsars

Figure 2: The galactic distribution of pulsars and their velocity vectors. The tails represent the approximate paths travelled during the last million years (After Harrison, Lyne & Anderson 1993).
Runaway pulsars
Pulsar bowshocks
Pulsar bowshocks

Fig. 2. X-ray (a) and radio (b) images of the bow shock G359.23 – 0.82 (a.k.a. “the Mouse”) powered by PSR J1747 – 2958 (Gaensler et al., 2004). In the X-ray image, the “tongue” and “tail” regions are indicated. In the radio image, the broad and narrow components of the tail are shown.
Pulsar bowshocks
Fig. 2.—X-ray images of the bow shock PWN G189.22+2.90 in SNR IC 443. 
(a) A Chandra image in the energy range 0.3–10 keV, made using the 2005 data 
and displayed using a linear transfer function ranging from 0 to 9 counts pixel$^{-1}$.
Fig. 1. Inner part of the Geminga EPIC MOS1 and MOS2 images summed together shown after Gaussian smoothing (the raw data can be seen in fig. S1). North is up; east is left. Events in the energy range from 0.3 to 5.0 keV are displayed. Net exposure time is $\sim 77$ ks per camera. The Geminga count rates are $0.083 \pm 0.001$ count s$^{-1}$ and $0.084 \pm 0.001$ count s$^{-1}$ for MOS1 and MOS2, respectively. Two elongated tails of diffuse emission are seen to emerge from the source, the point spread function of which dominates the count rate up to an angular distance of $\sim 1'$. The tails are $\sim 2'$ long and cover an area of $\sim 2$ square arc min. The diffuse emission shows a remarkable symmetry with respect to the pulsar proper motion vector, marked by the arrow. The tails' total flux is $\sim 2\%$ of that of Geminga in the energy range from 0.3 to 5 keV.
Fig. 3. Comparison of our x-ray data with the three-dimensional bow-shock geometrical models. The cases for inclination angles 0°, 20°, 30°, 40°, and 60° are shown. As apparent, inclination angles \( i > 30° \) do not fit the data. For \( i < 30° \), the fit constrains the stand-off angle in the range of 20 to 30°. (Inset) Bow-shock profile drawn from Eq. 2 as a function of the angle from the proper motion direction (θ) and shock front distance (R).
Asymmetric PWN
Fig. 1. XMM–Newton X-ray image of the emission in the 0.5–8.0 keV energy range of the extended source. Soft X-rays photons (0.5–2.0 keV) are shown in red, medium X-ray photons (2.0–3.5 keV) in green, and hard X-ray photons (3.5–8 keV) in blue. **Left-panel:** in magenta, radio contours at 843 MHz are overlaid in steps of 0.01, 0.03, 0.07 and 0.18 mJy beam$^{-1}$. **Right-panel:** X-ray spectra extracting regions are indicated using white and yellow ellipses. Background region is indicated in yellow-dashed line.
Spectral X-ray indices
What next?

- Full model & calculations
- Predictions for CTA
- Counterparts: optical, IR, & radio (ATCA?)
Conclusions

- Massive runaway stars can inject a significant amount of protons into a MC.
- They can accelerate and inject CRs inside a very young MC.
- The protons produce gamma luminosity, with \( L \sim 10^{34} \text{ erg s}^{-1} \)
- Secondary pairs emit synchrotron radiation from radio to X-rays, with \( L \sim 10^{32} \text{ erg s}^{-1} \)
- For the parameters adopted the emission dominates over the CRs sea locally

Cherenkov Telescope Array (CTA)
Thanks!