Star clusters as cosmic ray accelerators



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analogy with solar WTS (Parker, Jokipii...) + DSA (BOBALSKy...)



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Bonus: Wolf-Rayet WTR are enriched in ²²Ne \rightarrow composition \Im (with dilution)





Cassé & Paul 1980, 1982 – Cesarsky & Montmerle 1983



for the most massive stars:

$$\int \mathrm{d}t \ P_w \approx 10^{51} \mathrm{erg} \sim \mathrm{E_{SN}}$$





























Interstellar bubbles around star clusters

Castor+ 75, Weaver+ 77, McCray&Kafatos 87, Mac Low&McCray 88, Koo&McKee 92...



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weak shock —> spectra slightly steeper than E^{-2} —> good to fit CR data

Particle acceleration at WTSs: Emax

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

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Morlino+ 2021, Vieu+ 2022

$$L_w = 3 \times 10^{38} \text{erg/s}$$

 $u_w = 3000 \text{ km/s}$
 $n_{ISM} = 1 \text{ cm}^{-3}$
 $\eta_B = 0.1$

 $E_{max} \approx 2 - 3 \text{ PeV}$

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Particle acceleration in superbubbles

many papers by Bykov+, Parizot+, Ferrand&Marcowith, Vieu...

Vieu+ 2022

- cluster of N* massive stars following a standard (e.g. Salpeter...) IMF
- stars blow winds and eventually explode
- CRs injected by wind termination shocks (n ~ 10% efficiency)
- CRs accelerated/reaccelerated by SNR shocks (n ~ 10% efficiency)
- generation of magnetic turbulence (MHD waves), $(\eta_T \sim 30\%$ efficiency)
- CR turbulent reacceleration (Fermi II), energy transferred waves —> CRs
- CR escape from the bubble (diffusion coefficient in the bubble & in the shell)
 - energy losses (ionization/Coulomb)

A universal spectrum is not expected...

Vieu+ 2022

averaged over the entire bubble

Vieu+ 2022

Vieu+ 2022

Vieu+ 2022

Orion-Eridani —> no gammas, Cygnus region —> gammas

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

possible to go to PeV and possibly beyond

MHD simulations of young massive star clusters

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Vieu & Reville 2022

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Conclusions

- star clusters do accelerate CRs (WTS or in superbubbles)
- Source of energy: WTSs ~10%, SNae ~90%
- the acceleration proceeds in a different way in young and old clusters
- PeVatrons? Extreme WTS might do, doable for SBs if fast SNR shocks are there
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

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DSA @WTS, spherically symmetric, almost stationary, allows (almost) analytic solution, blah blah blah...

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