PROCEEDINGS OF SCIENCE

Clustered supernovae as the sources of very-high-energy galactic cosmic rays

Thibault Vieu[a,*] **and Brian Reville**[a]

[a] [1] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*

E-mail: thibault@mpi-hd.mpg.de

Although supernova remnants are believed to be the most plausible sources of galactic cosmic rays (CRs), it is yet unclear how they can accelerate particles beyond 1 PeV, especially when they evolve in the warm phase of the interstellar medium (ISM). On the other hand, the contribution of extra-galactic sources below hundreds of PeV is expected to be subdominant. This indicates a glaring gap in our understanding of the CR spectrum observed near the Earth. In this work, we propose a new model for the origin of Galactic CRs, taking into consideration the fact that most core-collapse supernovae explode within massive star clusters, and therefore their remnants do not expand in the warm ISM, but rather in a region where magnetic fields are amplified by the nearby powerful stellar wind outflows. By analyzing the population of young star clusters in the Milky Way, we find that a fraction of the supernova remnants expanding around the compact cluster cores are able to accelerate protons beyond 10 PeV. We show that particle acceleration around these clustered supernova remnant shocks can explain the observed CR spectrum up to several hundreds of PeV.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)192

1. Introduction

Several arguments suggest that the transition between galactic and extragalactic cosmic rays (CR) occurs around several hundreds of PeV [1–3]. This implies that 20% of the sources of galactic CRs (GCRs) must be able to accelerate heavy nuclei up to hundreds of PeV, i.e. protons beyond 10 PeV, assuming rigidity-dependent acceleration [1, 4]. The nature of these very efficient galactic accelerators is still actively debated. In particular, supernova remnant (SNR) shocks expanding in the warm interstellar medium (ISM) struggle to reach PeV energies [5, 6].

Alternative scenarios include e.g. particle re-acceleration at the galactic wind termination shock [7], collective effects in superbubbles [8], a contribution from the Galactic centre [9], hypernovae [10], or young massive stars [11] and young stellar clusters blowing a collective wind [12]. Light has been recently shed on the latter after the discovery that several massive star clusters emit very-high energy gamma-rays [13, 14].

Most massive stars are actually found in clusters [15], around which stellar winds carve hot "superbubbles" [16] where efficient particle acceleration could take place [17, 18]. A recent paper [12] identified the promising possibility to accelerate particles around a SNR shock launched beyond the core of a compact cluster. Large magnetic fields are amplified in the core of the cluster, which facilitate efficient particle acceleration beyond 1 PeV. In favourable conditions, a fast SNR shock could even accelerate protons beyond 10 PeV. The question is then, are these "clustered supernovae" frequent enough to account for the GCR spectrum in PeV bands?

2. Maximum energy estimate

Provided that the characteristic velocity u, the average magnetic field B and the relevant system scale L are correctly identified, the Hillas criterion, $E_{max} \approx ZuBL$ provides an estimate for the maximum achievable energy. In the case of a SNR shock propagating beyond the core of a compact cluster, the scale is typically 1 pc and the velocity about 5000 km/s providing the shock escaped the core without being dramatically slowed down by interacting stellar winds or turbulent eddies. As for the magnetic field, a simple estimate can be obtained assuming equipartition between the magnetic and kinetic energy in the turbulent cluster core:

$$\frac{B^2}{8\pi} \approx \left(\frac{\sqrt{\rho_c} S}{k_0}\right)^{2/3}, \tag{1}$$

where ρ_c is the density in the core, $2\pi/k_0$ is the largest turbulence scale assumed to be equal to the average distance between massive stars, and $S = \eta_T L/V$ with $L \approx 10^{38-39}$ erg/s the stellar power of the cluster, V the volume of the core and η_T the efficiency of turbulence generation. Adopting an efficiency of $\eta_T = 10\%$ and typical parameters for the cluster lead to an estimate of 200 µG for the average magnetic field. From the Hillas criterion we see that protons could be easily accelerated up to several PeV. We have performed a detailed calculation in [12] which led to $E_{max} \lesssim 4Zu_5$ PeV, where u_5 is the initial SN shock velocity in units of 5000 km/s.

For comparison, a similar calculation performed in the case of a SNR expanding in a "loose" cluster, that is, a cluster which is neither compact nor young enough to blow a collective wind, leads to $E_{max} \lesssim 0.1Zu_5^{1/3}$ PeV [12].

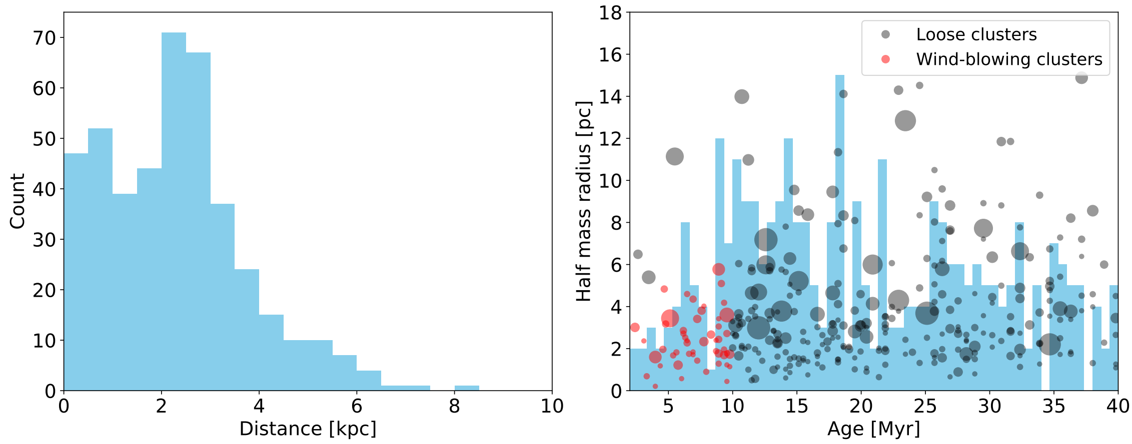

Figure 1: Left: Radial distribution (centred at the Sun) of the MSCs listed in [19]. Right: MSCs located within 3 kpc, where wind-blowing clusters are shown in red and loose clusters in grey. The histogram in the background shows the age distribution of the clusters.

3. The rate of clustered supernovae in the Galaxy

Most massive stars ($\approx$ 80%), i.e. most SN progenitors, are gathered within either "wind-blowing clusters" (WBC) or "loose clusters". WBCs have enough power and are compact enough to blow a collective wind, such that winds merge within the core and collective effects, such as turbulence generation, are strong. On the other hand, loose clusters are not powerful enough, or too extended, for the stellar winds to interact, and therefore the scenario of particle acceleration described in the previous section does not apply. In order to estimate the frequency of supernovae in WBCs, we must therefore first estimate the fraction of massive clusters which have the necessary properties to blow a collective wind. Typically, we calculated that their half-mass radius must be smaller than about 5 pc, and they must be in the "young" stage of their evolution, where the cluster power is dominated by the powerful Wolf-Rayet stars ($t \lesssim 10$ Myr).

In [19], almost 2000 open clusters identified in the second Gaia data release were analysed. As seen on the left panel of Figure 1, the distribution of clusters drops beyond about 3 kpc, which suggests that the catalogue is incomplete beyond this distance. We limit the analysis to the clusters identified within 3 kpc. These clusters are then discriminated in regard of their size and age, as shown on the right panel of Figure 1. The clusters which are young and compact enough to blow a collective wind are displayed by the red dots. One sees that most clusters are in fact too old to blow a collective outflow, such that only about 16% of the massive star clusters are actually "wind-blowing", which means that only about 16% of clustered core-collapse supernovae (CCSN) can accelerate protons beyond 1 PeV. Assuming a clustering fraction of SN progenitors of 80%, and a rate of CCSN of 2 per century, we conclude that clustered SN occur in WBC at a rate of about 2.6 per millennium.

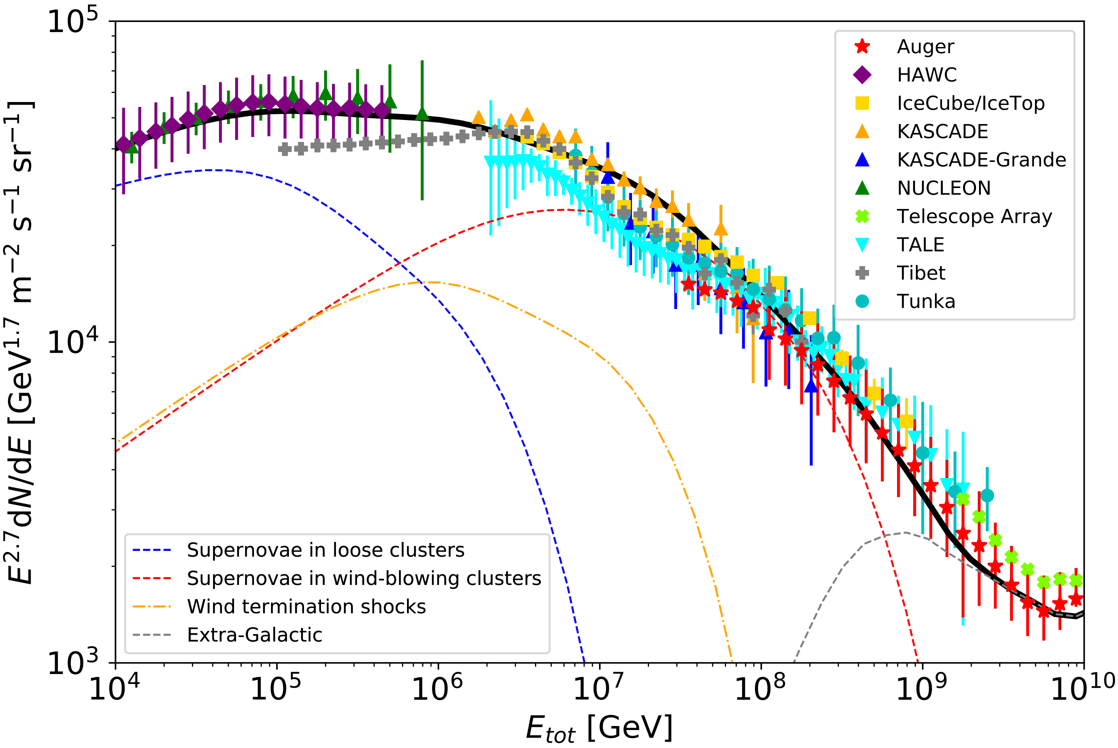

Figure 2: All-particle spectrum obtained from our computation, compared with recent data (see references in [20]). The extra-galactic component is taken from [21] (UFA model).

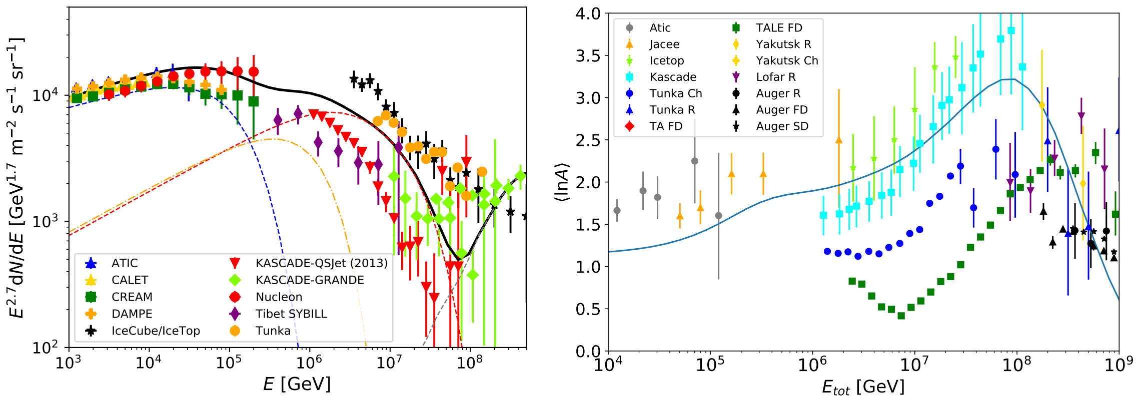

Figure 3: Left: Proton spectrum obtained from our computation, compared with recent data (see references in [20]). Right: CR composition (mean logarithmic atomic mass) obtained from our computation, compared with recent data taken from [2, 22], and references therein.

4. Galactic CR spectrum from clustered supernovae

The contribution of supernovae in WBC to the galactic cosmic rays is modelled as a hard E^{-2} spectrum with an exponential cut-off at $4Zu_5$ PeV. We normalise the spectrum assuming the rate derived in the previous section, an energy per SN of 10^{51} erg, and an injection efficiency left as a parameter. We also expect that only part of the SN shock is able to expand through the turbulent core (e.g., if the SN explodes close to the edge, only about half of its power will be available for efficient particle acceleration), such that we introduce a last parameter, $\xi \ll 1$, to reduce the normalisation accordingly. Finally, as the maximum energy depends on the shock velocity, we introduce a distribution of shock velocities up to 30000 km/s.

The contribution of SNR shocks which expand in loose clusters is assumed to scale as $E^{-2-\Delta s}$ with an exponential cut-off at $0.1Zu_5^{1/3}$ PeV [5]. We allow the slope to deviate from the canonical value by a small shift Δs, as suggested by observations [23].

For completeness, we also model the contribution of the acceleration at wind termination shocks (WTS) surrounding compact clusters, although this contribution is found to be subdominant.

Transport in the Galaxy is computed using a one-zone model, assuming a Galactic diffusion coefficient of the form $D_{Gal}(E, Z) = D_0(E/Z)^{\delta}$, where $D_0 = 10^{28}$ cm^2/s and $\delta \sim 0.3 - 0.5$ is left as a fitting parameter.

Figure 2 shows the spectrum obtained after adjustment of the 4 fitting parameters. We obtain a good agreement up to 300 PeV with a reasonable proton injection efficiency of 18%, a spectral steepening of SNR spectra in loose cluster $\Delta s = 0.17$, an escape fraction $\xi = 0.25$ (only a quarter of the shock is able to escape the core on average) and a Galactic diffusion coefficient close to the Kolmogorov scaling ($\delta = 0.35$). Above 300 PeV, we also show that a smooth transition with a light sub-ankle extra-galactic component can be achieved. Good agreement is also obtained for the proton component alone (left panel of Figure 3), and the model reproduces the trend on CR composition (right panel of Figure 3).

5. Preliminary hydrodynamic simulations

Can supernovae escape the turbulent core of a wind-blowing cluster? Which fraction of the energy budget remains under the form of a fast shock launched beyond the cluster boundary? To answer these key questions, we run 3D hydrodynamic (HD) simulations with the publicly available PLUTO code [24]. We show in Figure 4 the preliminary result of a test run. We used a simplified setup with 10 identical massive stars randomly distributed within a sphere of diameter 1 pc. Each star is blowing a wind with mass-loss rate 10^{-6} $M_{\odot}$/yr and terminal velocity 1000 km/s. This is typical for early O stars in the main-sequence. The setup is stationary, we use an ideal equation of state and thermal conduction and cooling are not yet implemented. After 3 Myr the cluster wind termination shock has only partially decoupled from individual winds (see left panel of Figure 4). Mild turbulence in the downstream region slows down its expansion. On the other hand, outflows escape under the form of one-dimensional structures which we refer to as “tentacles”.

After about 3 Myr, the cluster transitions from the “nascent” stage to the “young” stage as the most massive stars reach the end of their hydrogen-burning cycle and eventually explode in supernovae, launching fast shocks in the cluster core. The middle panel of Figure 4 shows a density

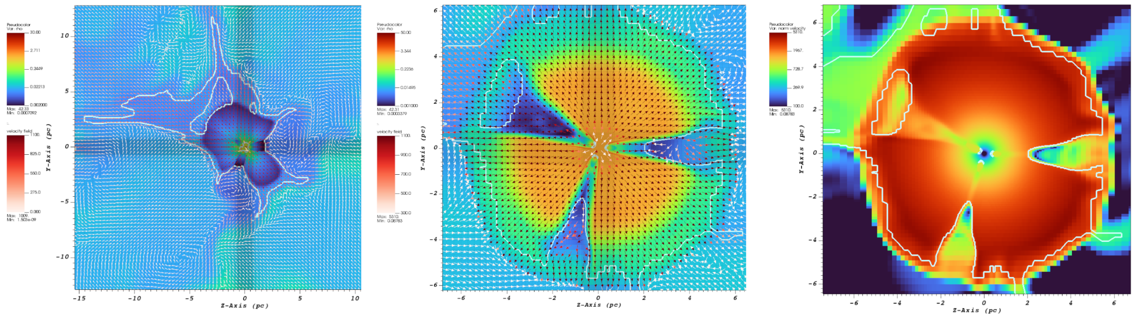

Figure 4: Preliminary results from a HD simulation with PLUTO. Left slice: density map of the region surrounding the cluster core after 3 Myr. The white outline shows the transition between subsonic and supersonic flows. Middle slice: density map 1 kyr after the explosion of a supernova inside the core of the cluster. Right slice: velocity map 1 kyr after the SN explosion.

slice 1 kyr after a SN has exploded. Immediately after the passage of the shock, the stellar winds carve again their cavities, leading to strong density inhomogeneities. However, the forward shock is not slowed down dramatically by the stellar winds. As seen on the right panel of Figure 4, most of the shock keeps propagating at several thousands km/s beyond the cluster core.

Although encouraging, this result is still very preliminary. A more realistic setup, with several layers of massive stars in the cluster core, will be tested in the future in order to probe the dynamics of SN shocks in and around a WBC.

6. Conclusion

We highlight the promising possibility to accelerate PeV protons around SNR shocks which are launched from the core of young compact clusters. We have shown that these events are frequent enough to account for the Galactic CRs up to hundreds of PeV, filling the gap between the contribution from nominal SNR (up to a few PeV) and the extragalactic contribution (beyond a few hundreds of PeV).

Our model relies on two strong assumptions: i) a fraction of the SNR shock can escape the turbulent cluster core and ii) strong magnetic fields are generated in the core. We are now running HD and MHD simulations in order to test these hypotheses, which are at the moment not disproved by our preliminary results. Indeed, Wolf-Rayet winds seem to generate strong magnetic fields [25], and a reasonable fraction of the SN shocks can reach the edge of the core without being slowed down.

Acknowledgments

TV acknowledges F. Aharonian, L. Härer and J. Wang for helpful discussions.

References

[1] E. Parizot, *Cosmic ray origin: Lessons from ultra-high-energy cosmic rays and the galactic/extragalactic transition*, *Nuclear Physics B - Proceedings Supplements* **256-257** (2014) 197–212.

[2] A.D. Supanitsky, *Determination of the Cosmic-Ray Chemical Composition: Open Issues and Prospects*, *Galaxies* **10** (2022) 75.

[3] M. Kachelrieß and D.V. Semikoz, *Cosmic ray models*, *Progress in Particle and Nuclear Physics* **109** (2019) 103710 [1904.08160].

[4] W.I. Axford, *The Origins of High-Energy Cosmic Rays*, ApJS **90** (1994) 937.

[5] P.O. Lagage and C.J. Cesarsky, *The maximum energy of cosmic rays accelerated by supernova shocks.*, A&A **125** (1983) 249.

[6] A.R. Bell, K.M. Schure, B. Reville and G. Giacinti, *Cosmic-ray acceleration and escape from supernova remnants*, MNRAS **431** (2013) 415 [1301.7264].

[7] J.R. Jokipii and G. Morfill, *Ultra–High Energy Cosmic Rays in a Galactic Wind and Its Termination Shock*, ApJ **312** (1987) 170.

[8] A.M. Bykov and I.N. Toptygin, *A Model of Particle Acceleration to High Energies by Multiple Supernova Explosions in OB Associations*, *Astronomy Letters* **27** (2001) 625.

[9] HESS Collaboration, A. Abramowski, F. Aharonian, F.A. Benkhali, A.G. Akhperjanian, E.O. Angüner et al., *Acceleration of petaelectronvolt protons in the Galactic Centre*, Nature **531** (2016) 476 [1603.07730].

[10] L.G. Sveshnikova, *The knee in the Galactic cosmic ray spectrum and variety in Supernovae*, A&A **409** (2003) 799 [astro-ph/0303159].

[11] P.L. Biermann and J.P. Cassinelli, *Cosmic rays. II. Evidence for a magnetic rotator Wolf-Rayet star origin*, A&A **277** (1993) 691 [astro-ph/9305003].

[12] T. Vieu, B. Reville and F. Aharonian, *Can superbubbles accelerate ultrahigh energy protons?*, MNRAS **515** (2022) 2256 [2207.01432].

[13] F. Aharonian, R. Yang and E. de Oña Wilhelmi, *Massive stars as major factories of Galactic cosmic rays*, *Nature Astronomy* **3** (2019) 561 [1804.02331].

[14] Z. Cao, F. Aharonian, Q. An, Axikegu, Y.X. Bai, Y.W. Bao et al., *The First LHAASO Catalog of Gamma-Ray Sources*, *arXiv e-prints* (2023) arXiv:2305.17030 [2305.17030].

[15] J.C. Higdon and R.E. Lingenfelter, *OB Associations, Supernova-generated Superbubbles, and the Source of Cosmic Rays*, ApJ **628** (2005) 738.

[16] R. Weaver, R. McCray, J. Castor, P. Shapiro and R. Moore, *Interstellar bubbles. II. Structure and evolution.*, ApJ **218** (1977) 377.

[17] E. Parizot, A. Marcowith, E. van der Swaluw, A.M. Bykov and V. Tatischeff, *Superbubbles and energetic particles in the Galaxy - I. Collective effects of particle acceleration*, A&A **424** (2004) 747.

[18] T. Vieu, S. Gabici, V. Tatischeff and S. Ravikularaman, *Cosmic ray production in superbubbles*, MNRAS **512** (2022) 1275 [2201.07488].

[19] T. Cantat-Gaudin, F. Anders, A. Castro-Ginard, C. Jordi, M. Romero-Gómez, C. Soubiran et al., *Painting a portrait of the Galactic disc with its stellar clusters*, A&A **640** (2020) A1 [2004.07274].

[20] T. Vieu and B. Reville, *Massive star cluster origin for the galactic cosmic ray population at very-high energies*, MNRAS **519** (2023) 136 [2211.11625].

[21] S. Thoudam, J.P. Rachen, A. van Vliet, A. Achterberg, S. Buitink, H. Falcke et al., *Cosmic-ray energy spectrum and composition up to the ankle: the case for a second Galactic component*, A&A **595** (2016) A33 [1605.03111].

[22] L.G. Sveshnikova, S.F. Berezhnev, N.M. Budnev, A. Chiavassa, O.A. Chvalaev, O.A. Gress et al., *Cosmic Ray Spectrum Above the Knee Measured by the Tunka-133 Experiment: Special Features and Possible Interpretations*, in *International Cosmic Ray Conference*, vol. 33 of *International Cosmic Ray Conference*, p. 1538, Jan., 2013.

[23] A.R. Bell, J.H. Matthews and K.M. Blundell, *Cosmic ray acceleration by shocks: spectral steepening due to turbulent magnetic field amplification*, MNRAS **488** (2019) 2466 [1906.12240].

[24] A. Mignone, G. Bodo, S. Massaglia, T. Matsakos, O. Tesileanu, C. Zanni et al., *PLUTO: A Numerical Code for Computational Astrophysics*, ApJS **170** (2007) 228 [astro-ph/0701854].

[25] L. Härer, B. Reville, T. Vieu, J. Wang and J. Hinton, *MHD simulations and gamma-ray signatures*, in *38th International Cosmic Ray Conference*, 2023.