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Can massive star clusters produce PeV protons?

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We assess limits on the maximum energy of protons accelerated within superbubbles, considering a number of detailed scenarios. In particular, we derive under which circumstances PeV protons are to be expected. Large-scale turbulent outflows that fill the cavity are not found to accelerate particles beyond a few hundreds of TeV. We also show that primary shocks such as supernova remnants expanding in the low density medium or the collective wind termination shock which forms around a compact stellar cluster could barely accelerate PeV protons. A more promising scenario is the case of a supernova remnant shock expanding into the collective wind of a compact stellar cluster. We show that protons of several PeV are achievable in this scenario. This provides a natural explanation for the galactic cosmic rays in the very-high energy range. On the other hand, the scarcity of these events make it unlikely to detect associated ultra-high energy gamma-ray sources.

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Acceleration mechanism	U [km/s]	B [µG]	L [pc]	$E_{\max}$ [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01
SNR inside SB	3000	10 – 50	10 – 30	1
WTS around a compact cluster	2000	10 – 50	5 – 30	1
SNR embedded in a WTS	5000	10 – 50	5 – 30	5
HD turbulence	100	1 – 10	50 – 100	0.5
Collection of individual winds (loose cluster)	10 – 100	10 – 50	1 – 10	0.05

Table 1: Benchmark estimates of the maximum proton energy achievable via various acceleration mechanisms expected to take place inside superbubbles.

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1. Introduction

Galactic sources able to accelerate protons up to at least several PeV, if not tens of PeV, are needed to explain the local cosmic ray spectrum [e.g. 1] as well as recent gamma-ray detections [e.g. 2]. However, these sources are still to be identified. In particular, standard scenarios of particle acceleration, e.g. at supernova remnant (SNR) shocks around isolated massive stars, fall short of PeV bands [e.g. 3, 4]. On the other hand, most massive stars are not isolated but rather clustered. Clustered stars heat their surrounding medium, which inflates a low-density cavity called a superbubble (SB) [5]. In the cavity, the stellar feedback is believed to create multiple shocks, a strongly turbulent environment, and to amplify strong magnetic fields [6], which is necessary for efficient particle acceleration [3]. Interestingly, several of these objects are associated with sources of very-high energy gamma-rays [7]. The Hillas criterion [8] is often invoked to support the idea that particles can be accelerated up to PeV in superbubbles which can inflate up to hundreds of parsecs. Although these systems indeed appear to be ideal environments for particle acceleration, the relevant acceleration mechanism is still an open question. The present work summarises the findings of [9] who addressed this question, considering all known scenarios of particle acceleration in SB environments and discussing in each case the possibility of producing PeV protons.

2. Maximum energy estimates

Provided that the characteristic velocity u, the average magnetic field B and the relevant system scale L are correctly identified, the Hillas criterion, $E_{max} \approx ZuBL$ generically provides an accurate estimate for the mechanisms we consider in the following. More details and *ab initio* calculations can be found in [9].

Several acceleration mechanisms must be distinguished: acceleration at the SB forward shock, at the cluster wind termination shock (WTS), in the turbulence, in a collection of individual winds (in the case of a “loose” cluster), at a SNR shock expanding in the low-density interior of the SB, or at a SNR embedded in the cluster wind.

Table 1 summarises the velocity, magnetic field and scale estimates in each of these scenarios, which provides estimates for the maximum energy according to the Hillas criterion. Clearly, the forward shock is too weak to accelerate very-high energy protons. The stochastic acceleration in turbulence also falls short off the PeV regime. SNR shocks expanding in the low-density SB in the

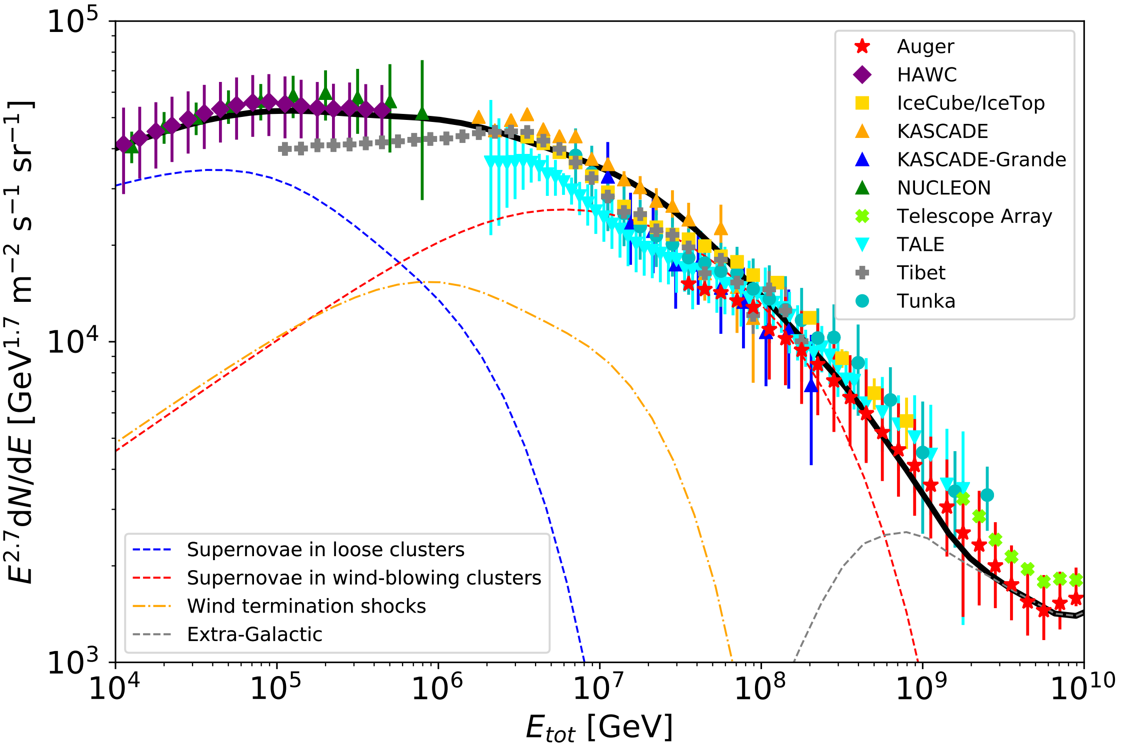

Figure 1: All-particle spectrum obtained from our computation, compared with recent data (see references in [13]).

case of a non-compact cluster might barely reach 1 PeV [10], which is also the estimate obtained for the collective wind termination shock in the case of a compact cluster [11]. In all these scenarios, either the characteristic velocity or the scale is too small. The most promising possibility, is to accelerate particles at a SNR shock which expands initially within the core of a compact cluster and is then launched in the collective cluster wind. In this case, particles probe high velocities (of the order 10^4 km/s) and large magnetic fields (of the order 100 μG) which are produced via efficient turbulence generation in the core of the cluster [e.g. 12]. Protons could then be accelerated up to several PeV (a more detailed computation may be found in [9]).

3. Clustered supernovae as the sources of galactic cosmic rays

Is the latter mechanism enough to account for the local cosmic ray population detected in PeV bands between the “knee” and the “ankle”? To answer this question requires first to estimate the average power of clustered supernovae in the Galaxy. We have used the galactic cluster catalogue established in [14] from Gaia DR2 data in order to infer the proportion of massive star clusters which are compact and young enough to blow a large-scale (≈ 10 pc) collective wind, as this is a necessary condition to efficiently generate MHD turbulence in the core and excite strong magnetic fields probed by the expanding SNR. We found that about 15% of the Galactic massive star cluster provide suitable environments (see details in [13]). Assuming an explosion rate of core-collapse

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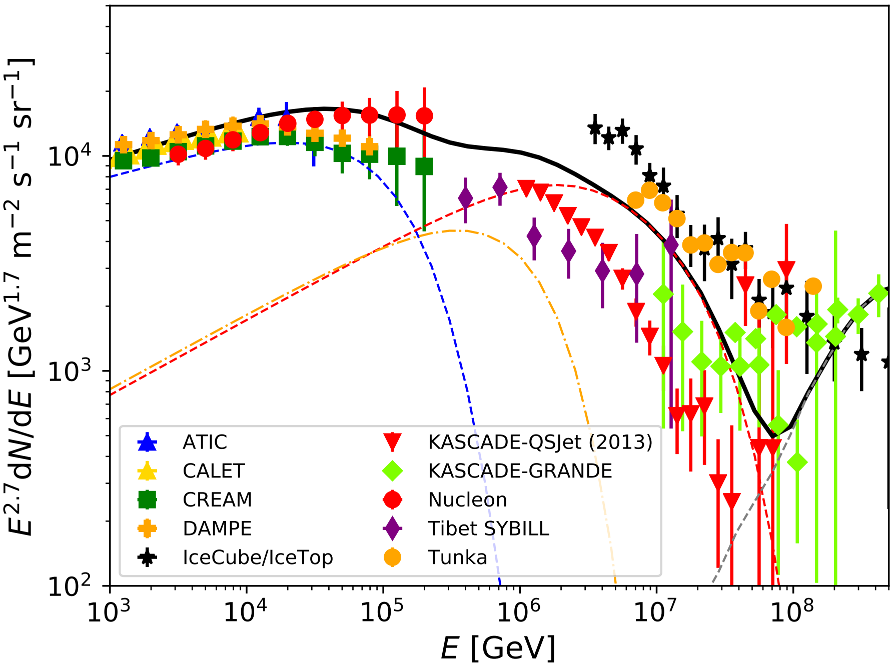

Figure 2: Proton spectrum obtained from our computation, compared with recent data (see references in [13]).

supernova (CCSN) of 2 per century, and a clustering fraction of CCSN of 80% [15], we conclude that one supernova every 400 yr is able to accelerate protons up to about 5 PeV.

The contribution of young and compact star clusters to the Galactic cosmic rays is therefore modelled as a hard power-law scaling as E^{-2}, with an exponential cut-off at $5Zu_5$ PeV, where u_5 is the SNR shock velocity in units of 5000 km/s. The normalisation of the proton component is set according to the available clustered SN power derived above, assuming that each CCSN releases 10^{51} erg, with an efficiency left as a fitting parameter. The model includes a distribution of SN shock velocities up to 30000 km/s.

We further add the contribution of SNR shocks which expand in loose (non-compact) clusters, scaling as $E^{-2-\Delta s}$ with an exponential cut-off at $0.1Zu_5^{1/3}$ PeV [3]. We allow the slope to deviate from the canonical value by a small shift Δs, as suggested by observations [16].

Eventually, for completeness, we add the contribution of the collective WTS surrounding compact clusters, although this contribution will be found to be always subdominant. Its normalisation is computed from the total stellar power of the young compact clusters in the Galaxy, assuming the same acceleration efficiency as for SNR shocks.

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 δ is left as a fitting parameter.

Fitting parameters, namely the proton injection efficiency, the spectral index deviation Δs between spectra produced at SNR shocks in loose SB and spectra produced around clustered SNR, and the Galactic diffusion coefficient scaling δ, are adjusted in order to obtain the best possible fit

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to the all-particle spectrum. The result is shown in Figure 1. 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 $\Delta s = 0.17$ and a Galactic diffusion coefficient close to the Kolmogorov scaling ($\delta = 0.35$). Above 300 PeV, we show that a light sub-ankle galactic component, plotted using the UFA model considered in [17], can take over. Good agreement is also obtained for the proton component alone (Figure 2), where our prediction fits the data within the experimental uncertainties.

4. Star clusters as sources of ultra-high energy gamma-rays?

The recent detection by the LHAASO observatory of PeV photons [2] from the Cygnus cocoon suggests that a mechanism operating within star-forming regions might be able to accelerate ultra-high energy protons. However SB cavities are low-density regions ($n \sim 0.01 - 0.1$ cm^{-3}), in particular around the WTS, which generically disfavours the production of gamma-rays via p-p interactions, except if the acceleration takes place within the dense core, as it is the case around a clustered SNR shock. In the latter case, it might be possible in principle to produce PeV photons. However, these events are very intermittent. As only very fast SNR shocks can accelerate protons well above 1 PeV, we estimate that only about 1 clustered supernova per $5 - 10$ kyr is actually able to produce UHE photons. The typical diffusion time of 10 PeV protons in the SB cavity is 1 kyr [10], which implies that it is very unlikely to observe an active source producing UHE photons via the mechanism presently analysed.

5. Conclusion

Although, in principle, star clusters and their surrounding SBs are promising particle accelerators, an analysis of the possible acceleration mechanisms shows that neither the large-scale shocks, nor the turbulence, are able to accelerate protons well above PeV, thus failing to produce UHE gamma-rays. We have nevertheless highlighted an interesting possibility, that is to consider particle acceleration around clustered SNR shocks. These could in principle expand in a strongly magnetised medium, and the fastest SNR shocks might accelerate protons up to tens of PeV. In particular, we have shown that these events, although scarce, 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). Interestingly, as very few of these events are expected, there might be no detectable gamma-ray counterpart at present, unless an unusual mechanism of particle confinement takes place in the source (e.g. a peculiar magnetic field topology in the shell as suggested in [10]).

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