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The sources of ultrahigh-energy cosmic rays (UHECRs) have been stubbornly elusive. However, the latest report of the Pierre Auger Observatory provides a compelling indication for a possible correlation between the arrival directions of UHECRs and nearby starburst galaxies. We argue that if starbursts are sources of UHECRs, then particle acceleration in the large-scale terminal shock of the superwind that flows from the starburst engine represents the best known concept model in the market. We investigate new constraints on the model and readjust free parameters accordingly. We show that UHECR acceleration above about 10^{11} GeV remains consistent with observation. We also show that the model could accommodate hard source spectra as required by Auger data. We demonstrate how neutrino emission can be used as a discriminator among acceleration models.

The search for the sources of ultrahigh-energy cosmic rays (UHECRs) remains one of the cornerstone components of high energy astrophysics. The source hunting exploration is mostly driven by three observables: the energy spectrum, the nuclear composition, and the distribution of arrival directions. From these observables, the last one allows the most direct conclusions about the locations of UHECR accelerators.

Very recently, the Pierre Auger Collaboration reported an indication of a possible correlation between UHECRs ($E > 10^{10.6}$ GeV) and nearby starburst galaxies, with an *a posteriori* chance probability in an isotropic cosmic ray sky of 4.2×10^{-5}, corresponding to a 1-sided Gaussian significance of 4σ [1]. The smearing angle and the anisotropic fraction corresponding to the best-fit parameters are 13° and 10%, respectively. The energy threshold coincides with the observed suppression in the spectrum [2–5]. Interestingly, when we properly account for the barriers to UHECR propagation in the form of energy loss mechanisms [6–8] we obtain a self consistent picture for the observed UHECR horizon.

On a separate track, the Telescope Array Collaboration has reported an intriguing excess of UHECRs ($E > 10^{10.76}$ GeV) above the isotropic background-only expectation, with a chance probability of 3.7×10^{-4}, corresponding to 3.4σ [9, 10]. This *hot spot* spans a $\sim 20°$ region of the sky, and the starburst galaxy M82 is close to the best-fit source position [11, 12].

In this paper we argue that if starbursts are sources of UHECRs, then particle acceleration in the large-scale terminal shock of the superwind that emanates from the starburst nucleus [13] represents the best known concept model in the market. We investigate new constraints on the model and readjust free parameters accordingly. We show that acceleration of UHECR nuclei in the range $10^{10.6} \lesssim E/\text{GeV} \lesssim 10^{11}$ remains consistent with the most recent astrophysical observations. We also show that the model could accommodate hard source spectra as required by Auger data.

Extremely fast spinning young pulsars [14, 15], newly born magnetars [16], gamma-ray bursts (GRBs) [17, 18], and tidal disruption events (TDEs) caused by black holes [19] have been identified as potential UHECR accelerators inside starburst galaxies [1, 20]. Given the ubiquity of pulsars, magnetars, and black holes we can ask ourselves why the correlation of UHECRs with starburst galaxies would be explained by the presence of these common objects. Rather there must be some other inherently unique feature(s) of starburst galaxies to account for this correlation. A true smoking gun for the pulsar/magnetar/TDE scenario would be a correlation with the distribution of *all* nearby matter as opposed to a particular class of objects [21].

There are numerous indications that long GRBs are extreme supernova events, which arise from the death of massive stars [22]. Starburst galaxies are characterized by high star-formation rates per unit area, of the order of 15 to 20 $M_\odot\ \text{yr}^{-1}\ \text{kpc}^{-2}$ [23]. This is up to several hundred times larger than the characteristic value normally found in gas-rich galaxies like the Milky Way. The observed supernova rate in starbursts is also higher than average, and so it seems only natural to expect a high rate of long GRBs too [24, 25]. However, the star formation rates per unit stellar mass of GRB host galaxies are found to be higher than for typical nearby starburst galaxies [26]. Moreover, stronger and stronger experimental evidence has been accumulating that implies GRB hosts are low mass irregular galaxies and have low metallicity, see e.g. [27–29]. Altogether, this makes the GBR $\leftrightharpoons$ (metal-rich) starburst connection highly unlikely.

The universal fast star formation in starburst galaxies is directly correlated with the efficient ejection of gas, which is the fuel for star formation. This happenstance generates a galactic-scale superwind, which is powered by the momentum and energy injected by massive stars in the form of supernovae, stellar winds, and radiation [23, 30]. Multi-wavelength observations seem to indicate that these superwinds are genuinely multi-phase: with hot, warm, cold, and relativistic (cosmic rays) phases. These observations also suggest a pervasive development of the hot ($T \sim 10^7$ K) and warm diffuse ionized ($T \sim 10^4$ K) phases. Namely, experiment shows that the hot and warm large-scale supersonic outflows escalate along the rotation axis of the disk to the outer halo area in the form of local chimneys. Such a supersonic outflow, however, does not extend indefinitely. As the superwind expands adiabatically out beyond the confines of the starburst region, its density decreases. At a certain radial distance the pressure would become too small to further support a supersonic flow. Whenever the flow is slowed down to subsonic speed a termination shock stops the superwind. The shocked gas continues as a subsonic flow. The termination shock would remain in steady state as long as the starburst lasts. As noted elsewhere [13] this set up provides a profitable arena for acceleration of UHECRs.

Next, in light with our stated plan, we examine new constraints on the model. Consider a spherical cavity where core-collapse supernovae and stellar winds inject kinetic energy. This kinetic energy then thermalizes and drives a super-heated outflow that escapes the sphere. Following [31], to a first approximation we ignore gravity, radiative cooling, and other effects. In this approximation energy conservation leads to the asymptotic speed of the outflow

$$v_\infty \approx \sqrt{\frac{2\dot{E}_{\rm sw}}{\dot{M}_{\rm sw}}} \sim 10^3 \sqrt{\frac{\epsilon}{\beta}} \ \ {\rm km \ s^{-1}}\,, \qquad (1)$$

where $\dot{E}_{\rm sw}$ and $\dot{M}_{\rm sw}$ are respectively the energy and mass injection rates inside the spherical volume of the starburst region, and where β is the mass loading factor, i.e. the ratio of the mass injection rate to the star formation rate. In the second rendition we have scaled the energy injection rate expected from core-collapse supernovae considering a thermalization efficiency ϵ. For this order of magnitude calculation, we have assumed that in total a $100 M_\odot$ star injects $\mathcal{O}(10^{51}$ erg) into its surroundings during the wind phase.

As the cavity expands adiabatically a strong shock front is formed on the contact surface with the cold gas in the halo. At the region where this occurs, the inward ram pressure is balanced by the pressure inside the halo, $P_{\rm halo}$. A point worth noting at this juncture is that the difference in pressure between the disk and the halo manifestly breaks the symmetry, and so the outflowing fluid which escapes from the starburst region features back-to-back chimneys with conic profiles. Rather than considering a spherical shock we assume the outflow cones fill a solid angle Ω, and hence the ram pressure at radius r is found to be

$$P_{\rm ram} = \frac{\rho_{\rm sw}\, v_\infty^2}{2} = \frac{\dot{p}_{\rm sw}}{2\Omega\, r^2} = \frac{\dot{M}_{\rm sw}\, v_\infty}{2\Omega\, r^2} = \frac{\sqrt{2\, \dot{E}_{\rm sw}\, \dot{M}_{\rm sw}}}{2\Omega\, r^2}\,, \qquad (2)$$

where $\rho_{\rm sw} = \dot{M}_{\rm sw}/(\Omega v_\infty r^2)$ is the density of the outflow and $\dot{p}_{\rm sw} = \dot{M}_{\rm sw}\, v_\infty$ is the asymptotic momentum injection rate of the superwind [32]. The agitated superwind

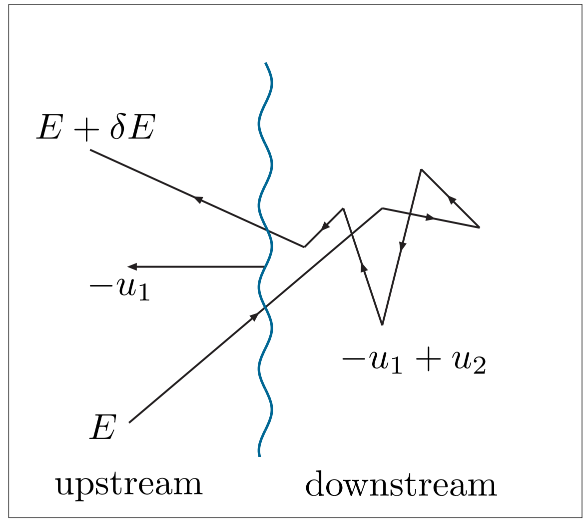

FIG. 1: An sketch of diffusive shock acceleration. A plane shock front moves with velocity $-u_1$. The shocked gas flows away from the shock with a velocity u_2 relative to the shock front, where $|u_2| < |u_1|$. This implies that in the lab frame the gas behind the shock moves to the left with velocity $-u_1 + u_2$. It is easily seen that the average energy gain per encounter $\xi = \langle \delta E \rangle / E = 4(u_1 - u_2)/3$.

gas inside the shock is in pressure equilibrium with the outside gas at a radius

$$R_{\rm sh} \sim \sqrt{\frac{\dot{M}_{\rm sw}\, v_\infty}{2\Omega\, P_{\rm halo}}}\,. \qquad (3)$$

The termination shock is a steady-state feature, present even if the starburst wind has always been active.

All told, we expect relativistic baryons of charge Ze, which could be dragged from the starburst core into the superwind, to experience diffusive shock acceleration [33–37]. Diffusive shock acceleration is a first-order Fermi acceleration process [38] in which charged particles increase their energy by crossing the shock front multiple times, scattering off turbulence in the magnetic field B, as shown in Fig. 1. The magnetic field turbulence is assumed to lead to isotropization and consequent diffusion of energetic particles which then propagate according to the standard transport theory. The acceleration time scale is given by

$$\left(\frac{1}{E}\frac{dE}{dt}\right)^{-1} = \frac{T_{\rm cycle}}{\xi}\,, \qquad (4)$$

where

$$T_{\rm cycle} = 4\kappa \left(\frac{1}{u_1} + \frac{1}{u_2}\right) \qquad (5)$$

is the cycle time for one back-and-forth encounter,

$$\xi \sim \frac{4}{3}\,(u_1 - u_2) \qquad (6)$$

is the fractional energy gain per encounter,

$$\kappa = \frac{1}{3} R_L \sim \frac{1}{3} \frac{E}{ZeB} \tag{7}$$

is the Bohm diffusion coefficient, $u_1 \sim v_\infty$ is the upstream flow (unshocked gas) velocity, and u_2 the downstream (shocked gas) velocity [39]. Now, using the continuity of mass flow across the shock together with the kinetic theory of gases we arrive at the shock compression ratio

$$\zeta = \frac{u_1}{u_2} \approx \frac{\gamma + 1}{\gamma - 1}, \tag{8}$$

where γ is the adiabatic index and where we have assumed the strong shock condition in which the Mach number of the flow $\gg 1$ [35].

There exists *lore* that convinces us that diffusive shock acceleration of UHECRs is associated to the adiabatic index of a monoatomic classic gas $\gamma = 5/3$ [39]. This assumption leads to $\zeta = 4$. In what follows, we move away from the stereotype and take $\gamma = 9/7$, which is associated to a three-atomic gas with non-static bindings. Our assumption gives $\zeta = 8$ and $\xi \sim v_\infty$. The rationale for this particular choice will be given below. Assuming that the acceleration is continuous, the constraint due to the finite lifetime τ of the shock yields,

$$E_{\rm max} \sim \frac{1}{12}\, Ze\, B\, v_\infty^2\, \tau\,. \tag{9}$$

Before proceeding, we note that the rate of acceleration for our choice of $\gamma = 9/7$ is slower by a factor of 1.8 when compared to the rate for $\gamma = 5/3$, and consequently $E_{\rm max}$ is reduced. In the preceding discussion it was implicitly assumed that the magnetic field is parallel to the shock normal. Injecting additional constraints into the model may reduce the maximum achievable energy [40].

To develop some sense of the orders of magnitude involved, we assume that the prominent M82 typifies the nearby starburst population. For a standard Kroupa initial mass function [41], our archetypal starburst has a star formation rate $\sim 10 M_\odot\ {\rm yr}^{-1}$ and a radius of about 400 pc. Hard X-ray observations provide direct observational evidence for a hot-fluid phase. The inferred gas temperature range is $10^{7.5} \lesssim T/{\rm K} \lesssim 10^{7.9}$, the thermalization efficiency $0.3 \lesssim \epsilon \lesssim 1$, and the mass loading factor $0.2 \lesssim \beta \lesssim 0.6$. Substituting for ϵ and β into (1) we obtain $1.4 \times 10^3 \lesssim v_\infty/({\rm km\,s^{-1}}) \lesssim 2.2 \times 10^3$ [42]. The warm fluid has been observed through nebular line and continuum emission in the vacuum ultraviolet, as well as through mid- and far-infrared fine-structure line emission excitations [43–46]. High-resolution spectroscopic studies seem to indicate that the warm ($T \sim 10^4$ K) gas has emission-line ratios consistent with a mixture of photo-ionized gas by radiation leaking out of the starburst and shock-heated by the outflowing superwind fluid generated within the starburst [47]. The kinematics of this gas, after correcting for line-of-sight effects, yields an outflow speed of the warm ionized fluid of roughly 600 ${\rm km\,s^{-1}}$. The velocity field, however, shows rapid acceleration of the gas from the starburst itself out to a radius of about 600 pc, beyond which the flow speed is roughly constant. The inferred speed from cold and warm molecular and atomic gas observations [48, 49] is significantly smaller than those observed from the warm ionized phase. This is also the case for the starburst galaxy NGC 253: ALMA observations of CO emission imply a mass loading factor of at least 1 to 3 [50]. However, it is important to stress that the emission from the molecular and atomic gas most likely traces the interaction of the superwind with detached relatively denser ambient gas clouds [23], and as such it is not the best gauge to characterize the overall properties of the superwind plasma [51]. (See [52] for a different perspective.) Herein, we adopt the properties of the hot gas detected in hard X-rays to determine the shock terminal velocity. We take an outflow rate of $\dot{M}_{\rm sw} \sim 3 M_\odot\ {\rm yr}^{-1}$, which is roughly 30% of the star-formation rate ($\beta \sim 0.3$), yielding $\dot{E}_{\rm sw} \sim 3 \times 10^{42}\ {\rm erg}\, s^{-1}$ [23]. For $\Omega \sim \pi$, this leads to $v_\infty \sim 1.8 \times 10^3\ {\rm km\ s^{-1}}$ and $R_{\rm sh} \sim 8$ kpc, where we have taken $P_{\rm halo} \sim 10^{-14}\ {\rm erg\,cm^{-3}}$ [53].

Radio continuum and polarization observations of M82 provide an estimate of the magnetic field strength in the core region of 98 μG and in the halo of 24 μG; averaging the magnetic field strength over the whole galaxy results in a mean equipartition field strength of 35 μG [54]. Comparable field strengths have been estimated for NGC 253 [55–58] and other starbursts [59]. Actually, the field strengths could be higher if the cosmic rays are not in equipartition with the magnetic field [60–62]. If this were the case, e.g., the magnetic field strength in M82 and NGC 253 could be as high as 300 μG [63–65].

The duration of the starburst phenomenon is subject to large uncertainties. The most commonly cited timescale for a starburst is 5 to 10 Myr, comparable to the lifetime of massive stars [66–68]. However, it has been suggested that the starburst phenomenon can be a longer and more global event than related by the lifetime of individual massive stars or pockets of intense star formation [69–71]. In this alternative viewpoint the short duration timescales are instead interpreted as a measure of the *flickering* created by currently active pockets of star formation that move around the galaxy. Measuring the characteristics of just one of these flickers reveals much about an individual star formation region but of course does not measure the totality of the starburst phenomenon in the galaxy. If starbursts are indeed a global phenomenon, then the events are longer than the lifecycle of any currently observable massive star or area of intense star formation and the bursts are not instantaneous. An observation that measures currently observable star formation activity will therefore only measure the *flickering* associated with a starburst pocket and not the entire phenomenon. This aspect, frequently denied or not yet sufficiently emphasized, may bring still another rewarding dimension to the problem at hand.

A measurement of the starburst phenomenon in twenty nearby galaxies from direct evaluation of their star formation histories reconstructed using archival Hubble Space Telescope observations suggests the average duration of a starburst is between 450 and 650 Myr [71].

Since the large-scale terminal shock is far from the starburst region, the photon field energy density in the acceleration region drops to values of the order of the cosmic microwave background. Now, for $E \lesssim 10^{11}$ GeV and $Z \gtrsim 10$, the energy attenuation length $\gtrsim 30$ Mpc [72]. Therefore, we will restrict ourselves to $\tau \lesssim 100$ Myr. This duration range is in good agreement with the overall star formation history of M82 [73, 74] and NGC 253 [75, 76], and it is also consistent with the upper limit on the starburst age of these galaxies derived in [77].

In toto, substituting $v_\infty \sim 1.8 \times 10^3$ km s^{-1}, $B \sim 300\ \mu$G, and $\tau \sim 40$ Myr into (9) we obtain

$$E_{\rm max} \sim Z\, 10^{10}\ {\rm GeV}\,. \qquad (10)$$

Note that (10) is consistent with the Hillas criterion [78], as the maximum energy of confined baryons at a shock distance of $R_{\rm sh}$ is found to be

$$E_{\rm max} \simeq 10^9\ Z\ \frac{B}{\mu G}\ \frac{R_{\rm sh}}{\rm kpc}\ {\rm GeV}\,. \qquad (11)$$

The shape of the source emission spectrum is then driven by UHECR leakage from the boundaries of the shock (a.k.a. direct escape).

Next, we generalize the scaling arguments for direct escape given in [79] to provide a justification for our choice of the adiabatic index of a polyatomic gas. Consider an expanding shell that magnetically confines UHECR nuclei. Assuming that the nuclei are isotropically distributed in the shell, the number of escaping particles is proportional to the volume. The shell width expands as $\delta r \propto r$. This implies that the volume of the plasma increases as $V \propto r^3$ and the total energy scales as $U \propto V^{-(\gamma-1)} \propto r^{-3(\gamma-1)}$. Now, using the scaling of the volume and the total energy we derive the scaling of the magnetic field inside the plasma $B \propto \sqrt{U/V} \propto r^{-3\gamma/2}$. If we further assume that the energy of a single particle in the plasma scales in the same way as the total energy of the plasma, then the Larmor radius of the particle changes with time (or radius) as $R_L \propto E/B \propto r^{-3(\gamma-2)/2}$. For a relativistic gas, $\gamma = 4/3$ yielding $R_L \propto r$, and so the ratio $R_L/\delta r$ is constant. This means that a relativistic gas provides a critical balance for stability between losses and escape. For $\gamma > 4/3$, the adiabatic energy loss is faster than the escape, and the particles are more strongly confined for larger radii. For $\gamma < 4/3$, the Larmor radius increases faster than the particles lose energy, and the particles are getting less confined at larger radii. Now, the main prediction of diffusive shock acceleration is that the final cosmic ray distribution function is a power-law function in momentum space $f(p) \propto p^{-3\zeta/(\zeta-1)}$ [35]. The source energy spectrum $N(E) \propto E^{-\alpha}$ is related to the momentum spectrum by $N(E)\, dE = f(p)\, 4\pi\, p^2\, dp$. Interestingly, for $\gamma = 9/7$ we obtain a hard source spectrum, with spectral index $\alpha = 1.4$. Note that simultaneously reproducing Auger data on the spectrum together with the observed nuclear composition also requires hard spectra at the sources [80–82].

At this stage, we pause to compare our results with those in [40, 52]: *(i)* The efficiency of the acceleration process (i.e., the normalization constant of the acceleration rate) is reduced by factor of 1.8 in our calculations due to a larger shock compression ratio. *(ii)* The fiducial value of the magnetic field strength in the halo adopted in this paper is a factor of 375 larger than the one considered in [40] and a factor of 60 larger than the one in [52]. *(iii)* The duration of the starburst phenomenon considered in this work is a factor of 2.5 smaller than the one adopted in [40] and a factor of 4 larger than that adopted in [52]. The magnetic field strength considered herein is supported by multi-frequency observations [63–65]. The duration of the starburst phase is based on the hypothesis that the non-equilibrium energy output and mass transfer from an individual pocket of star formation may only impact the local star cluster without shutting down the bursting phenomenon, which to first order is not self-quenching; this is also supported by experiment [71]. Spanning the allowed range τ could be up to a factor of 2.5 larger, relaxing the requirements on B and v_∞.

The Galactic magnetic field is not well constrained by current data, but if we adopt recent models [83–86], typical values of the deflections of UHECRs crossing the Galaxy are

$$\theta \sim 10^\circ\ Z \left(\frac{E}{10^{10}\ {\rm GeV}}\right)^{-1}\,, \qquad (12)$$

depending on the direction considered [87, 88]. To account for the potential anisotropic signal, which spans the energy range $10^{10.6} \lesssim E/{\rm GeV} \lesssim 10^{11}$, (12) argues in favor of baryonic UHECR with $Z \lesssim 10$, in agreement with the nuclear composition observed in this energy range [89–92].

In closing, we note that if a source produces an anisotropy signal at energy E with cosmic ray nuclei of charge Ze, it should also produce a similar anisotropy pattern at energies E/Z via the proton component that is emitted along with the nuclei, given that the trajectory of cosmic rays within a magnetic field is only rigidity-dependent [93]. To suppress the accompanying proton flux we follow [94] and assume that the relativistic flux of nuclei that is dragged into the starburst superwind originates in the surface of newly born pulsars [15, 95]. As noted in [96], secondary protons produced during propagation could also create an anisotropy pattern in the "low" energy regime. This sets a constraint on the maximum distance to nucleus-emitting-sources. Making the extreme assumption that the source does not emit any proton, the source(s) responsible for the suggested anisotropies should lie closer than $\sim$ 20 to 30, 80 to 100, and 180 to 200 Mpc, if the anisotropy signal is mainly composed of oxygen, silicon and iron nuclei, respectively [96]. This sets an interesting constraint on the model and provides a distinctive signal to be tested by future data.

In summary, we have shown that UHECR acceleration ($10^{10.6} \lesssim E/\mathrm{GeV} \lesssim 10^{11}$) in the superwind of starburst galaxies remains consistent with observation. Even though from an astronomical perspective starbursts are thought to be a short-lived phenomena, UHECR acceleration requires longer global starburst durations. The longer durations would imply that starbursts may not extinguish themselves through energy and mass transfer, but instead may be self-regulating environments. If these longer duration and more global starburst events are typical of bursting galaxies, then the starburst phenomenon could have a larger impact on galactic evolution than previously thought. For example, a long-duration starburst would make the ratio of baryons to dark matter drop rapidly with decreasing halo mass, relaxing the discrepancy between theory and experiment [97]. Future data from AugerPrime [98] and POEMMA [99] may confirm the cross-correlation between UHECRs and starbursts, supporting longer duration global bursts and thereupon extending the scope of multi-messenger astrophysics.

We have also shown that the starburst superwind hypothesis could develop hard source spectra as required by Auger data. These hard spectra would also have profound implications for the multi-messenger program. Note that since the maximum energy in the acceleration process is constrained by direct escape of the nuclei, the flux of photons and neutrinos accompanying the starburst UHECR emission would be strongly suppressed. Interestingly though, we can use the suppressed emission of ultrahigh-energy neutrinos to differentiate between UHECR acceleration models. This is because for UHECRs crossing the supernova ejecta surrounding neutron stars, the effective optical depth to hadronic interactions is larger than unity, and so even in the most pessimistic case we expect fluxes of neutrinos in the energy range $10^8 \lesssim E_\nu/\mathrm{GeV} \lesssim 10^9$ [100]. Indeed, upper limits on the diffuse neutrino flux from IceCube [101, 102] and the Pierre Auger Observatory [103] already constrain models of UHECR acceleration in the core of starburst galaxies [104, 105]. Note, however, that if high-energy cosmic rays are re-accelerated to ultrahigh energies at the terminal shock of the starburst superwind, we expect the neutrino emission from starbursts to cutoff somewhat above 10^7 GeV, as entertained in [106].

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