Feasibility of superwinds-generated ultrahigh-energy cosmic rays upon the light of large-scale modeling of starbursts

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The Pierre Auger Collaboration has provided a compelling indication for a possible correlation between the arrival directions of ultrahigh-energy cosmic rays and nearby starburst galaxies. Herein we show how the latest large-scale modeling of starburst galaxies is compatible with the cosmic rays producing the anisotropy signal being accelerated at the terminal shock of superwinds.

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I. INTRODUCTION

Starburst-driven superwinds are complex, multi-phase phenomena primarily powered by the momentum and energy injected by massive stars in the form of supernovae, stellar winds, and radiation \([7]\). According to the book, these superwinds are ubiquitous in galaxies where the star-formation rate per unit area exceeds \(10^{-1} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}\). The deposition of mechanical energy by supernovae and stellar winds results in a bubble filled with hot \((T \leq 10^8 \text{ K})\) gas that is unbound by the gravitational potential because its temperature is greater than the local escape temperature. The over-pressured bubble expands adiabatically, becomes supersonic at the edge of the starburst region, and eventually blows out of the disk into the halo forming a strong shock front on the contact surface with the cold gas in the halo. It was conjectured that charged particles can be accelerated by bouncing back and forth across this terminal shock up to extremely high energies \([2,8]\). However, criticisms on the choice of model parameters characterizing the speed of the shock and magnetic field strength were reported in \([4,5]\).

Two recent results have further promoted a reanalysis, though. On the one hand, it was recently proven that the photo-disintegration of \(^4\)He on the cosmic microwave background (CMB) is less severe than earlier thought \([7]\). This implies that the physical survival probability of a 10 EeV helium nuclei coming from the nearest starbursts is 40% larger. On the other hand, full-blown simulations have been performed to accurately capture the hydrodynamic mixing and dynamical interactions between the hot and cold \((T \sim 10^4 \text{ K})\) phases in the outflow \([8]\), as well as to provide a precise determination of the magnetic field in the halo \([9]\). Armed with the results of these Monte Carlo simulations, we reexamine here the acceleration mechanism in starburst superwinds and show that cosmic ray acceleration up to the highest observed energies is indeed feasible.

II. OBSERVATIONAL STATUS

The Pierre Auger Collaboration reported a 4.5\(\sigma\)-significant correlation between the arrival direction of cosmic rays with energy \(E > 38 \text{ EeV}\) and a model based on a catalog of bright starburst galaxies \([10,11]\). In the best-fit model, 11\(\pm\)4% of the cosmic-ray flux originates from these objects and undergoes angular diffusion on a scale \(\theta \sim 15^\circ \pm 5^\circ\). The angular spread derives from a Fisher-Von Mises distribution, the equivalent of a Gaussian on the sphere, and corresponds to a top-hat scale \(\psi \sim 1.59 \times \theta = (24 \pm 8)^\circ\). Median deflections of particles in the Galactic magnetic field are estimated to be

\[
\theta_C \sim 3^\circ \left( \frac{E}{100 \text{ EeV}} \right)^{-1}, \tag{1}
\]

where \(z\) is the charge of the ultrahigh-energy cosmic ray (UHECR) in units of the proton charge \([12]\). Thus, the requirement \(\theta_C \leq \psi\) implies that UHECRs contributing to the Auger anisotropy signal should have \(Z \lesssim 10\) and \(E/Z \sim 10 \text{ EeV}\).

First generation UHECR experiments also pointed to a possible starburst origin for the highest energy events \([13]\). With current statistics, the Telescope Array Collaboration cannot make a statistically significant corroboration or refutation of the UHECR \(\approx\) starburst connection \([14]\). Constraints based on the isotropic gamma-ray background at \(\lesssim \text{ TeV}\) measured by the Fermi Large Area Telescope \([15]\) seem to support the association of UHECRs and starburst galaxies \([16]\).

Whereas evidence is mounting, a definite answer as to whether a fraction of UHECRs indeed correlates with starburst galaxies will be given during this decade \([17]\).

III. MODEL UPTAKE

By now, it is well-established that charged particles can gain energy by diffusing in converging flows \([18]\).
Diffusive shock acceleration has been widely accepted as the acceleration mechanism for UHECRs \cite{19, 23}.

Consider a steady state collisionless shock propagating with velocity \( u_s > 0 \) along a plasma at rest with a magnetic field \( \mathbf{B} \) in the direction of the shock normal. In the shock rest frame, the flow can be characterized by speeds \( u_t \) and \( u_s/c \) on different sides of the shock, where \( \zeta \) is the density compression ratio at the shock. For a non-relativistic shock with a high Mach number, \( \zeta \approx 4 \). Next, assume that particles of charge \( Ze \) and speed \( v \sim c \) start off on the upstream \( (u_t) \) side of the shock, and diffuse around through collisions with plasma magnetic turbulence until they eventually cross the shock and get off downstream with lower velocity \( u_s/c \). The diffusion coefficient \( D \) depends on the particle’s energy \( E \) as well as on the strength and structure of the inhomogeneous magnetic field upstream. In the absence of a fully predictive theory of wave generation and particle diffusion, it is generally assumed that the diffusion coefficient is close to the so-called Bohm limit at all energies, defined by \( D = r_L B / 3 \), where \( r_L = E/(ZeB) \) is the Larmor radius of the particle. This particular value of \( D \) is the lowest possible for isotropic turbulence and can only be achieved if the magnetic field is disordered on the scale of a particle’s Larmor radius (i.e., if \( \lambda / r_L \sim 1 \), where \( \lambda \) is the mean free path of the charged particles). Now, in the frame in which the upstream plasma is at rest the diffusion process isotropizes the angular distribution of particles. After a period of time \( \Delta t = 4D/(u_s) \) in which the particles have diffused in a magneto-hydrodynamic plasma of speed \( u_s \), the particles experience the magnetic turbulence produced by the downstream plasma. Since the downstream plasma also gravitates to isotropize the particles elastically, the population of particles effectively see a plasma moving towards it with speed \( u_s (\zeta - 1) / \zeta \) upon arrival downstream (see e.g. \cite{24} for details). This process of quasi-isotropization leads to a net increase in the average particle speed in the rest frame of the shock interface, yielding a mean fractional increase in energy of order \( \Delta E/E \sim u_s/c \). Using the average time that particles spend upstream between shock crossings we find that the particles accelerate at a rate \( dE/dt \sim \Delta E / \Delta t \sim E u_s^2 / (4D) \). The characteristic time scale for acceleration to energy \( E \) is then \( E/(dE/dt) = 4D / u_s^2 \). However, in our back-of-the-envelope estimate we have overlooked the time spent by the particles downstream. The downstream diffusion coefficient is expected to be much smaller than the upstream coefficient, because the downstream magnetic field is larger due to compression in the shock and probably highly turbulent. Therefore, inclusion of the downstream dwell time probably does not increase the acceleration time scale by more than a factor of 2 and following \cite{25} hereafter we proceed by assuming that \( E/(dE/dt) = 8D / u_s^2 \). In the absence of energy losses it is straightforward to see that in this approximate model the maximum energy of the particles is

\[
E_{\text{max}} \sim 10 \ Z \left( \frac{u_s}{1000 \ \text{km/s}} \right)^2 \left( \frac{\mathbf{B}}{150 \ \mu \text{G}} \right) \left( \frac{\tau}{50 \ \text{Myr}} \right) \text{EeV},
\]

(2)

where \( \mathbf{B} \) is the average magnetic field strength and \( \tau \) the lifetime of the starburst.

The maximum energy of the particles is constrained by the Hillas criterium, which states the Larmor radius of the particle should be no larger than the linear size of the accelerator,

\[
E_{\text{max}} \leq Z \left( \frac{\mathbf{B}}{150 \mu \text{G}} \right) \left( \frac{R_{\text{acc}}}{10 \ \text{kpc}} \right) \text{ZeV},
\]

(3)

where \( R_{\text{acc}} \) is the length scale of acceleration \cite{26}. Large-scale optical emission-line and X-ray nebulae oriented perpendicular to the stellar disks have been observed in several nearby starburst galaxies, suggesting that the superwind activity can be traced out to \( R_{\text{acc}} \approx 10 \ \text{kpc} \) \cite{27, 30}.

We now turn to justify the fiducial parameters adopted in \cite{19}. The modelling of magnetic field is challenging because it is not directly visible to us and we have only a very limited idea about the structure of the fields that may exist in the acceleration region. Because no measurement technique is capable of capturing the entire complexity of the magnetic field, observations only reveal hints on \( \mathbf{B} \). Recently, however, a comprehensive study to understand the magnetic field structure in the core and halo of the starburst M82 has been carried out \cite{9}. This study relies on the cosmic ray propagation code GALPROP that self-consistently model the cosmic ray distribution and their diffuse emission.\(^1\) The analysis focus on two-dimensional axisymmetric models of the starburst core and superwind.

The starburst core is modelled as an oblate-ellipsoid, with cylindrical-radius \( R_{\text{core}} = 0.2 \ \text{kpc} \) and thickness \( z_{\text{core}} = 0.05 \ \text{kpc} \). Throughout the core the magnetic field strength \( B \) and the gas number density \( n \) are constants \( \rho_0 \) and \( n_0 \). Outside the core the field \( B(r) \) is defined as \( \max \{ B_{\text{exp}}, B_{\text{pow}} \} \) where

\[
\frac{B_{\text{exp}}}{B_0} = \exp \left( -\frac{r - r_{\text{core}}(\phi)}{r_{\text{scale}}(\phi)} \right),
\]

(4)

and

\[
\frac{B_{\text{pow}}}{B_0} = \left( \frac{r - z_{\text{core}} + z_{\text{scale}}}{z_{\text{scale}}} \right)^{-\beta}.
\]

(5)

and where \( r = (R^2 + z^2)^{1/2} \) is the spherical radius, with \( \phi = \tan^{-1} |z|/R \), \( r_{\phi}(\phi) = (\cos \phi/R)^2 + (\sin \phi/z)^2 \)^{-1/2}, \( z_{\text{scale}} = 0.2 \ \text{kpc} \), and \( i = \{ \text{core, scale} \} \). If \( B_{\text{pow}} > B_{\text{exp}} \), along

\(^1\) https://galprop.stanford.edu/
the minor axis (i.e. $R = 0$) the magnetic field strength becomes

$$B(z) = B_0 \left( \frac{z - z_{\text{core}} + z_{\text{scale}}}{z_{\text{scale}}} \right)^\beta.$$  \hfill (6)

To a first approximation we can estimate the average magnetic field as

$$\bar{B} \sim \frac{B_0}{z_{\text{max}} - z_{\text{core}}} \int_{z_{\text{core}}}^{z_{\text{max}}} \left( \frac{z - z_{\text{core}} + z_{\text{scale}}}{z_{\text{scale}}} \right)^{-\beta} dz \hfill (7)$$

$$= \frac{B_0 z_{\text{scale}}^\beta}{(z_{\text{max}} - z_{\text{core}})(1 - \beta)} \left[ (z_{\text{max}} - z_{\text{core}} + z_{\text{scale}})^{1 - \beta} - z_{\text{scale}}^{1 - \beta} \right],$$

with $z_{\text{max}} = 10$ kpc. The normalization constants were determined from a simultaneous fit to the gamma-ray data from VERITAS [31] and Fermi [32], as well as the integrated radio data reported in [33,35]. Using these datasets, the cosmic ray propagation models were constrained in the parameter plane $(B_0, n_0)$ [9]. There are three possible combinations ($\mathcal{A}, \mathcal{B},$ and $\mathcal{B}'$) of the two parameters, which provide excellent fits to the combined data and illustrate unique regions of the full parameter space. The numerical values for the parameters of models $\mathcal{A}, \mathcal{B},$ and $\mathcal{B}'$ are given in Table I; $u_{\text{b}}$ denotes the maximum assumed superwind velocity. We note in passing that the values of $B_0$ given in Table I are consistent with previous estimates and they are also similar to the magnetic field strength observed in the nearby starburst galaxy NGC 253 [37-41]. The power-law index $\beta$ was inferred from the propagation of the cosmic rays out to several kpc, which must create the large radio halo seen at 22 and 92 cm [24]. As can be seen in Fig. 1 the condition $B_{\text{exp}} < B_{\text{pow}}$ holds for the set of fiducial parameters of model $\mathcal{B}'$. Substituting for $B_0$ and $\beta$ into (7) we obtain $\bar{B} = 180$ $\mu$G. To visualize the behavior of $B_{\text{pow}}$ out of the minor axis, in Fig. 2 we show a comparison of the ratio $B_{\text{pow}}(R, z)/B_{\text{pow}}(R = 0, z)$ for various values of $R$. Since $\bar{B} \geq B_{\text{pow}}$, we conclude that (7) provides a reasonable estimate of $\bar{B}$ for model $\mathcal{B}'$ in the acceleration region. For models $\mathcal{A}$ and $\mathcal{B}$, the values of $\bar{B}$ given in Table I represent (strictly speaking) lower bounds on the magnetic field strength along the minor axis, as $\bar{B} \geq B_{\text{pow}}$. One would have to consider that $B_{\text{exp}}$ may exceed $B_{\text{pow}}$ for some values of $z$, that is why the estimation using only $B_{\text{pow}}$ is a lower limit, although the real value would not exceed this estimation by more than a factor of 2.

Now, the magnetic field $\bar{B}$ carries with it an energy density $\bar{B}^2/(8\pi)$, and the flow carries with it an energy flux $> u_{\text{b}} \bar{B}^2/(8\pi)$. This sets a lower limit on the rate at which the energy is carried by the out-flowing plasma,

$$L_B \sim \frac{1}{8} u_{\text{b}}^2 R_{\text{acc}}^2 \bar{B}^2,$$  \hfill (8)

and which must be provided by the source. The flux carried by the outgoing plasma is a model-dependent parameter, which can be characterized within an order of magnitude. More concretely, $0.035 \lesssim L_P/L_{IR} \lesssim 0.35$, where $L_{IR} \sim 10^{43.9}$ erg/s is the infrared luminosity [27]. The lower limit of $L_B$ corresponds to the estimate in [27] considering a supernova rate of 0.07 yr$^{-1}$, whereas the upper limit concurs with the estimate in [42], and could be obtained considering a supernova rate of 0.3 yr$^{-1}$ [43] while pushing other model parameters to the most optimistic values. The relation (8) yields a magnetic field strength in the range $15 \leq \bar{B}/\mu$G $\leq 150$, which reinforces the $\bar{B}$ interval given in Table I.

Very recently, a series of extremely high resolution global disk simulations of galaxy outflows have been carried out using the Cholla Galactic Outflow Simulations (CGOLS) program [8]. A physically-motivated prescrip-

| Model | $n_0$ (cm$^{-3}$) | $B_0$ (µG) | $\beta$ | $\bar{B}$ (µG) | $u_{\text{b}}$ (km/s) |
|-------|------------------|------------|--------|---------------|-------------------|
| $\mathcal{A}$ | 150 | 150 | 1.0 | 12 | 800 |
| $\mathcal{B}$ | 675 | 325 | 1.2 | 18 | 1000 |
| $\mathcal{B}'$ | 1000 | 325 | 0.2 | 180 | 1000 |

**TABLE I: Model Parameters $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{B}'$.**
tion for clustered supernova served as a rough proxy for the full-blown simulation of a multiphase outflow from a disk galaxy. CGOLS is equipped with a two-phase analytic model capable of fitting the properties of the superwind as a function of radius. To accurately capture the hydrodynamic mixing and dynamical interactions between the hot and cold phases in the outflow the simulations were performed with high resolution (< 5 pc) across a relatively large domain (20 kpc). CGOLS studies favor a volume average median velocity for the hot phase of the superwind of $u_h \sim 1500 \text{ km/s}$. CGOLS studies also show that mixing between hot and cold gas in the wind is an effective way of transferring momentum from one phase to another and occurs at all radii. This process accelerates cold gas to $u_c \sim 800 \text{ km/s}$ on kpc scales.

The terminal velocities of the hot ($h$) and cold ($c$) phases of the superwind can be parametrized in terms of the thermalization efficiency $\epsilon$ (the fraction of energy of the central supernovae and stellar winds that goes into the outflow) and the mass loading factor $\alpha$ (a parameter commonly used to indicate the relative amount of mass loading; if $\alpha = 1$ the superwind is not mass loaded),

$$\lim_{t \to \infty} u_{h,c} \sim 10^{3} \sqrt{\epsilon/\alpha} \text{ km/s},$$

where for this order of magnitude calculation, we have assumed that in total a 100$M_\odot$ star injects $O(10^{51} \text{ erg})$ into its surroundings during the wind phase [1]. Observational constraints derived from hard X-ray measurements of M82 pin down medium to high thermalization efficiencies ($0.3 \leq \epsilon \leq 1.0$) and require the volume-filling superwind hot fluid that flows out of the starburst region to be only mildly centrally mass loaded ($0.2 \leq \alpha \leq 0.6$) [30]. The allowed phase space then implies a terminal velocity of the M82 superwind in the range $1400 \leq u_h/(\text{km/s}) \leq 2200$, which is consistent with CGOLS simulations. The cold phase structure of the superwind must be examined using a tracer that can be directly related to the cold gas. $\alpha$ was estimated using observations of $^{12}$CO $\Delta J = 1 \rightarrow 0$ transition lines in NGC 253, obtained with the Atacama Large Millimeter Array (ALMA) [44]. ALMA data favor a mass loading $\alpha \sim 3$ (with a lower limit of $\alpha \sim 1$). This yields $600 \leq u_c/(\text{km/s}) \leq 1000$, a range which is also consistent with CGOLS studies. Altogether, these numbers justify the fiducial value, $u_c \sim 1000 \text{ km/s}$, which agrees with the maximum superwind velocity assumed in the simulations with GALPROP; see Table I [9].

The age of the starbursts is also subject to large uncertainties. Observations seem to indicate that about 500 Myr ago M82 experienced a tidal encounter with its large spiral neighbor galaxy, M81, resulting in a large amount of gas being channelled into the core of the galaxy over the last 200 Myr, which produced a concentrated starburst and an associated pronounced peak in the cluster age distribution [45]. This starburst has continued for up to about 50 Myr at a rate of 10$M_\odot$ yr$^{-1}$ [46]. A survey of bright evolved stars in the NGC 253 disk suggests that about 200 Myr ago this galaxy also interacted with a now defunct companion [17]. Some models predict that the age of the starburst in NGC 253 is similar to that of M82 [48]. Altogether this motivated our choice for the starburst age of $\tau \sim 50$ Myr.

Concerning the energy losses, the accelerating nucleus will gain energy until it eventually suffers a photodisintegration. The photodisintegration rate depends on the energy density of the ambient radiation field. This is governed by the spatial distribution of photons, including both those from the CMB and stellar radiation fields. For compact regions near the galaxy core, starbursts exhibit an energy density in their stellar radiation fields which may exceed (or be comparable to) that of the CMB, but at the superwind scale starlight is expected to have a negligible energy density compared to that of the CMB [49, 50]. An acceleration time scale of 50 Myr, energy losses during the acceleration process can be safely neglected [51] and therefore (9) gives the maximum attainable energy.

IV. CONCLUSIONS

A number of conclusions are in order connecting back with (2). If we assume the fiducial values for the velocity and age in (2), two of the three models examined (i.e., $A$ and $B$, always in the notation of (2) would produce too low averaged values of energies for the accelerated particles; $E_{\text{max}} \sim Z \text{ EeV}$. Unless of course there is observational evidence for $Z$ being sufficiently high, if models $A$ or $B$ are realized, starbursts superwinds as a possible origin of the correlation commented in Sec. II will be challenging. Model $B'$, on the other hand, would naturally lead to particles whose averaged energy could be in excess of 38 EeV and beyond, $E_{\text{max}} \gtrsim Z \times 10 \text{ EeV}$. In this case, relatively light nuclei (e.g., in the CNO region) would reach very high energies easily. Even He nuclei would reach the needed UHECR regime. This would be helped by a less-dramatic photodisintegration along the way: that new cross section parameterizations [7] have shown that, e.g., at $E \sim 10^{18} \text{ EeV}$ and a propagation distance of 3.5 Mpc, the $^4$He intensity would be 35% larger than the output of CRPropa 3 program and 42% larger than the output of SimProp v2r4 program. Thus, $^4$He could also contribute to the signal. The latter would of course be easier for larger velocities: We have assumed a fiducial value of 1000 km/s in (2), but in reality, $u_c < u_h < u_h$ and thus it is plausible to expect this could be greater than assumed. All in all, we have shown that UHECR acceleration in starburst superwinds is feasible.

Interestingly, we note that if with future data we indeed confirm the correlation with starbursts, in the context of superwinds, UHECR observations would directly feedback on models: The correlation would favor larger magnetic fields in the outflow. Observational guidance in assessing this conundrum is, at this point, essen-
tial. Tidal disruption events caused by black holes [52], low-luminosity gamma-ray bursts [53], and black hole unipolar induction [6] have been identified as potential UHECR accelerators inside starburst galaxies. However, all of these possible UHECR origins fail to explain which is the inherently unique feature(s) of starburst galaxies to account for their correlation [54]. A true smoking gun for all these proposals would be a correlation with the distribution of nearby matter or the more extreme AGNs as opposed to starburst galaxies. The data yield-the distribution of nearby matter or the more extreme gun for all these proposals would be a correlation with to account for their correlation [54]. A true smoking is the inherently unique feature(s) of starburst galaxies all of these possible UHECR origins fail to explain which UHECR accelerators inside starburst galaxies. However, low-luminosity gamma-ray bursts [53], and black hole

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