Ultra High Energy Cosmic Ray Acceleration in Engine-driven Relativistic Supernovae

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The origin of the highest energy cosmic rays remains an enigma. They offer a window to new physics, including tests of physical laws relevant to their propagation and interactions, at energies unattainable by terrestrial accelerators. They must be accelerated locally, as otherwise background radiations would severely suppress the flux of protons and nuclei, at energies above the Greisen-Zatsepin-Kuzmin (GZK) limit ($\sim 60\text{EeV}=6 \times 10^{19}\text{eV}$). Nearby Gamma Ray Bursts (GRBs), Hypernovae, Active Galactic Nuclei (AGNs) and their flares, have all been suggested and debated as possible sources. A local sub-population of type Ibc supernovae (SNe) with mildly relativistic outflows have been detected as sub-energetic GRBs or X-Ray Flashes (XRFs) and recently as radio afterglows without detected GRB counterparts. We measure the size-magnetic field evolution, baryon loading and energetics, using the observed radio spectra of SN 2009bb. We place such engine-driven SNe above the Hillas line and establish that they can readily explain the post-GZK UHECRs.

The highest energy cosmic rays pack such a large amount of energy and have such a low
flux that direct detection by satellite-borne instruments is infeasible, allowing them to be detected only by cosmic ray air showers. UHECRs beyond the GZK limit have been invoked to propose tests of known physical laws and symmetries. Understanding their origin is a crucial step in using them as probes of new physics. But, the sources of the highest energy cosmic rays pose an intriguing problem, since the magnetic rigidity of these particles are such that the magnetic fields in our galaxy are neither strong enough to contain them nor bend them sufficiently. Yet, among the UHECRs which have been detected until now, no concentration have been found towards the Milky Way. Hence, it is anticipated that their sources are extragalactic. However, UHECR protons with energies above 60 EeV can interact with a significant fraction of CMB photons via the resonance. The cross section of this interaction is such that only those extragalactic cosmic ray sources locally (within 200 Mpc of the Earth) can contribute significantly to the flux of UHECRs above the so called GZK limit. At least 61 sources are required by observations of UHECRs until now, to provide cosmic rays with energies above the GZK limit. Since particles of such high energy could not have traveled to the Earth from cosmological distances, unless Lorentz invariance breaks down at these energies, they encourage the search for potential cosmic ray accelerators in the local Universe. AGNs have been considered as UHECR sources. But, most of them are not luminous enough, leaving proposed very intense, short duration AGN flares, which are yet to be observed, as possible sources. Classical Gamma Ray Bursts (GRBs) are also considered as possible sources, but most of them occur beyond the GZK horizon and cannot contribute significantly to the local flux beyond the GZK limit. Hypernovae have also been suggested as sources where particles are boosted to successively higher energies in an ejecta profile extending
upto mildly relativistic velocities\textsuperscript{11,12}. However, they require excessive explosion energy and fail to reproduce the flat injection spectrum of UHECRs (see Suppl. Info for discussion of some of the proposed sources).

Soon after their suggestion that SNe come from collapse of a normal star to a neutron star, Baade and Zwicky went on to suggest that SNe may be the source of cosmic rays as well\textsuperscript{13}. Since then, SNe and SN remnants have been studied as sources of high energy cosmic rays. However, ordinary SNe and their remnants can not produce UHECRs due to two fundamental limitations. Firstly, they well lie below the line representing the combination of size and magnetic field required to confine and accelerate Iron nuclei with energies of 60 EeV, in the so called Hillas diagram\textsuperscript{14} (Figure 1). The second, even more restrictive, condition obviously not fulfilled by ordinary SNe is because ordinary SNe have $\beta/\Gamma \sim 0.05$ ($\beta \equiv v/c$ and $\Gamma \equiv 1/\sqrt{1 - \beta^2}$, where $v$ is the speed of the blastwave and $c$ is the speed of light in vacuum) which restricts the highest energy cosmic rays accelerated in ordinary SNe to well below the GZK limit.

Until recently, SNe with relativistic ejecta have been spotted exclusively through Long GRBs associated with them like GRB 980425\textsuperscript{13} or its twin GRB 031203. The discovery of XRF 060218\textsuperscript{16} associated with SN 2006aj showed that mildly relativistic SNe are hundred times less energetic but thousand times more common (in their isotropic equivalent rate, which is relevant for UHECRs actually reaching the observer) than classical GRBs\textsuperscript{16}. Radio follow up of SNe Ibc have now discovered the presence of an engine driven outflow from SN 2009bb\textsuperscript{17} without a detected GRB. The mildly relativistic SNe, detected either using XRFs or radio afterglows, a subset of SNe Ibc are far
more abundant at low redshifts required for the UHECR sources, than the classical GRBs. Moreover, given their mildly relativistic nature, they have the most favorable combination of $\beta/\Gamma \sim 1$, unlike both non-relativistic SNe and ultra-relativistic classical Long GRBs.

In order to derive the highest energy up to which these relativistic SNe can accelerate cosmic rays, we have to determine the evolution of the size and the magnetic field in the blast-wave. It has been demonstrated that a Synchrotron Self Absorption (SSA) model fits the initial radio spectrum of SN 2009bb rather well\cite{17} with a low frequency turnover defining the spectral peak shifting to lower frequency with time, characteristic of the expansion of the shocked region that powers the radio emission. This allows us to measure the evolution of the radii and magnetic fields from VLA and GMRT data (see Suppl. Info) at 5 epochs, plotted on the Hillas diagram (Figure 1). This clearly demonstrates that SN 2009bb and XRF 060218 can both confine UHECRs and accelerate them to highest energies seen experimentally. At the time of the earliest radio observations\cite{17} with its fortunate combination of $\beta/\Gamma \sim 1$, SN 2009bb could have accelerated nuclei of atomic number $Z$ to an energy of $\sim 6.5 \times Z$ EeV. For example, the source could have accelerated protons, Neon, and Iron nuclei to 6.4, 64 and 166 EeV respectively. In this scheme, the highest energy particles are likely to be nuclei heavier than protons, consistent with the latest results indicating an increasing average rest mass of primary UHECRs with energy\cite{18}. Therefore, our results support the claimed preference of heavier UHECRs at the highest energies of the Auger collaboration, although this claim is disputed by another experiment\cite{19}.

To estimate whether there are enough relativistic SNe to explain the target objects associated
with the $\sim 60$ detected UHECRs, we require the rate of such transients. SNe Ibc occur at a rate\textsuperscript{[20,21]} of $\sim 1.7 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$. The fraction of Ibc which have relativistic outflows is still a somewhat uncertain number, estimated\textsuperscript{[21]} to be around $\sim 0.7\%$. Hence the rate of SN 2009bb-like mildly relativistic SNe is $\sim 1.2 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$, which is comparable to the rate of mildly relativistic SNe detected as sub-energetic GRBs or XRFs of $\sim 2.3 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$. This gives us $\sim 4$ (or 0.5) such objects within a distance of 200 (or 100) Mpc every year. Since SN 2009bb is still a unique object, only a systematic radio survey can establish their cosmic rate and statistical properties (see Suppl. Info). However, cosmic rays of different energies have different travel delays due to deflections by magnetic fields. For a conservative mean delay\textsuperscript{[7]} of $\langle \tau_{\text{delay}} \rangle \approx 10^5 \text{ yrs}$ we may receive cosmic rays from any of 4 (or 0.5) $\times 10^5$ possible sources at any point in time. Given the situation, in which a direct association between a detected UHECR and its source is unlikely\textsuperscript{[22]}, the literature in the subject has focused on the constraints\textsuperscript{[14,23]} placed on plausible sources. We have shown in our work that indeed this new class of objects satisfy all these constraints.

Nuclei are also subject to photo-disintegration by interaction with Lorentz boosted CMB photons and can travel up to a distance of $\sim 100 \text{ Mpc}$ (see Suppl. Info), smaller than but comparable to the GZK horizon. So, the local rate of mildly relativistic SNe is high enough to provide enough ($\gg 60$) independent sources of cosmic rays with energies above the GZK limit. The value of $\langle \tau_{\text{delay}} \rangle$ also implies that it will not be possible to detect UHECRs from a known relativistic SN, such as SN 2009bb, within human timescales. However, high energy neutrinos from photo-hadron interaction at the acceleration site may be a prime focus of future attempts at detecting these sources with neutrino observatories like the IceCube (see Suppl. Info).
The required energy injection rate per logarithmic interval in UHECRs is \( \Gamma_{\text{inj}} = (0.7 - 20) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \). Given the volumetric rate of mildly relativistic SNe in the local universe, if all the energy injected into UHECRs is provided by local mildly relativistic SNe, then each of them has to put in around \( E_{\text{SN}} = (0.3 - 9) \times 10^{51} \) ergs of energy, which is comparable to the kinetic energy in even a normal SN and can easily be supplied by a collapsar model. The minimum energy in the relativistic outflow of SN 2009bb, required to explain the radio emission alone, was found to be \( E_{\text{eq}} \approx 10^{49} \) ergs. Moreover, the mildly relativistic outflow of SN 2009bb has been undergoing almost free expansion for \( \sim 1 \) year. Our measurements of this expansion allows us to show (see Suppl. Info) that this relativistic outflow, without a detected GRB, is significantly baryon loaded and the energy carried by the relativistic baryons is \( E_{\text{Baryons}} \gtrsim 3.3 \times 10^{51} \) ergs.

If a relativistic outflow carries similar energies in protons, electrons and magnetic fields, the radiative cooling of the electrons will lead to an X-ray transient. In our model, the acceleration occurs in the forward shock produced by the engine driven relativistic ejecta, characterized by a single bulk Lorentz factor. Protons and nuclei in such a collisionless shock show a flat spectrum of UHECRs, consistent with the extragalactic component of the cosmic ray spectrum. Our radio observations of SN 2009bb constrain the energy carried by the radiating electrons and the energy of the relativistic baryons powering the almost free expansion for \( \sim 1 \) year until now (see Suppl. Info). These observations indicate a spectral index of \( \approx 1 \) in the optically thin part of the radio spectrum. This implies a power law distribution of relativistic electrons, with an energy index between \( p \approx (2 - 3) \), depending upon the relative positions of the breaks in its spectrum.
The observed rate of relativistic SNe in the local universe is consistent with the required rate of X-Ray\textsuperscript{23} and radio (see Suppl. Info) transients accompanying the UHECR accelerators.

It has been found that the arrival direction of the Auger events correlate well with the locations of nearby AGNs\textsuperscript{1}, this suggests that they come from either AGNs or objects with similar spatial distribution as AGNs. Note that the HiRes events\textsuperscript{28} do not show such a correlation. Furthermore, UHECRs correlate well\textsuperscript{29} with the locations of neutral hydrogen (HI) rich galaxies from the HI Parkes All Sky Survey (HIPASS). Our proposal relies on the acceleration of UHECRs in the mildly relativistic outflow from a subset of SNe Ibc, for which we have determined the size and magnetic field evolution using our radio observations, rather than hypothetical magnetars, with as yet unknown magnetic fields, supposedly formed during sub-energetic GRBs\textsuperscript{29} considered in that work. SNe Ibc occur mostly in gas rich star forming spirals. In particular the 21 cm fluxes of NGC3278 (hosting SN 2009bb) obtained from the HyperLeda database amount to $\sim 1.9 \times 10^9 M_\odot$ of HI. Hence, the observed correlation of UHECR arrival directions with HI selected galaxies\textsuperscript{29} is consistent with our hypothesis.

In this letter we have shown that the newly established subset of nearby SNe Ibc, with engine-driven mildly relativistic outflows detected as sub-energetic GRBs, XRFs or solely via their strong radio emission, can be a source of UHECRs with energies beyond the GZK limit. Our study demonstrates for the first time, a new class of objects, which satisfy the constraints which any proposed accelerator of UHECRs has to satisfy. If SN 2009bb is characteristic of this newly discovered class, a radio survey to detect all such events should be undertaken (see Suppl. Info).
As an example, an all sky radio survey at $\nu = 1$ GHz with a sensitivity of 1 mJy and cadence of 2 months, can detect all such transient sources which can accelerate Neon nuclei to 60 EeV, within 200 Mpc of the Earth ($\sim 4$ per yr). Such a survey will also detect radio emission from ordinary SNe and non-relativistic transients. However, their faster rise to peak will easily separate out the relativistic SNe for multi-frequency follow up.

1. The Pierre Auger Collaboration et al. Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects. *Science* **318**, 938–943 (2007).

2. Linsley, J. Evidence for a Primary Cosmic-Ray Particle with Energy $10^{20}$ eV. *Physical Review Letters* **10**, 146–148 (1963).

3. Bhabha, H. J. & Heitler, W. The Passage of Fast Electrons and the Theory of Cosmic Showers. *Royal Society of London Proceedings Series A* **159**, 432–458 (1937).

4. Greisen, K. End to the Cosmic-Ray Spectrum? *Physical Review Letters* **16**, 748–750 (1966).

5. Zatsepin, G. T. & Kuz’min, V. A. Upper Limit of the Spectrum of Cosmic Rays. *Soviet Journal of Experimental and Theoretical Physics Letters* **4**, 78–80 (1966).

6. Coleman, S. & Glashow, S. L. High-energy tests of Lorentz invariance. *Phys. Rev. D* **59**, 116008 (1999).

7. Farrar, G. R. & Gruzinov, A. Giant AGN Flares and Cosmic Ray Bursts. *ApJ* **693**, 329–332 (2009).
8. Waxman, E. Cosmological Gamma-Ray Bursts and the Highest Energy Cosmic Rays. *Physical Review Letters* **75**, 386–389 (1995).

9. Milgrom, M. & Usov, V. Possible Association of Ultra–High-Energy Cosmic-Ray Events with Strong Gamma-Ray Bursts. *ApJ* **449**, L37–L40 (1995).

10. Jakobsson, P. *et al.* A mean redshift of 2.8 for Swift gamma-ray bursts. *A&A* **447**, 897–903 (2006).

11. Wang, X., Razzaque, S., Mészáros, P. & Dai, Z. High-energy cosmic rays and neutrinos from semirelativistic hypernovae. *Phys. Rev. D* **76**, 083009 (2007).

12. Budnik, R., Katz, B., MacFadyen, A. & Waxman, E. Cosmic Rays from Transrelativistic Supernovae. *ApJ* **673**, 928–933 (2008).

13. Baade, W. & Zwicky, F. Cosmic Rays from Super-novae. *Proceedings of the National Academy of Science* **20**, 259–263 (1934).

14. Hillas, A. M. The Origin of Ultra-High-Energy Cosmic Rays. *ARA&A* **22**, 425–444 (1984).

15. Kulkarni, S. R. *et al.* Radio emission from the unusual supernova 1998bw and its association with the $\gamma$-ray burst of 25 April 1998. *Nature* **395**, 663–669 (1998).

16. Soderberg, A. M. *et al.* Relativistic ejecta from X-ray flash XRF 060218 and the rate of cosmic explosions. *Nature* **442**, 1014–1017 (2006).

17. Soderberg, A. M. *et al.* A relativistic type Ibc supernova without a detected $\gamma$-ray burst. *Nature* **463**, 513–515 (2010).
18. Abraham, J. et al. Measurement of the Depth of Maximum of Extensive Air Showers above $10^{18} \text{eV}$. *Physical Review Letters* **104**, 091101 (2010).

19. Abbasi, R. U. et al. Indications of Proton-Dominated Cosmic-Ray Composition above 1.6 EeV. *Physical Review Letters* **104**, 161101 (2010).

20. Cappellaro, E., Evans, R. & Turatto, M. A new determination of supernova rates and a comparison with indicators for galactic star formation. *A&A* **351**, 459–466 (1999).

21. Dahlen, T. et al. High-Redshift Supernova Rates. *ApJ* **613**, 189–199 (2004).

22. Kashti, T. & Waxman, E. Searching for a correlation between cosmic-ray sources above $10^{19} \text{eV}$ and large scale structure. *Journal of Cosmology and Astro-Particle Physics* **5**, 6–21 (2008).

23. Waxman, E. & Loeb, A. Constraints on the local sources of ultra high-energy cosmic rays. *Journal of Cosmology and Astro-Particle Physics* **8**, 26 (2009).

24. Berezinsky, V. Propagation and origin of ultra high-energy cosmic rays. *Advances in Space Research* **41**, 2071–2078 (2008).

25. MacFadyen, A. I. & Woosley, S. E. Collapsars: Gamma-Ray Bursts and Explosions in “Failed Supernovae”. *ApJ* **524**, 262–289 (1999).

26. Blandford, R. & Eichler, D. Particle acceleration at astrophysical shocks: A theory of cosmic ray origin. *Phys. Rep.* **154**, 1–75 (1987).

27. Piran, T. Gamma-ray bursts and the fireball model. *Phys. Rep.* **314**, 575–667 (1999).
28. The High Resolution Fly’S Eye Collaboration et al. Search for correlations between HiRes stereo events and active galactic nuclei. *Astroparticle Physics* **30**, 175–179 (2008).

29. Ghisellini, G., Ghirlanda, G., Tavecchio, F., Fraternali, F. & Pareschi, G. Ultra-high energy cosmic rays, spiral galaxies and magnetars. *MNRAS* **390**, L88–L92 (2008).

30. Waxman, E. Extra Galactic Sources of High Energy Neutrinos. *Physica Scripta Volume T* **121**, 147–152 (2005).

31. Chevalier, R. A. Synchrotron Self-Absorption in Radio Supernovae. *ApJ* **499**, 810–819 (1998).

32. Chandra, P., Ray, A. & Bhatnagar, S. The Late-Time Radio Emission from SN 1993J at Meter Wavelengths. *ApJ* **612**, 974–987 (2004).

33. Hooper, D., Sarkar, S. & Taylor, A. M. The intergalactic propagation of ultra-high energy cosmic ray nuclei. *Astroparticle Physics* **27**, 199–212 (2007).

34. Hague, J. D. & The Pierre Auger Collaboration. Correlation of the Highest Energy Cosmic Rays with Nearby Extragalactic Objects in Pierre Auger Observatory Data. In *Proceedings of the 31st ICRC, LODZ*, vol. 143, 1 (2009).

35. Abbasi, R. U. et al. First Observation of the Greisen-Zatsepin-Kuzmin Suppression. *Physical Review Letters* **100**, 101101 (2008).

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Figure 1: Hillas Diagram: Mildly relativistic sources ($\beta/\Gamma \sim 1$) must lie above the solid red line, to be able to accelerate Iron nuclei to 60 EeV by diffusive shock acceleration\textsuperscript{[26]}, according to $E_Z \lesssim \beta e Z B R / \Gamma$\textsuperscript{[26]}. In comparison, non-relativistic SNe ($\beta/\Gamma \sim 0.05$) must lie above the dashed blue line to reach the same energies. Radius and magnetic field of SN 2009bb (red crosses, at 5 epochs, determined here from radio observations with VLA and GMRT assuming equipartition) and XRF 060218 (magenta ball) lie above the solid red line. Other\textsuperscript{[31]} radio SNe with SSA fits are plotted as blue balls. Only the SN 1993J magnetic fields are obtained without assuming equipartition\textsuperscript{[32]}. Note that all of the observed non-relativistic SNe (blue balls) including SN 1993J (green balls) lie below the dashed blue line and are unable to produce UHECRs unlike the mildly relativistic SN 2009bb and XRF 060218 which lie above the red line. Sizes of crosses are twice the standard errors, sizes of balls are bigger than the standard errors.
Supplementary Information

Radius-Magnetic Field Evolution: With a robust set of assumptions for the electron energy distribution and magnetic fields\(^{31}\), the radius of the forward shock wave at the time of the synchrotron self-absorption peak can be written as\(^{31}\)

\[
R \simeq 4.0 \times 10^{14} \alpha^{-1/19} \left( \frac{f}{0.5} \right)^{-1/19} \left( \frac{F_{op}}{\text{mJy}} \right)^{9/19} \left( \frac{D}{\text{Mpc}} \right)^{18/19} \left( \frac{\nu}{5 \text{ GHz}} \right)^{-1} \text{cm},
\]

where \(\alpha = \epsilon_e/\epsilon_B\) is the ratio of relativistic electron energy density to magnetic energy density, \(f\) is the fraction of the spherical volume occupied by the radio emitting region, \(F_{op}\) is the observed peak flux, and \(D\) is the distance. Using the same variables, the magnetic field is given by

\[
B \simeq 1.1 \alpha^{-4/19} \left( \frac{f}{0.5} \right)^{-4/19} \left( \frac{F_{op}}{\text{mJy}} \right)^{-2/19} \left( \frac{D}{\text{Mpc}} \right)^{-4/19} \left( \frac{\nu}{5 \text{ GHz}} \right) \text{G}.
\]

The radio spectrum of SN 2009bb at all epochs from discovery paper (Fig. 2 of ref\(^{17}\)) and this work, as obtained from observations using the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT), is well fit by the SSA model, giving us a rare opportunity to explicitly measure the size and magnetic field of a candidate accelerator, instead of indirect arguments connecting luminosity with the Poynting flux.

Equi-partition: As already stated, non-relativistic SN have sizes and magnetic fields which are characteristically inadequate to accelerate charged particles to the highest energies. However the inferred magnetic fields are based mostly on equi-partition arguments. The only young SN where
the magnetic field was determined independent of the equipartition assumption was SN 1993J (this was however a type IIb SN, unlike the type Ibc’s being considered here). However, the magnetic field determined using a synchrotron cooling break was found to be $\sim 9$ times larger than the equipartition value. This only helps by placing the SN 1993J much closer to the Hillas line (but still below it) due to enhanced $BR$ product. The energy requirement to explain the radio emission has a minimum at the assumed equipartition factor of $\alpha = 1$. In the absence of an independent measurement of the magnetic field, as in SN 1993J, Very Long Base Interferometry of the outflow can constrain the deviation from equipartition using Equation (1). However, because of the very slow dependence of the radius on $\alpha$, even for a slight deviation from equipartition in SN 2009bb, it can easily inflate the energy in the radio emitting plasma. In the case of SN 2009bb, even a more conservative assumption of equipartition, aided by its demonstrated mildly relativistic outflow enables it to be in a class of SN which can readily account for possible accelerators of UHECRs.

**Energy Budget in SN 2009bb:** The radius evolution of SN 2009bb, as inferred from our radio observations (Table 1), is consistent with almost free expansion. This can only be explained if the mass of the relativistic ejecta is still much larger than the swept up mass. The computed Lorentz factor has barely decreased from 1.32 to 1.23 between days 20 and 222 post explosion. Using the model for collisional slowdown of the ejecta, we modify Equation 115 of Ref\textsuperscript{27}, to give

$$\frac{m(R_2)}{m(R_1) + M_0} = -(\gamma_1 - 1)^{1/2}(\gamma_1 + 1)^{1/2} \int_{\gamma_1}^{\gamma_2} (\gamma' - 1)^{-3/2}(\gamma' + 1)^{-3/2} d\gamma',$$

where $m(R_1)$ and $m(R_2)$ are the swept up mass at the two respective epochs. We have neglected radiative losses, as they are unlikely to be important for protons in the time range of interest.
Moreover radiative losses would only help increase our initial energy budget. Performing the integral numerically from $\gamma_1$ to $\gamma_2$, the Lorentz factors at the two epochs and substituting for $m(R)$ using the progenitor mass loss rate$^{17}$, we solve for the ejecta mass to get $M_0 \simeq 1.4 \times 10^{-3} M_\odot$. Most of the mass in the relativistic outflow is due to baryons. The energy associated with these relativistic protons and nuclei is found to be $E_{Baryons} \gtrsim 3.3 \times 10^{51}$ ergs. Compared to this blast-wave calorimetric value, the equipartition energy in the electrons and magnetic fields determined from SSA fit to the radio spectrum was was reported$^{17}$ to be $E_{eq} \simeq 1.3 \times 10^{49}$ ergs. This gives the electrons only a fraction $\epsilon \equiv \epsilon_e \epsilon_p \simeq 0.002$ of the energy in the relativistic baryons. If $E_{Baryons}$ is distributed equally over 10 decades in energy, it can account for $\sim 0.33 \times 10^{51}$ ergs of energy in UHECRs per logarithmic energy interval. Given the rate of relativistic SNe in the local universe, this is consistent with the volumetric energy injection rate for UHECRs.

**Rate of X-Ray transients:** The number density of X-Ray flares associated with UHECR accelerators has been prescribed$^{23}$ assuming that, the accelerated electrons have the same initial power-law index for their energy spectrum as the protons, and that they lose all their energy radiatively. Using the values of the physical parameters, motivated by SN2009bb, the number density of active X-ray flares with a luminosity $\gtrsim \nu L_\nu$ is then given by recasting Equation 2.5 of Ref$^{23}$ to give

$$\dot{n} \Delta t \simeq 3 \times 10^{-7} \left( \frac{\epsilon}{0.002} \right) \left( \frac{\Gamma_{inj}}{10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1}} \right) \left( \frac{\nu L_\nu}{10^{40} \text{ erg s}^{-1}} \right)^{-1} \text{Mpc}^{-3}. \quad (4)$$

SN 2009bb was observed with the Chandra ACIS-S instrument, at age 31 days, in the energy range 0.3-10 keV. It had an X-ray luminosity$^{17}$ of $L_X = 4.4 \pm 0.9 \times 10^{39}$ erg s$^{-1}$. This luminosity and the rate of the relativistic SNe, considered in this work, together can account for the UHECR flux, if they remain active accelerators for $\Delta t$ of order $\sim 1$ year. This is consistent with our radio
observations, which confirm that the $BR$ product remains above the threshold throughout the $\sim 1$ year of observation (See Table 1).

**Rate of radio transients:** The required rate of radio transients, which can supply the observed $\Gamma_{inj}$ is given by $\dot{n} = \Gamma_{inj}/E_{SN}$. Assuming that the electrons and magnetic fields together have a fraction $\epsilon$ of the energy of the relativistic protons (which is assumed to be divided equally into $\sim 10$ logarithmic bins, assuming $p \approx 2$ for the protons), we compute the minimum required rate of such transients with peak radio luminosity $L_{op}$, which remain mildly relativistic at least until the SSA peak frequency drops to $\nu$, as

$$\dot{n} \simeq 3 \times 10^{-7} \left(\frac{\Gamma_{inj}}{10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1}}\right) \left(\frac{\epsilon}{0.002}\right) \left(\frac{L_{op}}{10^{29} \text{ ergs/sec/Hz}}\right)^{-23/19} \times \left(\frac{\nu}{0.5 \text{ GHz}}\right) \left(\frac{2}{\eta^{11}(1 + \eta^{-17})}\right) \text{ Mpc}^{-3} \text{yr}^{-1}. \tag{5}$$

Here $\eta = \theta_{obs}/\theta_{eq}$ is the ratio between the observed angular radius and the one obtained by assuming equipartition between electrons and magnetic fields\textsuperscript{15}. This criterion works for an electron energy index between $p = 2$ (with the cooling break shifted below the SSA peak) to $p = 3$ (with the cooling break above the observed radio frequencies), so as to explain the observed spectral index of $\approx 1$ in the optically thin part of the radio spectrum. Here, Equation (5) is the radio analogue of Equation 2.5 of Ref\textsuperscript{23} (which is for X-ray transients). Hence, the observed rate of relativistic SNe can easily explain the energy injection rate.

**Survey Parameters:** The prototypical mildly relativistic SN 2009bb has been discovered\textsuperscript{17} in a dedicated radio follow-up of type Ibc SNe. To firmly establish the rate of occurrence of such relativistic SNe in the local universe, a systematic large area radio survey is required. Here we
estimate the maximum energy to which relativistic SNe can accelerate nuclei of charge $Ze$ from

$$E_Z \lesssim ZeBR \text{ as } \frac{\beta}{\Gamma} \sim 1 \text{ for mildly relativistic outflows.}$$

Substituting the expressions for the radius (Equation 1) and magnetic field (Equation 2) we have

$$E_z \simeq 6.4 \times Z \alpha^{-5/19} \left( \frac{f}{0.5} \right)^{-5/19} \left( \frac{F_{op}}{\text{mJy}} \right)^{7/19} \left( \frac{D}{200 \text{ Mpc}} \right)^{14/19} \text{ EeV}, \quad (6)$$

which is independent of the observed SSA peak frequency $\nu$. Further, assuming that $R \sim \Gamma \beta ct$ and we get the time to reach the synchrotron peak is

$$t_{peak} \simeq 23 \times \left( \frac{1}{\Gamma \beta} \right) \left( \frac{F_{op}}{\text{mJy}} \right)^{9/19} \left( \frac{D}{200 \text{ Mpc}} \right)^{18/19} \left( \frac{\nu_{\text{survey}}}{5 \text{ GHz}} \right)^{-1} \text{ days.} \quad (7)$$

Hence relativistic SNe will have faster rise times than non-relativist radio transients, allowing them to be easily identified for multi-frequency follow up with targeted observations. These considerations determine the cadence and sensitivity of the proposed radio survey as mentioned in the main text.

**Propagation and Survival of Nuclei:** In the particle acceleration scheme outlined in this work, the highest energy particles are likely to be nuclei rather than protons. This is borne out by the latest Auger data which favors an increasing average rest mass of primary cosmic ray particles at the highest energies.[19] As for protons, the flux of ultra high energy nuclei are also suppressed over cosmological distances via interaction with background radiations. CMB photons appear has high energy $\gamma$-rays when Lorentz boosted into the rest frames of ultra high energy protons or nuclei. Protons above $\sim 60 \text{ EeV}$, interact with CMB photons via the $\Delta$ resonance ($\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow p + \pi^0$ or $\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+$) and give rise to the GZK limit.[19] Similarly ultra high energy nuclei can be photo-disintegrated by Lorentz boosted cosmic infrared background
photons interacting mainly via Giant Dipole Resonances. The distance over which this effect suppresses the flux of ultra high energy nuclei is a function of the nuclear species and its energy. Detailed calculations\textsuperscript{33} using updated photo-disintegration cross-sections indicate that the energy loss lengths for 100 EeV intermediate mass nuclei such as Ne, Si and Ca are around $\sim 100$ Mpc.

As discussed in the main text, relativistic supernovae can provide enough number of UHECR sources within this distance, to be consistent with observation of independent arrival directions for the UHECRs.

**High Energy Particle Detection:** UHECRs from the same source but with different energies will travel by different trajectories due to deflections by magnetic fields\textsuperscript{8}. For current estimates of the average intergalactic magnetic field, the mean delay in the arrival time of UHECRs, when compared to photons is found\textsuperscript{21} $\langle \tau_{\text{delay}} \rangle \approx 10^5$ yrs. Hence, barring chance coincidences, detected cosmic rays will not point back to known astrophysical transients\textsuperscript{23}. However, detected UHECRs should point back (within the errors from deflection) to the host galaxies. As type Ibc supernovae occur mostly in HI rich spirals, the detected correlation with HI selected galaxies\textsuperscript{29} is consistent with our hypothesis. Similarly direct detection of UHECRs from say SN 2009bb is unlikely. However photo-hadron interaction between accelerated protons or nuclei and optical photons from the underlying SN may produce pions which then decay ($\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu$ or $\pi^- \rightarrow e^- + \nu_e + \nu_\mu + \nu_\mu$) to give high energy neutrinos. Neutrinos have no electric charge, hence they are not deflected by the intergalactic magnetic fields. They have very low rest masses compared to their very high energies and will travel at nearly the speed of light. These neutrinos will not be coincident with the initial core collapse as the number of accelerated charged particles which are the source of...
neutrinos grows with time. The peak of the high energy neutrino flux will approximately coincide with the peak in bolometric luminosity (at around a week after explosion for SN 2009bb) as the most number of photons will be available for interaction with the accelerated hadrons. Hence, high energy neutrinos may by found in future by neutrino detectors like the IceCube, in directional and rough temporal coincidence with relativistic supernovae.

**Alternative Sources: AGNs** The arrival directions of 20 of the 27 highest energy cosmic rays detected by The Pierre Auger Cosmic Ray Observatory, based in the southern hemisphere, were found to be within 3.2° of AGNs within 75 Mpc\(^1\). This leads The Pierre AUGER Collaboration to conclude that they possibly come from either AGNs or objects with a similar spatial distribution. Yet no significant correlation is seen for the UHECRs detected by the HiRes stereo events and AGNs\(^2\) in the northern hemisphere. Even, the degree of correlation in the Auger events now appears to be weaker\(^3\) than what was seen by the earlier data. It has been suggested that these cosmic rays may be accelerated in the relativistic outflows from powerful AGNs. However, particle acceleration to such high energies (\(E = 10^{20} \times E_{20} \text{ eV}\)) in turbulent shocks with bulk Lorentz factor \(\Gamma\) would be accompanied by a minimum power lost to the Poynting flux\(^7, 8\) of

\[
L \gtrsim 10^{45} \Gamma^2 E_{20}^2 \text{ erg s}^{-1}. \quad (8)
\]

Continuous sources of such luminosity would be easily detected within 200 Mpc and their absence rules out continuous AGN jets as the sources of a significant fraction of the UHECRs. Instead, a new class of very intense, short-duration AGN flares were proposed as possible sources\(^7\). However, no such flare has been observed until now.
**Alternative Sources: Classical GRBs** Classical GRBs have also been suggested as one of the most promising candidates for producing the highest energy cosmic rays, where protons would be accelerated by the Fermi mechanism in an ultra-relativistic outflow. For an astrophysical source driving a magnetized plasma outflow with a characteristic magnetic field $B$, at a velocity $v = \beta c$ (bulk Lorentz factor $\Gamma$), out to a radius $R$, the maximum energy to which a proton of charge $e$ can be accelerated by diffusive shock acceleration is given by

$$E_p \lesssim \left( \frac{\beta eBR}{\Gamma} \right). \quad (9)$$

GRBs satisfy the minimum luminosity criterion (Equation 8) derived from the Poynting flux carried out by this outflow. However, most classical GRBs are found at cosmological distances with a mean redshift of 2.8 for those discovered by the Swift, hence most GRBs cannot contribute to the flux of cosmic rays above the GZK limit. If classical GRBs are indeed the source of the observed flux of the UHECRs, then the observed local rate of GRBs implies that each GRB is required to provide of orders of magnitude more energy, than what is available from a collapsar scenario.

**Alternative Sources: Hypernovae** Hypernovae with a continuous ejecta profile (with $E_k \propto (\Gamma \beta)^{−2}$) between the non-relativistic and relativistic material have been suggested as sources of UHECRs. In such a model each shell of different velocity accelerates particles up to a different energy and adds up to a final power law energy spectrum with slope of $\approx −1$ for $E^2 dN/dE$, which was claimed fits the observed UHECR spectra. However, the observed spectrum of UHECRs is suppressed beyond the GZK limit via interaction with the CMB photons and has to be corrected for the propagation effects to get the original injection spectrum. Hence Hypernovae with continuous ejecta profiles cannot reproduce flat injection spectrum of UHECRs which requires equal en-
ergies in each logarithmic energy bin. Galactic trans-relativistic SNe have also been considered\textsuperscript{12}. However, this requires at least one trans-relativistic SNe per Galactic confinement time for the cosmic ray energies being considered. For particles with energies beyond the GZK limit, the magnetic rigidities are so high, that their confinement time is comparable to the light crossing time\textsuperscript{3} of $10^4$ years\textsuperscript{12}. There are around $\sim 100$ SNe in this time, of which say upto 10 are SNe Ibc. Given the fraction of Ibc SNe which have relativistic outflows\textsuperscript{17}, there are $\sim 0.07$ trans-relativistic SNe in this time. Clearly, if these events are galactic, the rate of such objects is too low and a galactic origin would neither explain the independent arrival directions\textsuperscript{11} nor the GZK suppression of the spectra\textsuperscript{15}. 

ix
| Observation Date (2009) | Age (Days) | $F_{\nu}$ (mJy) | $\nu$ (GHz) | $R (10^{15} \text{cm})$ | $B$ (mG) | $E_p$ (EeV) | $E_{Fe}$ (EeV) |
|-------------------------|-------------|----------------|-------------|-------------------------|---------|------------|-------------|
| 05 April                | 17          | $>24.53$       | ...         | ...                     | ...    | $>6.4$     | $>166$      |
| 08 April                | 20          | 17.87±0.95     | 7.63±0.63   | 34±3                   | 570±48 | 5.7±0.1   | 148±3       |
| 10 May                  | 52          | 13.69±0.79     | 3.33±0.17   | 68±4                   | 256±14 | 5.2±0.1   | 134±3       |
| 08 June                 | 81          | 10.82±0.34     | 1.93±0.07   | 106±4                  | 152±5  | 4.7±0.1   | 123±1       |
| 10 August               | 144         | 9.82±0.65      | 0.90±0.06   | 216±16                 | 72±5   | 4.6±0.1   | 119±3       |
| 27 October              | 222         | 8.35±0.59      | 0.53±0.04   | 337±28                 | 43±3   | 4.3±0.1   | 112±3       |

Table 1: Radius-Magnetic Field Evolution: Peak fluxes and peak frequencies of SN 2009bb are determined from VLA and GMRT observations by fitting a SSA spectrum to the observed fluxes. Fluxes until August can be found in Supplementary Info. of Ref\(^\text{[17]}\). The fluxes around 27 October 2009 are from new VLA (1.6±0.1 mJy at 8.46 GHz and 3.7±0.2 mJy at 4.86 GHz) and GMRT observations (4.4±0.3 mJy at 1.28 GHz, 8.7±0.7 at 617 MHz and 5.8±0.7 mJy at 332 MHz). Radius and magnetic fields are determined using Equations \((1, 2)\). Maximum energies to which protons and Iron nuclei can be accelerated are computed using Equation \((6)\), ± are standard errors. Note that both $E_p$ and $E_{Fe}$ decrease slowly by only $\sim 24\%$ in a span of $\sim 200$ days.