Revealing ultra-high-energy cosmic ray acceleration with multi-messenger observations of the nearby GRB 980425/SN 1998bw

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Abstract. The origin of ultra-high energy cosmic rays (UHECRs) is one of the most mystifying issues in astroparticle physics. It has been suggested that gamma-ray bursts (GRBs) are excellent acceleration sites for cosmic rays. The propagation of UHECRs from the GRB host galaxy to the Earth should generate delayed secondary photons and neutrinos. Here we present a dedicated search for delayed UHECR and neutrino emission centered around the position of nearby GRB 980425/SN 1998bw. Located at a distance of 36.9 Mpc, GRB 980425/SN 1998bw is well within the Greisen-Zatsepin-Kuzmin (GZK) distance horizon. We find no evidence for UHECR or neutrino clustering around the GRB 980425/SN 1998bw position between 2004 and 2020. Under ideal propagation conditions, we propose that it might be possible to detect an excess from delayed UHECRs around GRB 980425/SN 1998bw within the next 100 years if the intergalactic magnetic field (IGMF) strength is $B \leq 3 \times 10^{-13}$ G.

Keywords: cosmic ray theory, extragalactic magnetic fields, particle acceleration, ultra high energy photons and neutrinos

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1 Introduction

Gamma-ray bursts (GRBs) have long been considered excellent acceleration sites of UHECRs [1, 2]. Secondary neutrinos and photons should also form as UHECRs produced by the GRB interact with the photon background along the line of sight [3–5]. Unfortunately, without further experimental evidence, it is not yet possible to exclude alternative UHECR sources [6]. Therefore, we need to start thinking about actual signals that might reveal the UHECR source in multidecadal time-scales.

In our view, the minimum features that seem necessary for potential UHECR signals in our lifetime are as follows:

- Energetics: enter your favorite model here [6, 7]. There is an enormous amount of UHECR theoretical models that can satisfy the Hillas condition [7]. However, for each UHECR model, one can find one supporting publication and at least three publications stating that a different model is better. All things being equal, on paper most theoretical models appear to meet the stringent conditions required for UHECR energetics.

- Distance/Distribution: this is an actual physical limitation that cannot be easily altered. For UHECR energies above 20EeV, any successful UHECR source population must lie within 200Mpc (or even closer) in order to satisfy the Greisen-Zatsepin-Kuzmin (GZK) distance horizon requirements [8, 9].

- Time Delay: this condition is somewhat tied to distance, but it is also dictated by the strength and distribution of magnetic fields [10]. While there is no agreement on the actual UHECR accelerator, there is broad consensus that the arrival time of UHECRs will be delayed by tens to thousands of years [11]. A near real-time signature would require a relatively weak IGMF.

There is one GRB source that appears to meet all the three conditions for a potential UHECR signal over a lifetime, namely GRB 980425/SN 1998bw [12–15]. GRB980425/SN 1998bw was the first event to directly link core-collapse supernovae (SNe) and long-duration GRBs [14]. We know exactly when it triggered the UHECR acceleration [12]. The energetics for UHECR acceleration in GRB 980425/SN 1998bw can be achieved either within the GRB itself [2] or through the emerging SN 1998bw supernova [16–18]. Another excellent feature of GRB 980425/SN 1998bw is that a stellar explosion can readily provide heavy nuclei for UHECR acceleration. At a distance of 36.9Mpc, GRB 980425/SN 1998bw continues to hold the record for the smallest redshift of all known GRBs (z = 0.0085) and it lies well within the GZK distance horizon [8, 9]. In terms of time delay, we are approaching nearly 25 years since the discovery of GRB 980425/SN 1998bw.
The other key component needed for an actual signal detection is the availability of multi-messenger facilities. Fortunately, these already exist as a confluence of multi-messenger observatories has been operating over the past few years. UHECR data has been collected in the southern hemisphere by the Pierre Auger Observatory (PAO) since 2004 [19] and by the Telescope Array (TA) experiment in the northern hemisphere since 2008 [20]. Neutrinos have been collected by the IceCube Neutrino Observatory partially since 2008 and with the full 86-string design starting in May 2011 [21]. The Advanced LIGO and Advanced Virgo gravitational wave detectors have been collecting data since 2015 and 2017 respectively [22]. The Fermi Gamma-Ray Space Telescope has been surveying the MeV–TeV sky since 2008 [23]. With all these facilities working together, we are truly living in the multi-messenger era.

Here, we present a search for UHECRs and neutrinos centered around the position of GRB 980425/SN 1998bw. The paper is structured as follows: section 2 describes the UHECR search, section 3 describes the neutrino search and section 4 presents discussion and conclusions.

2 The Pierre Auger Observatory and the UHECR sample

The Pierre Auger Observatory [19] is located near Malargüe in Argentina, at a longitude of $69.4^\circ$ and a latitude of $-35.2^\circ$. Its Surface Detector (SD) array consists of 1600 water-Cherenkov stations spread over an area of 3000 km$^2$ to observe extensive air showers generated by UHECRs. With a duty cycle of nearly 100%, PAO can capture muons, electrons and photons reaching ground level.

The data used in this paper corresponds to more than 2600 UHECR arrival directions above 32EeV recorded with the SD array between 2004 January 1 to 2020 December 31 [24]. For our analysis, we determined the angular separation between UHECR arrival directions and the position of GRB 980425/SN 1998bw. For the GRB 980425/SN 1998bw position, we adopt reported measurements [25]. In figure 1 we show PAO UHECRs within a $5^\circ$ radius of the GRB 980425/SN 1998bw position. Out of all arrival directions, the nearest event to GRB 980425/SN 1998bw is a 32.9EeV UHECR located at (RA, dec.) = (296.3, $-54.6^\circ$) detected on 2010 January 27 with a deviation of $2.3^\circ$ from the position of GRB 980425/SN 1998bw.

Following [26, 27], we searched for an UHECR excess using the Li and Ma method [28] defining the on-region using a 20-degree circular region around GRB 980425/SN 1998bw and the remainder of the 3.47 steradians covered by PAO as the off-region from which the background rate could be estimated. The 20-degree search region yields a 3.3$\sigma$ significance centered at (RA, dec.) = (293.76, $-52.85^\circ$). In the future, we plan to perform a more sensitive search looking for groups of directionally-aligned events or multiplets [29, 30]. To put the size of the analysis region in context, we remind the reader that the expected deflection angle for nuclei of charge $Z$ propagating a distance $D$ through an magnetic field $B$ and a correlation length $l_c$ is given by $\theta_s \simeq 0.8^\circ Z (D/10 \text{ Mpc})^{1/2} (l_c/1 \text{ Mpc})^{1/2} (B/10^{-9} \text{ G}) (E/10^{20} \text{ eV})^{-1}$ [31]. As a result, our UHECR excess search is most sensitive to protons and relatively light nuclei.

3 IceCube neutrinos

The IceCube Observatory is a 1 km$^3$ deep Cherenkov detector located in glacial ice near the geographic South Pole [32]. It is optimized to detect neutrinos above an energy threshold of $\sim 100$ GeV. It consists of 5160 photomultiplier tubes (PMTs) along 86 strings. IceCube
identifies neutrino interactions by tracking Cherenkov light emitted by relativistic charged secondary particles traveling through ice. We used 10 years of publicly released all-sky data recorded between 2008 April 6 and 2018 July 8 to search for neutrinos around the explosion site of GRB 980425/SN 1998bw \[21\]. The data includes events in the TeV–PeV range from partial configurations (40, 59, 79 strings) as well as the full 86-string configuration. If pion production from UHECRs accelerated by GRBs takes place during the trajectory towards Earth there should be a measurable neutrino signal in the TeV–PeV range \[33, 34\].

In total, we collected 1134450 IceCube track-like events (see table 1). We restricted our search to events within 5° of the GRB980425/SN 1998bw position, motivated by the recent IceCube detection of the nearby active galaxy NGC 1068 \[35\]. This narrows the total to 1657 events. Specifically, we analysed the distribution of the parameter $\theta^2$, the squared angular distance between individual neutrinos and the location of GRB980425/SN 1998bw. This is shown in figure 2. Adopting a 1-degree signal region and a 5-degree background region yields a significance of 0.35σ \[28\]. Looking at the distribution it appears clearly dominated by background events from cosmic rays interacting with the atmosphere and producing atmospheric muons and neutrinos. Unfiltered, the atmospheric background may be too strong to detect the underlying signal from nearby UHECR sources.
Table 1. IceCube Data Set.

| Sample | Livetime (days) | Events (Number) |
|--------|----------------|-----------------|
| IC40   | 376.4          | 36900           |
| IC59   | 352.6          | 107011          |
| IC79   | 316.0          | 93133           |
| IC86-I | 332.9          | 136244          |
| IC86-II| 332.0          | 112858          |
| IC86-III| 362.9         | 122541          |
| IC86-IV| 370.7          | 127045          |
| IC86-V | 365.4          | 129311          |
| IC86-VI| 357.3          | 123657          |
| IC86-VII| 410.6         | 145750          |

To further guide our search, we used a refined subset of high-energy neutrinos [36]. The sample includes 70 well reconstructed and off the Galactic plane IceCube high-energy neutrinos recorded between 2009 August 13 and 2019 July 30 [36]. The sample selected the best events from IceCube’s diffuse astrophysical muon-neutrino search (DIF), high-energy starting tracks (HES) and alerts released through IceCube’s realtime program (AHES, EHE). Restricting the search to the Giommi et al. sample, we found that the closest match corresponds to IceCube-190124A located 22.9° from the GRB 980425/SN 1998bw explosion site. As discussed previously in section 2, angular deflections restrict the neutrino search to UHECRs dominated by light nuclei.

4 Discussion and conclusions

We have outlined three necessary conditions for finding a potential UHECR signal in multi-decadal time-scales. We have further identified GRB 980425/SN 1998bw as the best available event to probe UHECR acceleration in nearby GRBs using multi-messenger facilities. Unfortunately, we find no obvious clustering of UHECRs or neutrinos within 5° of the GRB 980425/SN 1998bw explosion site.

Assuming that a UHECR with energy $E_p$ and charge $Ze$ from GRB 980425/SN 1998bw travels a distance $d$ to reach us, we can use the time delay $\tau$ due to magnetic deflections to constrain the IGMF strength $B$ as a function of distance $d$ and the Larmor radius $r_L$. The expression for time delay of arrivals gives [10]

$$\tau \simeq \frac{d^3}{24c r_L^2} \simeq \left(0.5 \frac{d_{3.5}^3 Z^2 B_{-12}^2}{E_{60}^2}\right) \text{ days},$$

where $E_{60} = \frac{E_p}{60 \text{EeV}}$, $d_{3.5} = \frac{d}{3.5 \text{ Mpc}}$, $B_{-12} = \frac{B}{10^{-12} \text{G}}$ and electric charge $Z$.

At present, we have only studied the first 25 years of multi-messenger data since the GRB 980425/SN 1998bw explosion took place. The delay of UHECR arrivals could last tens to millions of years [11]. If magnetic voids are abundant and the IGMF strength is $B \leq 3 \times 10^{-13} \text{G}$, we expect that an excess of UHECRs might start to appear around the location of GRB 980425/SN 1998bw within the next few decades. We note that there might
Figure 2. Binned distribution of the parameter $\Theta^2$, the squared angular distance between the individual neutrinos and the localization of GRB 980425/SN 1998bw. The background from atmospheric events clearly overwhelms any signal from GRB 980425/SN 1998bw.

be additional time delays introduced by the UHECR transit within the GRB host galaxy and our own Galaxy, but we estimate such delays to be of order $\tau_{\text{Galaxy}} \simeq 4B^2\mu G$ days assuming $\sim$ kpc scales and $\mu$G magnetic field within the galaxies [5]. Innovative UHECR and neutrino analyses of this part of the sky are highly encouraged. Delayed secondary photons from the electromagnetic cascades initiated by UHECRs/electron-positron pairs from GRB 980425/SN 1998bw may arrive much earlier than charged UHECRs. We will discuss delayed secondary gamma-ray emission from GRB 980425/SN 1998bw in a separate paper.

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¹http://www.astropy.org.
References

[1] M. Vietri, On the acceleration of ultrahigh-energy cosmic rays in gamma-ray bursts, Astrophys. J. 453 (1995) 883 [astro-ph/9506081] [inSPIRE].

[2] E. Waxman, Cosmological origin for cosmic rays above 10^{19} eV, Astrophys. J. Lett. 452 (1995) L1 [astro-ph/9508037] [inSPIRE].

[3] V.S. Berezinsky and G.T. Zatsepin, Cosmic rays at ultrahigh-energies (neutrino?), Phys. Lett. B 28 (1969) 423 [inSPIRE].

[4] F.W. Stecker, Diffuse Fluxes of Cosmic High-Energy Neutrinos, Astrophys. J. 228 (1979) 919 [inSPIRE].

[5] E. Waxman and P. Coppi, Delayed GeV–TeV photons from gamma-ray bursts producing high-energy cosmic rays, Astrophys. J. Lett. 464 (1996) L75 [astro-ph/9603144] [inSPIRE].

[6] R. Alves Batista et al., Open Questions in Cosmic-Ray Research at Ultrahigh Energies, Front. Astron. Space Sci. 6 (2019) 23 [arXiv:1903.06714] [inSPIRE].

[7] A.M. Hillas, The Origin of Ultrahigh-Energy Cosmic Rays, Ann. Rev. Astron. Astrophys. 22 (1984) 425 [inSPIRE].

[8] K. Greisen, End to the cosmic ray spectrum?, Phys. Rev. Lett. 16 (1966) 748 [inSPIRE].

[9] G.T. Zatsepin and V.A. Kuz’min, Upper limit of the spectrum of cosmic rays, JETP Lett. 4 (1966) 78 [inSPIRE].

[10] C.D. Dermer, S. Razzaque, J.D. Finke and A. Atoyan, Ultrahigh Energy Cosmic Rays from Black Hole Jets of Radio Galaxies, New J. Phys. 11 (2009) 065016 [arXiv:0811.1160] [inSPIRE].

[11] H. Takami and K. Murase, The Role of Structured Magnetic Fields on Constraining Properties of Transient Sources of Ultra-high-energy Cosmic Rays, Astrophys. J. 748 (2012) 9 [arXiv:1110.3245] [inSPIRE].

[12] P. Soffitta et al., GRB 980425, IAUC 6884 (1998) 1.

[13] C. Tinney et al., GRB 980425, IAUC 6896 (1998) 3.

[14] T.J. Galama et al., Discovery of the peculiar supernova 1998bw in the error box of GRB 980425, Nature 395 (1998) 670 [astro-ph/9806175] [inSPIRE].

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

[16] K. Murase, K. Ioka, S. Nagataki and T. Nakamura, High Energy Neutrinos and Cosmic-Rays from Low-Luminosity Gamma-Ray Bursts?, Astrophys. J. Lett. 651 (2006) L5 [astro-ph/0607104] [inSPIRE].

[17] X.-Y. Wang, S. Razzaque, P. Mészáros and Z.-G. Dai, High-energy Cosmic Rays and Neutrinos from Semi-relativistic Hypernovae, Phys. Rev. D 76 (2007) 083009 [arXiv:0705.0027] [inSPIRE].

[18] S. Chakraborty et al., Ultra High Energy Cosmic Ray Acceleration in Engine-driven Relativistic Supernovae, Nature Commun. 2 (2011) 175 [arXiv:1012.0850] [inSPIRE].

[19] AUGER collaboration, Properties and performance of the prototype instrument for the Pierre Auger Observatory, Nucl. Instrum. Meth. A 523 (2004) 50 [inSPIRE].

[20] T. Abu-Zayyad et al., The surface detector array of the Telescope Array experiment, Nucl. Instrum. Meth. A 689 (2012) 87 [arXiv:1201.4964] [inSPIRE].

[21] M.G. Aartsen et al., All-sky Search for Time-integrated Neutrino Emission from Astrophysical Sources with 7 yr of IceCube Data, Astrophys. J. 835 (2017) 151 [arXiv:1609.04981] [inSPIRE].
[22] B.P. Abbott et al., *Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA*, Living Rev. Rel. **23** (2020) 3 [Living Rev. Rel. **19** (2016) 1] [arXiv:1304.0670] [isSPIRE].

[23] W.B. Atwood et al., *The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission*, Astrophys. J. **697** (2009) 1071 [arXiv:0902.1089] [isSPIRE].

[24] Pierre Auger collaboration, *Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory*, Astrophys. J. **935** (2022) 170 [arXiv:2206.13492] [isSPIRE].

[25] J.U. Fynbo et al., *HST/STIS imaging of the host galaxy of GRB 980425/SN 1998bw*, Astrophys. J. Lett. **542** (2000) L89 [astro-ph/0009014] [isSPIRE].

[26] A. Aab et al., *Searches for Large-Scale Anisotropy in the Arrival Directions of Cosmic Rays Detected above Energy of 10^{19} eV at the Pierre Auger Observatory and the Telescope Array*, Astrophys. J. **794** (2014) 172 [arXiv:1409.3128] [isSPIRE].

[27] J. Biteau et al., *Covering the celestial sphere at ultra-high energies: Full-sky cosmic-ray maps beyond the ankle and the flux suppression*, EPJ Web Conf. **210** (2019) 01005 [arXiv:1905.04188] [isSPIRE].

[28] T.-P. Li and Y.-Q. Ma, *Analysis methods for results in gamma-ray astronomy*, Astrophys. J. **272** (1983) 317 [isSPIRE].

[29] G. Golup, D. Harari, S. Mollerach and E. Roulet, *Source position reconstruction and constraints on the galactic magnetic field from ultra-high energy cosmic rays*, Astropart. Phys. **32** (2009) 269 [arXiv:0902.1742] [isSPIRE].

[30] Pierre Auger collaboration, *Search for signatures of magnetically-induced alignment in the arrival directions measured by the Pierre Auger Observatory*, Astropart. Phys. **35** (2012) 354 [arXiv:1111.2472] [isSPIRE].

[31] J. Miralda-Escude and E. Waxman, *Signatures of the origin of high-energy cosmic rays in cosmological gamma-ray bursts*, Astrophys. J. Lett. **462** (1996) L59 [astro-ph/9601012] [isSPIRE].

[32] IceCube collaboration, *First Year Performance of The IceCube Neutrino Telescope*, Astropart. Phys. **26** (2006) 155 [astro-ph/0604450] [isSPIRE].

[33] M. Bustamante, P. Baerwald, K. Murase and W. Winter, *Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts*, Nature Commun. **6** (2015) 6783 [arXiv:1409.2874] [isSPIRE].

[34] R. Abbasi et al., *Searches for Neutrinos from Gamma-Ray Bursts Using the IceCube Neutrino Observatory*, Astrophys. J. **939** (2022) 116 [arXiv:2205.11410] [isSPIRE].

[35] IceCube collaboration, *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, Science **378** (2022) 538 [arXiv:2211.09972] [isSPIRE].

[36] P. Giommi, T. Glauch, P. Padovani, E. Resconi, A. Turcati and Y. Chang, *Dissecting the regions around IceCube high-energy neutrinos: growing evidence for the blazar connection*, Mon. Not. Roy. Astron. Soc. **497** (2020) 865 [arXiv:2001.09355] [isSPIRE].