Time Structure of Ultra-High Energy Cosmic Ray Sources and Consequences for Multi-messenger Signatures

Günter Sigl

II. Institut für theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany

APC * (AstroParticules et Cosmologie), 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France

The latest results on the sky distribution of ultra-high energy cosmic ray sources have consequences for their nature and time structure. If the sources accelerate predominantly nuclei of atomic number $A$ and charge $Z$ and emit continuously, their luminosity in cosmic rays above $\sim 6 \times 10^{19}$ eV can be no more than a fraction of $5 \times 10^{-4} Z^{-2}$ of their total power output. Such sources could produce a diffuse neutrino flux that gives rise to several events per year in neutrino telescopes of km$^3$ size. Continuously emitting sources should be easily visible in photons below $\sim 100$ GeV, but not in TeV $\gamma$-rays which are likely absorbed within the source. For episodic sources that are beamed by a Lorentz factor $\Gamma$, the bursts or flares have to last at least $\sim 0.1 \Gamma^{-4} A^{-2} \text{yr}$. A considerable fraction of the flare luminosity could go into highest energy cosmic rays, in which case the rate of flares per source has to be less than $\sim 5 \times 10^{-3} \Gamma^4 A^2 Z^{-2}$ yr$^{-1}$. Episodic sources should have detectable variability both at GLAST and TeV energies, but neutrino fluxes may be hard to detect.

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I. INTRODUCTION

The sources of ultra-high energy cosmic rays (UHECR) above the “GZK threshold” [1] around $\sim 6 \times 10^{19}$ eV are still unknown. Recently, an important step forward has been made by the Pierre Auger Observatory which has revealed a correlation of the arrival directions of UHECR with the nearby cosmological large scale structure as mapped out by the distribution of active galactic nuclei (AGNs) [2]. At least if UHECR deflection in large scale cosmic magnetic fields is moderate, this requires a certain minimal density of sources within the ”GZK horizon” of about 75 Mpc. At the same time the observed spectrum normalizes the required injection power per volume. Together, these two numbers imply an upper limit on the time averaged UHECR injection power per source. Comparing this with the minimal power that needs to be dissipated in order to produce UHECR up to $\sim 10^{20}$ eV, this allows to constrain the time structure of the UHECR emission, in particular continuously emitting versus episodic sources. This can also have some implications on how the dissipated total power may be distributed between the cosmic ray, photon, and neutrino channels. The latter can be important for a multimesenger study of UHECR sources. In the present paper we attempt to work out these constraints in a largely model-independent way, including their dependence on the type of nuclei that are predominantly accelerated.

The remainder of this paper is structured as follows. In Sect. II we develop general requirements on the individual sources. In Sect. III and IV we consider continuously emitting and episodic sources, respectively. In Sect. V we discuss Centaurus A as a potential UHECR source and we conclude in Sect. VI. We will use the units in which $c = 1$ throughout.

II. REQUIREMENTS ON INDIVIDUAL SOURCES

Accelerating particles of charge $eZ$ to an energy $E_{\text{max}}$ requires an induction $E \gtrsim E_{\text{max}}/(eZ)$. With $Z_0 \sim 100 \Omega$ the vacuum impedance, this requires dissipation of a minimal power of [3, 4]

$$L_{\text{min}} \simeq \frac{E_{\text{max}}^2}{Z_0} \sim 10^{45} Z^{-2} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^2 \text{erg s}^{-1}. \quad (1)$$

We stress that this minimal power can be less by factors of order unity in specific geometrical circumstances, such as magnetic fields connecting accretion disks with jets in AGNs [3]. However, given other, larger uncertainties such as the chemical composition of UHECRs, we can ignore such details in the present work.

The ”Poynting” luminosity Eq. (1) can also be obtained from the expression $L_{\text{min}} \sim \Gamma^2 (BR)^2$ where $\Gamma$ is the beaming factor of the accelerating region and the product of the size $R$ and magnetic field strength $B$ of the acceleration region is given by the ”Hillas criterium” [5], which states that the Larmor radius $r_L = E_{\text{max}} / (\Gamma eZB)$ should be smaller than $R$,

$$\left( \frac{B}{G} \right) \left( \frac{R}{\text{cm}} \right) \gtrsim 3 \times 10^{17} \Gamma^{-1} \left( \frac{E_{\text{max}}}{Z10^{20} \text{eV}} \right). \quad (2)$$

In the following we denote cosmic rays above $6 \times 10^{19}$ eV as ultra-high energy cosmic rays (UHECR) and we take $E_{\text{max}} \approx 10^{20}$ eV as the benchmark for their typical production energy within the sources. Any source producing...
UHECR up to energy \( E_{\text{max}} \) at a given time has to have a total power output of at least the Poynting luminosity Eq. (1). Note that this is comparable to the Eddington luminosity \( L_{\text{Edd}}(M) = 1.3 \times 10^{38} (M/M_\odot) \text{erg s}^{-1} \) of a massive black hole of mass \( M \) in the centers of active galaxies. A considerable part \( L_\gamma \) of that power is presumably electromagnetic and thus emitted in photons.

We now assume that electromagnetic power is produced in the same area of size \( R \) in which UHECR are accelerated. Denoting the characteristic photon energy by \( \varepsilon \), the optical depth for pion production on such photons by accelerated protons with an energy above the photo-pion threshold, \( E \gtrsim 6.8 \times 10^{16} (\varepsilon / \text{eV})^{-1} \text{eV} \), is given by

\[
\tau_{p\gamma} \simeq \sigma_{p\gamma} n_\gamma R \simeq \frac{\sigma_{p\gamma} L_\gamma}{4\pi R \varepsilon} \approx 0.15 \left( \frac{L_\gamma}{10^{45} \text{erg s}^{-1}} \right) \left( \frac{R}{\text{pc}} \right)^{-1} \left( \frac{\varepsilon}{\text{eV}} \right)^{-1},
\]

where we have used \( \sigma_{p\gamma} \approx 300 \mu \text{barn} \) around the threshold for pion production. Note that \( R \sim 1 \text{pc} \) is the typical size of an accretion disk around a supermassive black hole at the centers of AGNs which is determined by the sphere of influence \( \sim 2G_M/v_s^2 \sim 2(M/10^7 M_\odot)/(v_s/200 \text{km s}^{-1})^{-2} \text{pc} \) where \( G_N \) is Newton’s constant and \( v_s \) is the velocity dispersion of the stars in the host galaxy. The optical depth for photon-disintegration of primary nuclei is comparable to Eq. (3).

If it is significantly larger than unity, most nuclei would be disintegrated before leaving the source and the maximal energy would have to be \( E_{\text{max}} \gtrsim A 10^{20} \text{eV} \) in order for UHECR to arrive at Earth with energies up to \( 10^{20} \text{eV} \).

On the other hand, the optical depth for hadronic interactions of accelerated protons and nuclei with the surrounding bulk matter of hadronic mass \( M_{\text{bulk}} \) extending over a characteristic scale \( R_{\text{bulk}} \gtrsim R \) can be written as

\[
\tau_{pp} \simeq \sigma_{pp} n_p R_{\text{bulk}} \simeq \frac{\sigma_{pp} M_{\text{bulk}}}{R_{\text{bulk}}^2 m_N} \approx 100 \left( \frac{M_{\text{bulk}}}{10^7 M_\odot} \right) \left( \frac{R_{\text{bulk}}}{\text{pc}} \right)^{-2},
\]

where we have estimated the nucleon density by \( n_p \approx M_{\text{bulk}}/R_{\text{bulk}}^3 \). Note that the mass of AGN accretion disks is roughly comparable to the mass of the central supermassive black hole whose typical mass is \( 10^{7-8} M_\odot \). Eq. (4) is only a rough estimate because the details will depend on the geometry, for example spherical versus disk-like accretion. Since the bolometric luminosities of most AGNs are \( \ll 10^{47} \text{erg s}^{-1} \), a comparison of Eqs. (4) and (1) suggests that hadronic interactions dominate over photo-hadronic interactions in the cores of AGNs.

Pionic and photo-hadronic processes will produce secondary \( \gamma \)-rays and neutrinos. The optical depth for photons of energy above the pair production threshold, \( E \gtrsim m_e^2/\varepsilon \approx 0.26 (\varepsilon / \text{eV})^{-1} \text{TeV} \), can be estimated as

\[
\tau_{\gamma\gamma} \simeq \sigma_{\gamma\gamma} n_\gamma R \simeq \frac{\sigma_{\gamma\gamma} L_\gamma}{4\pi R \varepsilon} \approx 300 \left( \frac{L_\gamma}{10^{45} \text{erg s}^{-1}} \right) \left( \frac{R}{\text{pc}} \right)^{-1} \left( \frac{\varepsilon}{\text{eV}} \right)^{-1},
\]

where \( \sigma_{\gamma\gamma} \approx 0.6 \text{ barn} \) is the Thomson cross-section.

We now deduce some requirements on the size \( R \) of the accelerating region. We will also take into account a possible beaming factor \( \Gamma \) such that \( B \) and \( R \) and other length scales are measured in the comoving frame, whereas luminosities and the energy \( E_{\text{max}} \) refer to the observer frame. The synchrotron loss length for a nucleus of atomic number \( A \) and charge \( Z \) in a magnetic field of strength \( B \)

\[
l_{\text{synch}} \simeq 0.43 \Gamma A^4 Z^{-2} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right) \left( \frac{B}{G} \right)^{-2} \text{pc}.
\]

and the Larmor radius can be written as

\[
r_L \simeq 0.1 \Gamma^{-1} Z^{-1} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right) \left( \frac{B}{G} \right)^{-1} \text{pc}.
\]

Since any energy loss time must be longer than the acceleration time which itself is larger than the Larmor radius, one has the condition \( l_{\text{synch}} \gtrsim r_L \), which gives an upper limit on the magnetic field strength,

\[
B \lesssim 4.3 \Gamma^2 A^4 Z^{-1} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^{-2} G.
\]

Together with Eq. (7) this results in a lower limit on the Larmor radius,

\[
r_L \gtrsim 2.3 \times 10^{-2} \Gamma^{-3} A^{-4} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^3 \text{pc}.
\]

In case of AGN sources, for example, this is certainly consistent with a size \( R \sim 1 \text{pc} \) for the typical size of an accretion disk. Acceleration could thus occur in small parts of such accretion disks.

### III. CONTINUOUSLY EMITTING SOURCES

Assuming at most moderate deflection in intergalactic space, the number of arrival directions observed by the Pierre Auger Observatory and other experiments implies a lower limit on the source density \( \delta, \delta_1 \),

\[
n_s \gtrsim 3 \times 10^{-5} \text{Mpc}^{-3}.
\]

The UHECR flux observed by the Pierre Auger observatory is \( \delta \)

\[
\frac{dN_{\text{CR}}}{dE} (E \approx 6 \times 10^{19} \text{eV}) \approx 6 \times 10^{-40} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{eV}^{-1},
\]

which corresponds to a power per volume of \( \delta \)

\[
Q_{\text{UHE}} \sim 1.3 \times 10^{47} \text{erg Mpc}^{-3} \text{s}^{-1}.
\]

...
Comparing Eqs. (10) and (12) implies for the time-averaged UHECR luminosity per source
\[ \dot{L}_{\text{UHE}} \lesssim 4 \times 10^{41} \text{erg s}^{-1}. \] (13)

This is much smaller than the instantaneous total luminosity required by Eq. (1).

If UHECR sources emit continuously, Eqs. (11) and (13) imply that these sources must emit at least \( \approx 2000 Z^{-2} \) times more energy in channels other than UHECR. This is consistent with the fact that at redshift zero an average AGN in an active state has a bolometric luminosity of \( \approx 5 \times 10^{44} \text{erg s}^{-1} \), comparable to Eq. (11), and the volume emissivity is \( \approx 3 \times 10^{30} \text{erg Mpc}^{-3} \text{s}^{-1} \), a factor of a few thousand larger than Eq. (12) \( \approx 1 \). The average AGN bolometric luminosity and volume emissivity corresponds to a density of "typical" AGNs of \( \approx 6 \times 10^{-5} \text{Mpc}^{-3} \), consistent with Eq. (10).

As a result, if sources emit continuously and the total power is distributed roughly equally between hadronic cosmic rays and electromagnetic power, the cosmic ray injection spectrum could extend down to \( \lesssim 10^{17} \text{eV} \) with a rather steep spectrum \( \propto E^{-\alpha} \), \( \alpha \lesssim 2.7 \). Using Eq. (12), this can be written as
\[ \frac{d\dot{n}_{\text{CR}}}{dE}(E) \approx (\alpha - 2) \frac{Q_{\text{UHE}}}{(10^{20} \text{eV})^2} \left( \frac{E}{10^{20} \text{eV}} \right)^{-\alpha}. \] (14)

Furthermore, Eq. (11) suggests that the optical depth for hadronic interactions can be of order unity and thus a considerable part of that cosmic ray flux could be transformed to neutrinos with energies \( \sim 10^{17} \text{eV} \). Following Ref. [13], for proton primaries, \( Z = 1 \), we can write for the production rate per volume of neutrinos
\[ \frac{d\dot{n}_\nu}{dE}(E) \approx \frac{2f}{3x_\nu} \frac{d\dot{n}_{\text{CR}}}{dE}(E/x_\nu), \] (15)

where \( x_\nu \approx 0.05 \) is the average neutrino energy in units of the parent cosmic ray energy and \( f = e^\gamma - 1 \) is the ratio of number of cosmic rays interacting within the source to cosmic rays leaving the source. If the cosmic ray injection spectrum \( \propto E^{-\alpha} \) extends down to \( E_{\text{min}} \) without break, \( f \) is limited by
\[ f \left( \frac{E_{\text{min}}}{10^{20} \text{eV}} \right)^{2-\alpha} \lesssim 2 \times 10^3 Z^{-2} \frac{L_{\text{tot}}}{L_{\text{min}}}, \] (16)

where \( L_{\text{tot}} \) is the total luminosity and \( L_{\text{min}} \) is given by Eq. (11). This condition just results from comparing the total emissivity with the output in UHECR and neutrinos and would be saturated if the total output would be dominated by neutrinos in case of "hidden sources". Since neutrinos do not interact during propagation and ignoring redshift evolution, we can estimate the all-flavor diffuse neutrino flux as
\[ j_\nu^{\text{diff}}(E) \approx \frac{1}{4\pi H_0} \frac{d\dot{n}_\nu}{dE}(E), \] (17)

where \( H_0 = 100 \text{hkm s}^{-1}\text{Mpc}^{-1} \) is the Hubble constant with \( h \approx 0.72 \). Putting together Eqs. (14), (15) and (17), we obtain
\[ E^2 j_\nu^{\text{diff}}(E) \approx 190 x_\nu^{-1} \alpha^{-2} \left( \frac{E}{10^{17} \text{eV}} \right)^{2-\alpha} \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \] (18)

If the ankle marks the transition from galactic to extragalactic cosmic rays, the injection spectral index of the latter has to be \( \alpha \lesssim 2.2 \), especially if heavier nuclei are accelerated [14]. The secondary neutrino spectrum would then extend down to at least \( \sim 10^{17} \text{eV} \) and Eq. (18) implies
\[ E^2 j_\nu^{\text{diff}}(E) \approx 4.2 f \left( \frac{E}{10^{17} \text{eV}} \right)^{-0.2} \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \] (19)

In contrast, if the ankle is due to pair production of extragalactic protons, then one needs \( \alpha \approx 2.6 [13] \). The secondary neutrino spectrum would then extend down to at least \( \approx 10^{16} \text{eV} \) and Eq. (18) implies
\[ E^2 j_\nu^{\text{diff}}(E) \approx 240 f \left( \frac{E}{10^{16} \text{eV}} \right)^{-0.6} \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \] (20)

We now compute the neutrino event rates in kilometer scale neutrino observatories for these two scenarios. Using the neutrino-nucleon cross section \( \sigma_{\nu N} \approx 1.9 \times 10^{-33} (E/10^{16} \text{eV})^2 \text{cm}^2 \) for \( E \approx 10^{21} \text{eV} [14] \), we obtain the rate
\[ R_\nu \sim \sigma_{\nu N}(E)2\pi E j_\nu^{\text{diff}}(E)n_N V_{\text{eff}} \] (21)
\[ \sim 2.3 \left( \frac{E}{10^{16} \text{eV}} \right)^{-0.637} \left( \frac{V_{\text{eff}}}{\text{km}^3} \right) \left( \frac{E^2 j_\nu^{\text{diff}}(E)}{100 \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}} \right) \text{yr}^{-1}, \]

where \( n_N \approx 6 \times 10^{23} \text{cm}^{-3} \) is the nucleon density in water/ice and \( V_{\text{eff}} \) the effective detection volume. The scenario \( \alpha = 2.2 \) with neutrino flux down to \( 10^{17} \text{eV} \) would give \( \sim 2 \times 10^{-2} \text{yr}^{-1} \text{km}^{-3} \lesssim 20 Z^{-2}(L_{\text{tot}}/L_{\text{min}}) \text{yr}^{-1} \text{km}^{-3} \), where we have used Eq. (10) for \( f \). The scenario \( \alpha = 2.6 \) with neutrino flux down to \( 10^{16} \text{eV} \) would give \( \approx 5.5 \text{yr}^{-1} \text{km}^{-3} \lesssim 180 Z^{-2}(L_{\text{tot}}/L_{\text{min}}) \text{yr}^{-1} \text{km}^{-3} \).

TeV \( \gamma \)-rays would mostly be absorbed within the source due to Eq. (5). As opposed to Ref. [13], we therefore do not get a constraint from the non-observation of AGNs at TeV energies in this scenario. In contrast, X-rays and GeV \( \gamma \)-rays could leave the source. Individual sources should be visible by X-ray telescopes and by GLAST. In fact, EGRET has seen a diffuse flux [17] which constrains the neutrino flux because a comparable amount of energy goes into photons and neutrinos in primary cosmic ray interactions,
\[ E^2 j_\nu^{\text{diff}}(E) \lesssim 10^3 \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \] (22)
Eqs. (19) and (20) satisfy this limit except for sources deeply in the hidden regime, \( f \gg 1 \).

### IV. FLARING SOURCES

If the sources flare on a typical time scale \( \delta t \) in the observer frame, the corresponding life time of the burst in the comoving frame, \( \Gamma \delta t \), must be larger than the comoving acceleration time scale which itself is larger than the Larmor radius, thus with Eq. (9) we have

\[
\delta t \gtrsim 0.1 \Gamma^{-4} A^{-4} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^3 \text{yr}.
\]

(23)

This is consistent with the variabilities observed for AGNs which are observed at time scales down to \( \sim 60 \) s [18], provided that \( \Gamma \gtrsim 20 \) and/or predominantly heavier nuclei are accelerated. The time scale is also consistent with \( \gamma \)-ray bursts which can easily have Lorentz factors \( \Gamma \gtrsim 20 \) [19].

If we denote the rate and UHECR luminosity of typical flares by \( R_{\text{f}} \) and \( L_{\text{UHE}} \), respectively, we can write for the time averaged UHECR power, Eq. (13),

\[
R_{\text{f}} \delta t L_{\text{UHE}} \sim \overline{L}_{\text{UHE}} \lesssim 4 \times 10^{41} \text{ergs}^{-1}.
\]

(24)

This means that the fraction of time a typical intermittent source emits the typical instantaneous UHECR luminosity \( L_{\text{UHE}} \), also called duty factor, is given by

\[
\mathcal{D} = \frac{R_{\text{f}} \delta t}{L_{\text{UHE}}} \lesssim 4 \times 10^{-4} Z^2 \left( \frac{L_{\text{min}}}{L_{\text{UHE}}} \right) \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^{-2} \text{yr}^{-1}.
\]

(25)

Eqs. (24) and (25) imply that a considerable fraction of the minimal flaring luminosity Eq. (1) can go into UHECR, \( L_{\text{UHE}} \sim L_{\text{min}} \), which could be the case if the UHECR acceleration spectrum is hard, \( \alpha \lesssim 2 \). From Eqs. (24) and (25) we then have

\[
R_{\text{f}} \lesssim 5 \times 10^{-3} \Gamma^{-4} A^{-4} Z^2 \left( \frac{L_{\text{min}}}{L_{\text{UHE}}} \right) \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^{-3} \text{yr}^{-1}.
\]

(26)

In the limit \( L_{\text{UHE}} \rightarrow \overline{L}_{\text{UHE}} \) we obviously recover the limit of continuous sources, \( R_{\text{f}} \delta t \rightarrow 1 \).

During one flare the total non-thermal energy release would be

\[
E_{\text{f}} \gtrsim L_{\text{min}} \delta t \gtrsim 3 \times 10^{51} \Gamma^{-4} A^{-4} Z^{-2} \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^5 \text{erg}.
\]

(27)

If this energy release is due to accretion onto a central black hole with an energy extraction efficiency of \( \sim 10\% \) [20], this corresponds to about 0.02 \( \Gamma^{-4} A^{-4} Z^{-2} M_\odot \). In AGN scenarios involving accretion, this energy requirement is certainly modest.

Individual sources would be observed with the apparatus UHECR luminosity

\[
L_{\text{UHE,obs}} \sim L_{\text{UHE}} \frac{\delta t}{t_{\text{delay}}},
\]

(28)

where \( t_{\text{delay}} \gtrsim Z^2 10^5 \) yr is the time delay of charged cosmic rays due to deflection in cosmic magnetic fields.

TeV \( \gamma \)-rays may or may not be observable from individual sources because the duty cycle is small and most of the time the source would have luminosities \( \ll 10^{45} Z^{-2} \text{ergs}^{-1} \), leading to fluxes \( \ll 2 \times 10^{-8} Z^{-2} (d/20 \text{Mpc})^{-2} \text{ergs}^{-1} \text{cm}^{-2} \text{s}^{-1} \) where \( d \) is the distance to the source. In the active phases, Eq. (5) suggests that TeV \( \gamma \)-rays may be absorbed by pair production within the sources. Note that flares in the electromagnetic luminosity are not expected to correlate with the UHECR luminosities due to the large UHECR time delays.

In the flaring limit we can have \( L_{\text{UHE}} \sim L_{\text{min}} \) in which case both \( \gamma \)-ray fluxes and secondary neutrino fluxes can not be much larger than the UHECR flux which would then be a considerable fraction of the total energy budget. Since the spectrum must be rather hard in this case, both the diffuse and discrete neutrino fluxes are likely unobservably small.

### V. CENTAURUS A AND OTHER AGN SOURCES

Centaurus A is the nearest AGN at a distance \( d \approx 4 \text{Mpc} \) with a central supermassive black hole of mass \( M \sim 10^8 M_\odot \) [21]. It is not a blazar as its jet has a large inclination angle to the line of sight. The Pierre Auger Observatory measured two UHECR events from the direction of Centaurus A [2]. This corresponds to a flux

\[
\frac{dN_{\text{CR}}}{dE}(E \approx 6 \times 10^{19} \text{eV}) \lesssim 10^{-40} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{eV}^{-1},
\]

(29)

and to an apparent UHECR luminosity of Centaurus A of \( L_{\text{UHE,obs}} \lesssim 10^{39} \text{ergs}^{-1} \). If Cen A is a continuous UHECR source, this is consistent with Eq. (13). The bolometric luminosity of Cen A is \( L_{\text{bol}} \approx 10^{44} \text{ergs}^{-1} \) which originates mostly within \( \lesssim 500 \text{pc} \) from the center and is mostly emitted around energies \( \varepsilon \sim 1 \text{eV} \) [21, 22]. This is consistent with Eq. (1) if predominantly heavier nuclei are accelerated, \( Z \gtrsim 4 \). At MeV energies Cen A has a luminosity \( \approx 10^{42} \text{ergs}^{-1} \) [21].

If Cen A is emitting UHECR continuously, and assuming the UHECR injection spectrum is \( \propto E^{-\alpha} \), the expression analog to Eq. (15) for a discrete source gives for the secondary neutrino flux

\[
j_\nu(E) \approx \frac{2 f}{3 \varepsilon_{\nu}} \frac{dN_{\text{CR}}}{dE}(E/x_\nu).
\]

(30)

Using Eq. (29), one obtains numerically for the neutrino energy flux

\[
E^2 j_\nu(E) \approx 0.24 x_{\nu}^{-1} f \left( \frac{E}{6 \times 10^{19} \text{eV}} \right)^{2-\alpha} \text{eV cm}^{-2} \text{s}^{-1}.
\]

(31)
For $\alpha \simeq 2.2$ this gives
\[ E^2 j_0(E) \simeq 0.024 f \left( \frac{E}{10^{17} \text{eV}} \right)^{-0.2} \text{eV cm}^{-2} \text{s}^{-1}, \] (32)
where from Eq. (16), $f \lesssim 100$. For $\alpha \simeq 2.6$ it yields
\[ E^2 j_0(E) \simeq 0.37 f \left( \frac{E}{10^{16} \text{eV}} \right)^{-0.6} \text{eV cm}^{-2} \text{s}^{-1}, \] (33)
where from Eq. (16), $f \lesssim 3.2$. The latter, more optimistic case would give an event rate of $\simeq 1.3 \times 10^{-3} \text{f yr}^{-1} \text{km}^{-3} \lesssim 4.2 \times 10^{-3} \text{yr}^{-1} \text{km}^{-3}$. It is clear that the rate due to the diffuse flux, estimated below Eq. (28), is always much larger as long as Cen A is an "average" source. This is consistent with the conclusion in Ref. [24].

If Cen A is an episodic UHECR source, as may be suggested by its variability on time scales of days observed in X-rays and $\gamma$-rays [21], Eqs. (28) and (29) imply for the UHECR luminosity during a flare,
\[ L_{\text{UHE}} \lesssim 10^{45} \Gamma^4 A^4 Z^2 \left( \frac{t_{\text{delay}}}{Z^2 10^{20} \text{yr}} \right) \left( \frac{E_{\text{max}}}{10^{20} \text{eV}} \right)^{-3} \text{erg s}^{-1}. \] (34)

Comparing with Eq. (1) this suggests that the UHECR flare luminosity is comparable to the total output, as long as the flare duration is not much larger than the theoretical minimal variability time scale Eq. (23).

The closest blazars whose jets are close to the line of sight and thus may have considerably beamed emission are in general too far away to be responsible for UHECR. As an example we briefly discuss Markarian 501. This blazar at a distance $d \simeq 130 \text{Mpc}$ shows emission up to TeV energies with variability on time scales of days and peak luminosities of close to $10^{46} \text{erg s}^{-1}$ [25, 26]. This is consistent with Eq. (1) even for protons, $Z = 1$. The power of such blazars is, therefore, certainly sufficient to provide the UHECRs. Even if they produce UHECR only in flares, the flare luminosity in UHECR, $L_{\text{UHE}}$, could be a small fraction of the total flare luminosity, and the necessary flaring time scale Eq. (23) and rate Eq. (28) would be consistent with observations, especially for significant beaming factors $\Gamma$ typical for blazars.

\section{VI. CONCLUSIONS}

We have discussed some consequences of latest results on ultra-high energy cosmic rays for the nature and variability of the sources as well as for the secondary $\gamma$-ray and neutrino fluxes produced within the sources. To this end we assumed predominant acceleration of nuclei of atomic mass $A$ and charge $Z$. In the limit of continuously emitting sources, their luminosity in cosmic rays above $\simeq 6 \times 10^{19} \text{eV}$ can be no more than a fraction of $\simeq 5 \times 10^{-4} A^{-2}$ of the total source power. If these cosmic rays are produced in the accretion disks in the centers of AGNs, significant neutrino fluxes could be produced by hadronic interactions, especially in scenarios in which extragalactic protons dominate down to $\simeq 10^{17} \text{eV}$ such that the ankle is due to pair production of these protons. The resulting cosmological diffuse neutrino flux can lead to detection rates up to several events per year and km$^3$ of effective detection volume. This also implies considerable photon fluxes at energies up to $\sim 100 \text{GeV}$, the latter of which should be easily visible by GLAST. In contrast, TeV $\gamma$-rays are likely absorbed within the source. For episodic sources that are beamed by a Lorentz factor $\Gamma$, individual flares have to last at least $\simeq 0.1 \Gamma^{-4} A^{-4} \text{yr}$. Such flares can also be visible in photons up to the TeV energy range. A considerable fraction of the flare luminosity could go into highest energy cosmic rays which suggests a hard injection spectrum. In this case the rate of flares per source has to be $\lesssim 5 \times 10^{-3} \Gamma^4 A^2 Z^2 \text{yr}^{-1}$. In contrast to continuously emitting sources, both neutrino fluxes from individual sources and the resulting cosmological diffuse flux may be hard to detect in the limit of flaring sources. Conversely, if high energy neutrinos are soon detected, this may suggest sources that produce ultra-high energy cosmic rays continuously.

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