UHECR Production and Curvature TeV Emission in Nearby, Dormant AGNs

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Abstract.

The possibility that rapidly rotating supermassive black holes associated with quasar remnants may provide sites for the acceleration of ultra-high energy cosmic rays (UHE-CRs) is considered. It is shown that prodigious TeV emission through curvature losses is an important consequence of this mechanism. Given the measured UHECR flux, it is expected that nearby dormant AGNs will be detectable by current Tev experiments. The implications for the Sgr A* source are also briefly considered.

I INTRODUCTION

Large efforts have been devoted in recent years to explore the origin of the ultra-high energy cosmic rays (UHECRs). Two distinctly different scenarios are commonly considered; the Top-Down and Bottom-Up scenarios. In the former one, the origin of the UHECRs is associated with the decay of some supermassive X particles (for a review see e.g., ref. [1]), whereas in the latter scenario the UHE-CRs are assumed to be accelerated by astrophysical objects. The main challenge confronted by the Bottom-Up scenario is to explain the apparent lack of a GZK cutoff [2,3] in the present data, and to identify counterparts that coincide with the arrival directions of observed UHECRs. Several classes of UHECR sources have been proposed, including: AGNs, GRBs, and neutron stars (see ref. [4] and references therein). However, at present there seems to be no clear association of UHECR events with any of these objects. In the following we consider further a recent idea, put forward by Boldt and Ghosh [5], that the UHECRs are accelerated by the supermassive black holes that appear to be present in the centers of normal galaxies [6]. Such systems may represent quasar remnants or dormant AGNs that were perhaps active during earlier phases in their evolution.

II PARTICLE ACCELERATION

A rotating black hole of mass $M = 10^9 M_\odot$ and specific angular momentum $a$ (measured in units of $c^2/G$), threaded by magnetic field of strength $B = 10^4 B_4$
Gauss, can induce an \textit{emf} of
\[ \Delta V \sim 4 \times 10^{30}(a/M)B_4 M_9 (h/R_g)^2 \ \text{volts}, \]  
(1)
where \( h \) is the gap height, and \( R_g = GM/c^2 \) is the gravitational radius. As pointed out in ref. [5], for the parameters corresponding to galaxies having \( M_9 > 1 \) in the list presented in ref. [6], the electric potential given by the above equation is more than sufficient to accelerate the UHECRs observed at Earth, provided that the \textit{emf} is not shorted out.

Now, in the case of AGNs, vacuum breakdown is likely to occur through the generation of pair cascades by the agency of the accretion disk radiation, ultimately leading to the formation of magnetically dominated outflows via the BZ process [7] with a maximum power on the order of \( 10^{46}(a/M)^2 M_9^2 B_4^2 \) erg s\(^{-1}\) [7,8]. These outflows are commonly associated with the powerful jets often seen in blazars. However, as shown in ref. [9], vacuum breakdown is not expected to occur in dormant AGNs (assuming that the electric field is not screened out by some surrounding plasma). This then suggests that those systems, instead of producing luminous radio jets as seen in blazars, may serve as accelerators of a small number of particles to ultra-high energies [5], provided that the associated black holes were spun up to nearly their maximal spins during a phase when the dormant AGNs were active.

The UHECR production efficiency implied by the observed CR spectrum above the ankle is rather small; the corresponding UHECR power is given approximately by
\[ L_{UHECR} = 2 \times 10^{42} \left( \frac{n_{CR}}{10^{-4}\text{Mpc}^{-3}} \right)^{-1} \ \text{erg s}^{-1}, \]  
(2)
with \( n_{CR} \sim \) a few times \( 10^{-4}\text{Mpc}^{-3} \) being the space density of objects contributing to the measured UHECR flux. This constitutes less than 0.1\% of the maximum rotational power available.

### III CURVATURE LOSSES AND TEV EMISSION

The dominant energy loss mechanism of the accelerating particles is curvature radiation [9,10]. In the limit of large suppression, the maximum energy attainable can be expressed as [9]:
\[ \epsilon_{\text{max}} = 3 \times 10^{19} \mu Z^{-1/4} M_9^{1/2} B_4^{1/4} (\rho^2 h/R_g)^{1/4} \ \text{eV}, \]  
(3)
where \( \rho \) denotes the mean curvature radius of magnetic field lines, \( \mu \) is the mass of accelerated particle in units of the proton mass, and \( Z \) is its charge. The suppression factor is given in eq. (5) of ref. [9]. For the parameters corresponding to some of the candidate UHECR sources (see ref. [5] for a list), the suppression factor for a proton lies in the range between 5 and 15, and the maximum acceleration energy
given by equation (3) is marginally sufficient to accelerate protons to the required energies [9,10]. The constraints imposed on heavy nuclei are more relaxed (although heavy nuclei may be photo-disintegrated before escaping the system, owing to the interaction with the ambient radiation field present in those galaxies [10]).

The emitted spectrum of curvature photons peaks in the TeV band [9]. The average TeV flux per UHECR source can be estimated using equation (2), and is shown [9] to exceed the detection limit of present TeV experiments. Given the IR luminosities and light profiles of the corresponding galaxies, as well as upper limits on the luminosity of a continuum source, if present, it is found that vacuum breakdown will not occur and that the TeV photons will escape the system. Thus, prodigious TeV emission appears to be a consequence of UHECR production by dormant AGNs. As pointed out in ref. [9], low luminosity AGNs for which the breakdown criterion is not satisfied, may also produce CRs and curvature emission. However, the energy of the curvature photons will be degraded to the sub-TeV range as a result of collisions with the ambient photons produced in the accretion disk. These sources should be potential targets for GLAST and MAGIC.

IV APPLICATION TO THE SGR A* SOURCE

Dynamical measurements indicate the presence of a black hole of mass \( \sim 3 \times 10^6 M_\odot \) in the Galactic center [11]. Estimates of the accretion rate (measured henceforth in Eddington units) based on observations of stellar winds in the vicinity of Sgr A* yield \( \dot{m} \sim 10^{-3} \) and, assuming a radiative efficiency of 10 %, accretion luminosity of \( \sim 10^{40} \text{erg s}^{-1} \) - several orders of magnitude greater than the observed value [12]. The low radiative output has been successfully explained in terms of an ADAF model [13]. A viable model fit to the observed spectrum yields values of \( M \) and \( \dot{m} \) consistent with those quoted above, and magnetic field pressure near equipartition, which, we estimate, corresponds to magnetic induction of the order of \( 10^4 \text{G} \) (\( B_4 \sim 1 \)). Taking \( a = M, h = R_g \) in eq. (1), the maximum energy attainable by a nucleon of charge \( Z \) is \( \epsilon_{\text{max}} \simeq 1.5 \times 10^{18}ZB_4 \text{eV} \); (since, as shown immediately below, curvature losses are small or at most mild eq. [3] is inapplicable in this case). The curvature loss rate per nuclei is \( P \sim 3 \times 10^5Z^6B_4^4\mu^{-4} \text{erg s}^{-1} \), and the corresponding radiative efficiency is \( (P/c)(eZ\Delta V/h)^{-1} \sim 0.5Z^5B_4^3\mu^{-4} \). Thus, for \( B_4 < 1 \) curvature losses are not severe.

The maximum rotational power that can be extracted from the Galactic black hole is approximately \( 10^{41}B_4^2 \text{erg s}^{-1} \). Denoting by \( \eta_{\text{CR}} \) the CR production efficiency, that is, the fraction of maximum power released as cosmic rays, we obtain a flux of curvature photons at Earth (adopting a distance of 8.5 kpc to the Galactic center) of \( \mathcal{F}_\gamma \sim 2 \times 10^{-5}\eta_{\text{CR}}B_4^5Z^5\mu^{-4} \text{erg cm}^{-2} \text{s}^{-1} \). The curvature spectrum will peak at an energy \( \epsilon_\gamma \sim 200Z^8\mu^{-3}B_4^3 \text{GeV} \). Adopting for illustration \( B_4 = 1 \) and \( \eta_{\text{CR}} = 10^{-3} \), roughly the efficiency inferred for the dormant AGNs (see above), we obtain a CR power of about \( 10^{38} \text{erg s}^{-1} \) for the Sgr A* source, with a comparable \( \gamma \)-ray luminosity (a flux at Earth of \( 10^{-8} \) in cgs units), and peak energy of the \( \gamma \)-ray...
spectrum in the range 20 - 200 GeV, depending on the composition of accelerated particles. This is well above detection limit of next generation γ-ray telescopes. We stress that these results are highly uncertain in view of the strong dependence on the magnetic field strength.

Finally, we note that there have been claims [14,15] that the measured CR flux near $10^{18}$ eV is anisotropic, indicating a strong CR source in the direction of the Galactic center. Whether this anisotropy can be accounted for by the model discussed above remains to be checked; predicting the CR flux at Earth and the anisotropy amplitude is complicated by virtue of the diffusive nature of cosmic ray propagation in the Galaxy. Detailed numerical simulations [15] appear to suggest that a CR source located in the vicinity of the Galactic center can account for the claimed anisotropy, provided the CR spectrum extends up to (or even slightly above) $10^{18}Z$ eV. This is compatible with the maximum energy gain estimated above for the parameters corresponding to the ADAF model.

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