1. INTRODUCTION

The origin of ultra high-energy (>10^{19} \text{ eV}) cosmic rays (UHECRs) remains a mystery (Bhattacharjee & Sigl 1998, Nagano & Watson 2000). The sources have not been robustly identified, and the models of particle acceleration are challenged by the fact that the energy spectrum extends to >10^{20} \text{ eV}. Several observational clues suggest that the UHECR flux is dominated by extra-Galactic light nuclei: the spectrum flattens at ~10^{19} \text{ eV} (Nagano & Watson 2000), there is evidence for a composition change from heavy to light nuclei at ~10^{19} \text{ eV} (Bird et al. 1993, Abbasi et al. 2005), and the UHECR arrival direction distribution is nearly isotropic (Finley & Westerhoff 2004, Abbasi et al. 2004). The recent detection of a weak anisotropy in the arrival distribution of >6 \times 10^{19} \text{ eV} cosmic-rays (Auger Collaboration et al. 2008) is consistent with that predicted by assuming that the spatial distribution of UHECR sources correlates with the large-scale distribution of galaxies (Waxman, Fisher & Pirani 1997, Kashti & Waxman 2009).

Although the identity of the UHECR particles is uncertain, we will assume here that they are protons. This assumption is motivated by two arguments. First, the observed spectrum of cosmic-rays with energies >10^{19} \text{ eV} is consistent with a cosmological distribution of proton accelerators producing (intrinsic) a power-law spectrum of high energy protons with d\log N/d\log E \approx -2, for the number N as a function of energy E (Waxman 1995b, Bahcall & Waxman 2003, Kashti & Waxman 2008). This intrinsic power-law spectrum is consistent with that expected in models of particle acceleration in collisionless shocks, for both non-relativistic (Blandford & Eichler 1993) and relativistic shocks (Waxman 2006; see however Keshtet 2006). Second, the leading candidates for extra-Galactic sources, namely gamma-ray bursts and active galactic nuclei (see below), are expected to accelerate primarily protons.

Robust model-independent considerations imply that UHECR protons can only be produced by sources with an exceedingly high power output (Waxman 2004), L > \Gamma^2 \beta^2 \times 10^{46} \text{ erg s}^{-1}, where \Gamma and \beta are the Lorentz factor and characteristic velocity associated with plasma motions within the source. Since no steady source above this power threshold is known to exist within the 100 Mpc GZK horizon, the distance to which the propagation of ~10^{20} \text{ eV} protons is limited by their interaction with the cosmic microwave background (Greisen 1966, Zatsepin & Kuzmin 1966), the UHECR sources are most likely transient. A possible alternative is, of course, an unknown class of "dark sources", which produce little radiation and therefore remain undetectable by telescopes.

Only two types of sources are known to satisfy the above minimum power requirement: active galactic nuclei (AGN) – the brightest known steady sources, and gamma-ray bursts (GRBs) – the brightest known transient sources. The absence of AGN with L > 10^{46} \text{ erg s}^{-1} within the GZK horizon had motivated Farrar & Gruzinov (2008) to suggest that UHECRs may be produced by a new, yet undetected, class of short duration AGN flares resulting from the tidal disruption of stars or accretion disk instabilities.

We show in \S 2 that if electrons are accelerated together with the protons in UHECR-producing flares, then their radiative losses will produce a bright flare of X-ray and \gamma-ray photons. We then show in \S 3 that existing X-ray and \gamma-ray surveys already put stringent constraints on the properties of UHECR flares. In \S 4 we discuss the possibility of "hiding" the X-ray emission. Our conclu-

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ions are summarized in § 5. Throughout our discussion, we consider a scenario in which the flare is associated with ejection of magnetized plasma from the source, and where the charged particles are accelerated within the magnetized outflow. The non thermal emission from a wide range of sources is described within the framework of such a scenario. This includes AGN jets and GRBs, as well as the transient AGN flares proposed by Farrar & Gruzinov (2008). We parametrize the UHECR flares by their power, $L$, duration, $\Delta t$, characteristic ejection speed $\beta c$, and rate per unit volume in the local Universe, $\dot{n}$. The fractions of the total energy output carried by protons, electrons and magnetic fields are denoted by $\epsilon_p$, $\epsilon_e$, and $\epsilon_B$, respectively, and we assume that the energy spectrum of accelerated electrons is similar to that of accelerated protons with a power-law index, $d \log N/d \log E \approx -2$. This index is expected for astrophysical sources which accelerate particles in strong collisionless shocks (Blandford & Eichler 1987, Waxman 2006), and is inferred from the radiation observed from a variety of high energy sources, such as supernova remnants (Reynolds & Ellison 1992) and GRBs (Waxman 1997).

It should be pointed out that the composition of the jets of high energy sources is unknown. Two classes of models are generally discussed: jets where the energy flux is dominated by the plasma kinetic energy, and jets where most of the energy is carried by electromagnetic flux. For the "kinetic" jets, a plausible mechanism exists for energy dissipation, particle acceleration and radiation emission, namely internal collisionless shocks within the outflow. Within this mechanism, a particle distribution following $d \log N/d \log E \approx -2$ is naturally expected. For the "electromagnetic" jets, the mechanism of energy dissipation and particle acceleration is not well understood. We will assume that $d \log N/d \log E \approx -2$ particle distribution is generated in this model too, as suggested by observations.

As explained at the end of § 2.1, our conclusions are valid for both spherical and jetted flows. Throughout the paper, $L$ stands for the "isotropic-equivalent power" (i.e. for a flow which is conical rather than spherical, $L$ stands for the power that would have been carried by the flow had it been spherically symmetric), and $\dot{n}$ stands for the "isotropic-equivalent rate density" (i.e. the rate inferred under the assumption of spherically symmetric emission).

2. FLARE PROPERTIES

2.1. Rates and luminosities

We define a transient source to have an active phase of duration $\Delta t$ shorter than the time delay $\Delta t_{CR}$ between the photon and the UHECR arrival times. With this definition, a "steady" source is one which is still active when the UHECRs from it are being detected. The arrival time delay originates from deflections of the charged UHECRs by intergalactic magnetic fields, and can be expressed in terms of the deflection angle, $\theta$, and propagation distance, $d$, as $\Delta t_{CR} \approx \theta d/4c$. The deflection angle is limited to $\lesssim 10^6 (d/100 \text{ Mpc})^{1/2} (E/10^{20} \text{ eV})^{-1}$ (see detailed discussion in §2.2 of Kashti & Waxman 2008), and therefore

$$\Delta t_{CR} \lesssim 10^{4.5} (d/100 \text{ Mpc})^{1/2} (E/10^{20} \text{ eV})^{-2} \text{ yr}. \quad (1)$$

For transient sources, the apparent number density of UHECR sources is energy dependent and given by $\dot{n} \Delta t_{CR}$.

The required number density of active flares is obtained from the observed energy production rate of UHECR protons per comoving volume, $\dot{\varepsilon} \equiv E^2 d\nu_p/dE = 0.7 \pm 0.3 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ (Waxman 1995b, Bahcall & Waxman 2003), giving

$$\dot{n} \Delta t = \frac{\dot{\varepsilon}}{\epsilon_p L/\Lambda} = 3.2 \times 10^{-10} \varepsilon_{44} \Lambda_{1} \text{ Mpc}^{-3}, \quad (2)$$

where $\varepsilon_{44} \equiv \varepsilon/10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$, $L_{47} = (L/10^{47} \text{ erg s}^{-1})$, $\epsilon_p L$ is the total energy output in protons, and $\epsilon_p L/\Lambda$ is the energy production per logarithmic proton energy ($E$) interval in the observed energy range. For the acceleration spectrum of strong collisionless shocks, $E^2 d\nu_p/dE \sim \text{const}$, we get $\Lambda = \ln (E_{\text{max}}/E_{\text{min}})$, and so $\Lambda_1 \equiv (\Lambda/10) \sim 1$.

The flare duration is limited by the absence of UHECR sources with multiple events, the so-called ‘repeaters’. The absence of repeaters sets a lower limit on the number density of sources $n_{\nu} \equiv \dot{n}$ (Waxman, Fisher & Piran 1997, Kashti & Waxman 2008). This can be derived by noting that the nearly isotropic distribution of the $\sim 30$ Auger events of energy $\gtrsim 6 \times 10^{19} \text{ eV}$ require tens of sources to be active within $\approx 200 \text{ Mpc}$ (the propagation distance of protons with energies $\gtrsim 6 \times 10^{19} \text{ eV}$) within Auger’s field-of-view, implying $n \gtrsim 10^{-5.5} \text{ Mpc}^{-3}$. For transient sources this requirement implies $\dot{n} \Delta t \gtrsim 10^{-5.5} (\Delta t/\Delta t_{CR}) \text{ Mpc}^{-3}$. For a GZK horizon distance of 200 Mpc corresponding to UHECR energy of $E = 6 \times 10^{19} \text{ eV}$, we get $\Delta t_{CR} \lesssim 10^5 \text{ yr}$, and therefore

$$\dot{n} \Delta t \gtrsim 3 \times 10^{-10} n_{-5} \left( \frac{\Delta t}{10 \text{ yr}} \right) \text{ Mpc}^{-3}, \quad (3)$$

where $n_{-5} \equiv (n/10^{-5} \text{ Mpc}^{-3})$. Using Eq. (2), we find

$$\Delta t \lesssim 10 n_{-5}^{-1} \varepsilon_{44} \Lambda_{1} \text{ yr}. \quad (4)$$

The number density of associated photon flares may be obtained by assuming that: (i) the accelerated electrons have the same initial power-law index for their energy spectrum as the protons, and (ii) the electrons lose all their energy to radiation (see below for the justification of the latter assumption). The photon luminosity per logarithmic frequency ($\nu$) index is then $\nu L_{\nu} = \epsilon_e L/2\Lambda = (\epsilon_e/2\epsilon_p) (\epsilon_p L/\Lambda)$, where the factor of 2 is introduced since typically $\nu \propto E^{-2}$. This implies that the number density of active photon flares with a luminosity $\gtrsim \nu L_{\nu}$ is

$$\dot{n} \Delta t = \frac{\epsilon_e \dot{\varepsilon}}{2\epsilon_p \nu L_{\nu}} = 1.6 \times 10^{-10} \varepsilon_{44} \nu_{46} \left( \frac{\epsilon_p (\nu L_{\nu})_{46}}{\epsilon_4} \right) \text{ Mpc}^{-3}, \quad (5)$$

where $(\nu L_{\nu})_{46} \equiv (\nu L_{\nu}/10^{46} \text{ erg s}^{-1})$.

Requiring that the acceleration time $t_{acc}$ be smaller than the plasma expansion time $t_{d\nu}$ and the proton energy loss time $t_{loss}$, sets lower limits on $L$ and the outflow Lorentz factor, $\Gamma$ (Waxman 1995a). In the following, we briefly describe these limits and derive the implied constraints on the photon luminosity. Assuming that acceleration results from electromagnetic processes within the outflowing plasma, the acceleration time must exceed
the Larmor gyration time of the accelerated particle\(^6\), \(\tau_{\text{acc}} \gtrsim 2\pi f R_L/c = 2\pi f E'/eBc\), where \(E' = E'/E\) and \(f\) is a dimensionless factor of order a few which depends on the details of the acceleration mechanism, and where the various times are defined in the plasma rest frame. Requiring \(\tau_{\text{acc}} < \tau_{\text{syn}} = r/\Gamma_3c\), where \(r\) is the radial distance from the source at which particle acceleration takes place, this implies \(B > fE'/e\gamma r\) and equivalently, \(\text{(Waxman [1995a])}\)

\[
\epsilon_B L > 2 \left(\frac{\pi f \Gamma E}{e}\right)^2 c = 6.6 \times 10^{46} f^2 \frac{\Gamma^2}{\beta} E_{20}^2 \text{ erg s}^{-1}, \tag{6}
\]

where \(\epsilon_B L = 4\pi^2 c\gamma^2 B^2/8\pi\), and \(E_{20} = (E/10^{20} \text{ eV})\). The minimum photon luminosity is therefore

\[
\nu L_\nu > 3.3 \times 10^{45} \frac{f^2 \epsilon_c \Gamma^2}{\Lambda_1 \epsilon B} \frac{E_{20}^2}{\beta} \text{ erg s}^{-1}
\]

\[
> 8.6 \times 10^{45} \frac{f^2 \epsilon_c E_{20}}{\Lambda_1 \epsilon B} \text{ erg s}^{-1}. \tag{7}
\]

One of our primary objectives is to demonstrate that exceptionally powerful flares with \(L > 10^{50} \text{ erg s}^{-1}\) are required. In what follows we limit the discussion to flares with \(\Gamma < 10^{1.5}\), since a higher \(\Gamma\) implies \(L > 10^{50} \epsilon_B c^4\) erg s\(^{-1}\).

A lower limit on the bulk Lorentz factor \(\Gamma\) is set by requiring that the synchrotron loss time would exceed the acceleration time, \(\tau_{\text{acc}} < \tau_{\text{loss}} = 6\pi \Gamma (m_p c^2)/e B^2\sigma_T(m_e/m_p)^2 E\), where \(m_p\) and \(m_e\) are the proton and electron masses. Using \(r > 2\Gamma^2\Delta t\), this condition implies \(\text{(Waxman [1995a])}\)

\[
\beta^{1/2} \Gamma > \left( \frac{f \sigma_T}{\delta \epsilon_e} \right)^{1/5} \left( \frac{m_e}{m_p m_p c^2} \right)^{2/5} \left( \frac{\epsilon_B L}{2c^3} \right)^{1/10} \Delta t^{-1/5},
\]

or numerically,

\[
\Gamma > 1.1 f^{1/5} E_{20}^{2/5} (\epsilon_B L_{\text{47}})^{1/10} \Delta t_{\text{yr}}^{-1/5}. \tag{9}
\]

Hereafter, we drop the dependence on \(\beta\) since the flow is required to be at least mildly relativistic with \(\beta \approx 1\). Combining this result with \(\text{Eq. (6)}\), we get

\[
\epsilon_B L > 7.9 \times 10^{46} f^3 \Gamma^{7/2} E_{20}^{1/2} \Delta t_{\text{yr}}^{-1/2} \text{ erg s}^{-1}. \tag{10}
\]

The constraints on \(L\) and \(\Gamma\) are the same for a spherical and conical (jet-like) outflow as long as the opening angle of the jet \(\theta_J\) is larger than \(1/\Gamma\) \(\text{(Waxman [1995a])}\). Thus, the constraints in equations \(\text{(6)–(10)}\) apply in both cases, provided that \(L\) is interpreted as the isotropic-equivalent power. In the case of jets, there could be a discrepancy between the apparent number of UHECR sources and photon sources, in case the deflection angle of CRs by the intergalactic magnetic field is larger than \(\max(\theta_J, 1/\Gamma)\). For the Lorentz factors considered here, \(\Gamma < 10^{1.5}\), the magnetic deflections are smaller than \(1/\Gamma > 1/30 = 2\theta_J\) (see the opening paragraph of this section), implying that we should see the same sources in both photons and UHECRs. Under these circumstances, the results in equations \(\text{(4)–(5)}\) hold, provided that \(n\) and \(\bar{n}\) refer to the isotropic equivalents quantities. This also implies that we can use isotropic equivalent luminosities in the luminosity functions.

\[\text{For acceleration in collisionless shocks, } \tau_{\text{acc}} \text{ is larger than the Larmor time by a factor } \sim (c/v)^2 \text{ where } v \text{ is the shock velocity in the plasma rest frame.}\]
plasma rest frame are expected to be mildly, but not highly, relativistic. Consider, for example, two equal mass elements moving along the same directions with Lorentz factors $\Gamma_1 \gg \Gamma_2 \gg 1$. The Lorentz factor of these mass elements in their center of mass frame is $\sqrt{\Gamma_1/\Gamma_2/2}$, implying that a mildly relativistic relative motion is obtained unless their respective Lorentz factors are very different. Thus, if electrons are coupled to the protons and carry a fraction $\epsilon_e$ of the energy density, then the lowest energy electrons will carry an energy of $E_{e,\text{min}} \sim \left(\epsilon_e/\epsilon_p\right)m_p c^2$, giving

$$\nu_{\text{syn, min}} \approx 0.02(\epsilon_e/\epsilon_p)^2(\epsilon_B L_{47})^{1/2} \Gamma^{-2} \delta_{\gamma^{1/5}}^{-1} \text{eV},$$

and

$$\frac{\nu_{\text{syn}}}{\nu_{\text{syn, min}}} < 3 \times 10^{-5} f^{-4} \Gamma^{6} E_{20}^{-4} \delta_{\gamma^{1/5}}^{-2}.$$  

Using Eq. 9 we also have

$$\nu_{\text{syn, min}} < 0.01(\epsilon_e/\epsilon_p)^2(\epsilon_B L_{47})^{3/10} E_{20}^{-4/5} \delta_{\gamma^{1/5}}^{-3/5} \text{eV}.$$  

The emission at a photon energy $\gg 10$ MeV is dominated by inverse Compton (IC) up-scattering of synchrotron photons. For collisionless shock acceleration in internal shocks with $E_{e,\text{min}} \sim (\epsilon_e/\epsilon_p)m_p c^2$, the gamma-ray luminosity at photon energies $\gg 10$ MeV is $\nu_{L\nu} = \min\left[1, \epsilon_e/\epsilon_B eL/\Lambda\right]$. If $E_{e,\text{min}} \sim (\epsilon_e/\epsilon_p)m_p c^2$, the IC emission may be limited to photon energies $\gg 100$ MeV, and may be shifted beyond the observable range ($\gg 0.1$ TeV). For $\epsilon_e \gg \epsilon_B$, the synchrotron luminosity is suppressed to $\nu_{L\nu} = \epsilon_e(E_B/\epsilon_e)^{1/2}/\Lambda$, modifying the factor $(\epsilon_e/\epsilon_B)$ in Eq. 10 to $(\epsilon_e/\epsilon_B)^{1/2}$ and the factor $(\epsilon_e/\epsilon_p)$ in Eq. 10 to $(\epsilon_e/\epsilon_B)^{1/2}/\epsilon_p$.

The high energy, $\gg 100$ MeV, emission may be suppressed by pair production. A photon of high energy $E_{\gamma} \gg m_e c^2$ may interact with lower energy photons, $E_{\gamma}' \sim \left(\epsilon_e/\epsilon_B\right)^2/E_{\gamma}$, to produce $e^+ e^-$ pairs. The optical depth is $\tau_{\gamma\gamma} = n_{\gamma}(E_{\gamma}') \sigma_{\gamma\gamma}/\Gamma$, where $n_{\gamma}(E_{\gamma}')$ is the co-moving number density of photons with observed energy $E_{\gamma}'$, and $\sigma_{\gamma\gamma}$ is the $e^+ e^-$ annihilation cross-section. Using $n_{\gamma}(E_{\gamma}') \approx \nu_{L\gamma}/4\pi r^2 c E_{\gamma}'$ and the lower limit on $\Gamma$ (Eq. 10), we find

$$\tau_{\gamma\gamma} \lesssim 10^{-3} \left(\frac{\nu L_{\nu}}{10^{46}}\right) \left(\frac{E_{\gamma}'}{m_e c^2}\right)^{1/5} \frac{\left(\epsilon_e/\epsilon_B\right)^{1/2}}{\delta_{\gamma^{1/5}}}.$$  

We therefore conclude that pair production may suppress the 100 MeV flux only for $(\nu L_{\nu}) > 10^{47}$ erg s$^{-1}$.

3. LUMINOSITY FUNCTION CONSTRAINTS

Equation 9 provides the number density of active flares required to account for the observed flux of UHECRs (Eq. 5), compared to the cumulative number density of bright extra-Galactic sources at various energy bands: 0.5–2 keV (ROSAT, Miyaji et al. 2000), 17–60 keV (INTEGRAL, Sazonov et al. 2007), 15–195 keV (Swift BAT, Tueller et al. 2008), and $> 100$ MeV (EGRET, Chiang & Mukherjee 1998). The measured luminosity in different bands is converted to $\nu L_{\nu}$ assuming a photon index of −2 (consistent with the observed spectra). The solid segments of the curves represent the measured component of the local ($z < 0.2$) luminosity function (LF), whereas the dashed segments of the curves represent the LF component which is inferred by measuring the number density of bright sources at higher redshift and then evolving it to $z = 0$ using the LF evolution with $z$ as measured at lower $\nu L_{\nu}$. The dotted segments of the curves represent the upper limit on the number density in the luminosity range where no sources have been observed. The GRB number density and luminosity (e.g. Guetta et al. 2009) are shown for comparison.

The Swift BAT sources are identified. We also note that obscuration by a high column density of hydrogen of soft X-ray sources can not dramatically alter the source number density since the AGNs selected in the hard or soft X-ray bands have similar number densities (see also Silverman et al. 2007). At the highest energy band, $> 100$ MeV, where the angular resolution is poorest, source identification is incomplete, but the contribution of unidentified sources can not lead to a significant change in the statistics of sources. In particular, EGRET had detected 60 high-latitude point sources that have not been identified, compared with the 44 high-latitude sources identified as AGN (Chiang et al. 1999). The hard X-ray (17–60 keV, $\sim 195$ keV) luminosity function (LF) shown in Fig. 1 is given by

$$n_{\nu \gamma} = 10^{-11}(\nu L_{\nu})_{10^{46}}^{-2.2} \text{Mpc}^{-3}.$$  

It is important to emphasize that the luminosity function constraints depicted in Fig. 1 refer to all the known bright sources on the sky, and so our conclusions do not apply exclusively to AGN flares, but to any other class of flaring sources.

We first consider the case of near equipartition between electrons and magnetic fields, $\epsilon_e/\epsilon_B \sim 1$. In this case, the flare luminosity should be $\nu L_{\nu} \gtrsim 10^{46}$ erg s$^{-1}$.

10.8

\begin{center}
\begin{tabular}{c}
\hline
[17–60, 14–195] keV
\hline
[0.1–30] GeV
\hline
[0.5–2] keV
\hline
\end{tabular}
\end{center}
Constraints on UHECR sources

(see Eq. 7). It is obvious by Fig. 1 or from comparing Eqs. (5) and (13), that for $e_\gamma/e_B \sim 1$ the observed number density of sufficiently bright sources is much smaller than the density of active flares required to account for the UHECR flux, unless $e_\gamma/e_B \ll 1$. For $\nu L_\nu \gtrsim 10^{47}$ erg s$^{-1}$ the number density of active flares is limited to $< 10^{-14}$ Mpc$^{-3}$, which implies based on Eq. (3) that $e_\gamma/\gamma_c \gtrsim 10^3 (\nu L_\nu)^{-3}_\Lambda$, and $e_\gamma L = \Lambda (\nu L_\nu) (e_\gamma/\gamma_c) \gtrsim 10^{41}$ A$_1$ erg s$^{-1}$. For $\nu L_\nu \sim 10^{46}$ erg s$^{-1}$, the number density of sources appears to be consistent with the required number density of active flares in Eq. (3) for $e_\gamma/e_B \sim 0.1$. However, the X-ray sources identified could be candidate UHECR sources only if they are transient, and only a small fraction of the sources observed are variable. 

Grupe et al. (2001) examined 113 bright ROSAT AGN on a time scale of $\sim 6$ yr, and found that only 3 showed a factor of 10 variation over this time scale (all others varied by a factor less than 3). Similarly, Winter et al. (2008) compared XMM-Newton and Swift XRT observations of 17 sources and found fractional variations of only a few tens of percent over $\sim 100$ days (see their Table 12), suggesting that $\lesssim 3\%$ of all hard X-ray sources have a lifetime of $\lesssim 10$ years. This implies that the number density of X-ray sources variable on $\sim 5$ min (the typical integration time in the analysis of Grupe et al. 2001 is $\sim 300$ s) to $\sim 10$ yr time scale is

$$n_{hX, var} \sim 3 \times 10^{-13} (\nu L_\nu)^{-2.2}_0 \text{ Mpc}^{-3}.$$  (19)

Comparing with Eq. (5), this implies that UHECR flares must satisfy $e_\gamma/e_B > 500$ and $e_\gamma L \gtrsim 10^{40} $ A$_1$ erg s$^{-1}$ for $(\nu L_\nu)^{-1}_0 = 1$. A similar constraint is obtained using EGRET’s LF.

The requirement $e_\gamma L \gtrsim 10^{50}$ A$_1$ erg s$^{-1}$ may be avoided if the magnetic field energy density is much higher than the electron energy density, $e_\gamma/e_B \ll 1$. For $e_\gamma/e_B < 10^{-2}$, the minimum flare luminosity is $(\nu L_\nu)^{-1}_\Lambda \gtrsim 10^{44}$ erg s$^{-1}$, and the required number density of active X-ray flares in Eq. (5) is consistent with the number density of variable X-ray sources in Eq. (13) for $e_\gamma/e_B \sim 1$. The gamma-ray luminosity is suppressed by $e_\gamma/e_B$ with $\nu L_\nu < 10^{42}$ erg s$^{-1}$, a range in which the number density of sources is poorly constrained by EGRET. Next, we consider the $e_\gamma/e_B \sim 0.1$ regime. Here the minimum flare luminosity is $\nu L_\nu \sim 10^{45}$ erg s$^{-1}$ and the required number density of active X-ray flares is consistent with the number density of variable X-ray sources for $e_\gamma/e_B < 10^{-2}$ and with EGRET’s LF for $e_\gamma/e_B < 10^{-3}$ (see Fig. 1). As mentioned in § 2 IC emission may be shifted above the observable range ($> 0.1$ TeV) in electromagnetically-dominated outflows. For $e_\gamma/e_B \sim 0.1$ and $e_\gamma/e_B < 10^{-2}$ we get $e_\gamma/e_B > 10$, which implies that the outflow can not be electromagnetically dominated. This, in turn, implies that the flares should be accompanied by observable gamma-ray emission, and hence that $e_\gamma/e_B < 10^{-3}$ must be satisfied.

The preceding discussion implies that for a flare duration in the range 1 hr $< \Delta t \lesssim 10$ yr, the requirement $e_\gamma L \gtrsim 10^{50}$ A$_1$ erg s$^{-1}$ may be avoided only for $e_\gamma/e_B < 10^{-2}$ or $e_\gamma/e_B < 10^{-3}$. These constraints are likely to improve in the near future with new $\gamma$-ray data from the recently launched GLAST satellite$^8$, and with proposed X-ray telescopes such as EXIST$^9$. Next, we consider the case of flares with $\Delta t \gg 10$ yr. Since there is little information on source variability on such time scales, all observed sources are flare candidates. For $\Delta t \gtrsim 100$ yr, the active flare number density is $> 10^{-8}$ Mpc$^{-3}$ (see Eq. 3). At this density, the X-ray LF requires (see Fig. 1) an X-ray flux $\nu L_\nu < 10^{45}$ erg s$^{-1}$, which implies through Eq. (2) that $e_\gamma/e_B < 0.1$. The EGRET LF requires either $e_\gamma/e_B < 10^{-3}$ or that the IC gamma-ray emission be shifted outside the observable range, which may be possible for flares that are electromagnetically dominated.

There is one important caveat to the above constraints. The required number density of sources is low, $\lesssim 0.1$ Gpc$^{-3}$, so that that no source is expected to be detected within a distance of $\sim 1$ Gpc, which is the GZK horizon of particles with $E \sim 10^{19}$ eV. This implies that snapshot surveys can not provide useful constraints on the local ($z \sim 0$) number density of high luminosity flares. For this reason, the $z \sim 0$ LF shown in Fig. 1 are not measured directly at high luminosities, $\nu L_\nu > 10^{45}$ erg s$^{-1}$. Rather, the number density of bright sources is measured at a higher redshift and the local number density is inferred from the evolution of the LF with $z$ as measured at lower values of $\nu L_\nu$. For example, the number density of soft X-ray sources with $\nu L_\nu > 10^{46}$ erg s$^{-1}$ is measured to be $\sim 5 \times 10^{-11}$ Mpc$^{-3}$ at $z \sim 1$ and inferred (but not measured) to be much lower than $\sim 10^{-12}$ Mpc$^{-3}$ at $z \sim 0$, based on the LF evolution measured at lower $\nu L_\nu$ (see, e.g. Figure 5 of Hasinger et al. 2003). Long-term monitoring surveys offer much better prospects for constraining the source population than snapshot surveys. For example, if the flare duration is a few days, then a survey that lasts for a year can put constraints that are $\sim 100$ times better than a snapshot survey. Upcoming surveys, such as Pan STARRS$^{10}$ are expected to provide relevant data soon, and planned surveys such as LSST$^{11}$ will provide better constraining power in the future.

We can not exclude the possibility that the number density of flaring sources with $\nu L_\nu > 10^{46}$ erg s$^{-1}$ does not decrease towards $z \sim 0$ as fast as the number density of lower $\nu L_\nu$ sources, and remains at a level of $\sim 5 \times 10^{-11}$ Mpc$^{-3}$, which is marginally consistent with that required for the local production rate per unit volume of UHECRs. However, such a scenario is unnatural since it requires two coincidences: the flares must become a dominant source of energy output only at $\nu L_\nu > 10^{46}$ erg s$^{-1}$ (or else they would modify the observed LF evolution at lower $\nu L_\nu$), and exist only at $z \sim 0$ (or else we would observe them at $z \gtrsim 0.5$).

4. "DARK, PROTON-ONLY" FLARES

It is difficult to rule out a scenario in which the UHECR flares involve "electromagnetically-dark" or "proton only" flares. Although there is currently no evidence or physical reasoning to motivate the consideration of a new class of hidden sources, we nevertheless discuss its required properties for the sake of generality.

Since the cross-section for inelastic $pp$ collisions is much smaller than the Thomson cross-section, $\sigma_T = 6.7 \times$

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9 http://exist.gsfc.nasa.gov/
10 http://pan-starrs.ifa.hawaii.edu/
11 http://www.lsst.org/

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8 http://glast.gsfc.nasa.gov/
10^{-25} \text{ cm}^2$, the X-ray emission may be suppressed (without affecting proton escape from the source) by postulating the UHECR source to be embedded within an opaque plasma cloud of column density, $\gtrsim \sigma_{\text{p}}^{-1} \sim 10^{42} \text{ cm}^{-2}$, which is optically thick to Compton scattering. If the outflow is jet-like and relativistic, scattering within the cloud would suppress the X-ray luminosity by a factor $> \Gamma^2/\theta_j^2$, where we assume that the jet opening angle $\theta_j > 1/\Gamma$. A suppression of the expected X-ray luminosity, $\gtrsim 10^{47} \text{ erg s}^{-1}$, by a large factor, $> \Gamma^4$, would allow a sufficiently high number density of candidate UHECR sources to satisfy current limits on their electromagnetic luminosity.

Similarly, since the cross-section for $p\gamma$ (pion photoproduction) collisions is much smaller than the Thompson cross-section, the gamma-ray emission may be suppressed (without affecting proton escape from the source) by postulating the source to be embedded within an isotropic X-ray radiation field, with sufficiently high photon density to prevent the escape of gamma-rays through pair-production. The required photon column density, $\sim 10^{29} \text{ cm}^{-2}$, implies an X-ray luminosity of $\sim 6 \times 10^{43} (R/10^{16} \text{ cm}) (E_\gamma/\text{1keV}) \text{ erg s}^{-1}$, where $R$ is the source size and $E_\gamma$ is the energy of the background photons.

The predicted X-ray emission could also be suppressed by assuming that the source is embedded in an intense isotropic radiation field at IR, optical or UV frequencies, with an energy density far exceeding that of the magnetic field of the outflow, thus suppressing the synchrotron emission of the electrons by rapid IC cooling. For a relativistic outflow, the luminosity $L_{\text{iso}}$ associated with the isotropic radiation field could be much smaller than that associated with the outflowing magnetic field, $\epsilon_B L$, since the energy density ratio in the plasma rest frame is $\Gamma^4 L_{\text{iso}}/\epsilon_B L$. Note that such X-ray suppression does not change the conclusion of the second paragraph of Eq. (3) that $\epsilon_p L > 10^{50} \text{ erg s}^{-1}$ is required for flares with X-ray luminosity of $\nu L_\nu > 10^{46} \text{ erg s}^{-1}$. The flux can be written as $\nu L_\nu = (\epsilon_e/f_X) L/\Delta$ with a suppression factor $f_X > 1$, implying that Eq. (3) should be modified to
\[
\dot{n}_\Delta t = \frac{\epsilon_e}{2\epsilon_p f_X \nu L_\nu} = 1.6 \times 10^{-10} \frac{\epsilon_e}{f_X \epsilon_p (\nu L_\nu)^{46}} \text{ Mpc}^{-3}.
\]

However, since the relation between proton and photon luminosities is also modified to $\epsilon_p L = \Lambda (\nu L_\nu) (f_X \epsilon_p/\epsilon_e)$, the constraint on $\epsilon_p L$ is independent of $f_X$. The X-ray suppression may affect, however, the constraint $\epsilon_e/\epsilon_B \ll 1$, that must be satisfied in the absence of X-ray suppression for flares with $\nu L_\nu \ll 10^{44} \text{ erg s}^{-1}$ (Eq. 7). In the presence of X-ray suppression, we may write Eq. (7) as $\Gamma^2 < 0.1 (\nu L_\nu)^{45} f_X (\epsilon_e/\epsilon_B)^{-1}$. Combined with $f_X \sim \Gamma^4 L_{\text{iso}}/\epsilon_B L < 1/\Gamma^2 L_{\text{iso},45}$ (see Eq. 8), this implies $L_{\text{iso}} > 10^{48} (\epsilon_e/\epsilon_B) (\nu L_\nu)^{45} \text{ erg s}^{-1}$. This isotropic luminosity requires the associated AGN to involve the most massive black holes in the Universe ($\sim 10^{10} M_\odot$) shining near their limiting (Eddington) luminosity, in order for the X-ray suppression to have a significant effect on our results. The absence of known sources of this extreme luminosity within the GZK horizon of UHECRs in the local Universe (see Fig. 11 in Greene & Ho 2007, and Fig. 6 in Hopkins et al. 2007) rules out long-lived sources, but still allows for rare flares. We note that the minimum flaring time associated with the light crossing-time of the Schwarzschild radius of these black holes is $\gtrsim 1$ day, and that the IR-UV variability of active AGN is observationally constrained to be weak on longer timescales (Sesar et al. 2006, 2007) of up to several decades (De Vries et al. 2005).

5. CONCLUSIONS

The absence of steady sources of sufficient power to accelerate UHECRs within the GZK horizon of 100 Mpc, implies that UHECR sources are transient. We have shown that UHECR “flares” should be accompanied by strong X-ray and $\gamma$-ray emission. Figure 1 demonstrates that X-ray and $\gamma$-ray surveys constrain flares which last longer than $\sim 5$ min and less than a decade to satisfy at least one of the following conditions: (i) $L > 10^{50} \text{ erg s}^{-1}$; (ii) the power carried by accelerated electrons is lower by a factor $> 10^2$ than the magnetic field power or by $> 10^3$ than that carried by accelerated protons; or (iii) the sources exist only at low redshifts, $z \ll 1$. The implausibility of requirements (ii) and (iii) argue in favor of transient sources with $L > 10^{50} \text{ erg s}^{-1}$.

The required luminosity is well above the brightest luminosity ever recorded in an AGN flare, and exceeds by two orders of magnitude the Eddington limit for a black hole of $10^{10} M_\odot$, the highest mass expected to exist within a distance of 100 Mpc (Lauer et al. 2005; Natarajan & Treister 2008). The results shown in Fig. 1 exclude the regime of low flare luminosities considered by Farrar & Gruzinov (2008).

The lower bound of $\sim 300$ s on the window of flare durations over which our constraints apply, originates from the integration time of the X-ray data used in Fig. 1. For flare durations $\Delta t \lesssim 300$ s, Eq. (11) requires $\epsilon_B L > 0.3 \times 10^{50} \text{ erg s}^{-1}$, not significantly different from the minimum luminosity inferred for longer flare durations.

We have also explored potential caveats to the above conclusions. Long-duration ($\gtrsim 100$ years) flares which are electromagnetically dominated could evade the constraints illustrated in Fig. 1 if their gamma-ray emission peaks outside the EGRET energy band. In addition, an unknown population of “electromagnetically-dark” flares is in principle possible (see Eq. 4 for details), although there is no physical motivation to make its existence natural. Future gamma-ray observations with GLAST and X-ray observations with EXIST would improve the statistical constraints on the source population of UHECRs and potentially shed more light on their nature.

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