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THE γ-RAY BACKGROUND CONSTRAINS THE ORIGINS OF THE RADIO AND X-RAY BACKGROUNDS

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ABSTRACT

Cosmic ray protons generate γ-rays, neutrinos, and secondary electrons and positrons ($e^{\pm}$) through pion-producing collisions with gas atoms. Any synchrotron or Inverse Compton (IC) radiation from secondary $e^{\pm}$ is therefore accompanied by pionic γ-rays. Using the extragalactic γ-ray background, we constrain the contribution of secondary $e^{\pm}$ to the cosmic radio, X-ray, and soft γ-ray backgrounds. We find that IC-upscattered light from secondaries is $\lesssim 1/4$ of the MeV γ-ray background, and $\lesssim 10\%$ of the X-ray background. The low intensity of the observed γ-ray background is marginally inconsistent with a secondary $e^{\pm}$ origin for the radio background reported by ARCADE, unless the magnetic field strength in their sources is milliGauss or greater. These limits on the magnetic field strength are sensitive to uncertainties. However, any contribution to the γ-ray background from sources not responsible for the ARCADE excess increases the inconsistency.

Subject headings: cosmic rays — gamma rays: diffuse background — radio continuum: galaxies — X-rays: diffuse background — diffuse radiation

1. INTRODUCTION

Cosmic rays (CRs) are accelerated in a variety of environments including star-forming galaxies (e.g., Condon 1992) and galaxy clusters (e.g., Ferrari et al. 2008; Rephaeli et al. 2008). The bulk of the energy in CRs is in protons. These collide with ambient nuclei, creating pions, which decay into γ-rays, neutrinos, and secondary electrons and positrons ($e^{\pm}$). Whether secondary or primary, CR $e^{\pm}$ radiate synchrotron emission in magnetic fields and Inverse Compton (IC) as they scatter low energy photons. CR protons therefore contribute to the γ-ray and neutrino backgrounds, while CR $e^{\pm}$ contribute to the radio, X-ray, and γ-ray backgrounds.

The origins of the cosmic backgrounds associated with CRs are understood to varying degrees. The γ-ray background was once attributed to blazars, but *Fermi* has revealed that some other source must be responsible for most of the emission above 100 MeV (Abdo et al. 2010c). Star-forming galaxies, either normal or starburst, are one explanation for the γ-ray background (e.g., Fields et al. 2010; Lacki et al. 2010a). The neutrino background has yet to be detected, although IceCube will improve sensitivity greatly (Achterberg et al. 2007). The radio background is assumed to be produced by CR $e^{\pm}$ in star-forming galaxies and possibly AGNs (Protheroe & Biermann 1996; Haarsma & Partridge 1998; Dwek & Barker 2002). However, the radio bolometer ARCADE has detected an extragalactic radio background apparently six times greater than expected from the radio luminosities of $z \approx 0$ galaxies (Fixsen et al. 2009; Seiffert et al. 2009). Singal et al. (2010) suggested that redshift evolution of the radio luminosities of star-forming galaxies explains the ARCADE background. The X-ray background is the best understood of the backgrounds, with most of it being resolved into AGNs (Gilli et al. 2007, and references therein).

A powerful way of limiting one cosmic background is to compare it with another of the same origin. For example, the Waxman-Bahcall argument limits the flux of ultra-high energy neutrinos from the observed spectrum of ultra-high energy CR protons, which are expected to produce the neutrinos (Waxman & Bahcall 1999; Bahcall & Waxman 2001). Simply put, the Universe must be at least as luminous in the protons that generate secondaries as in the secondaries themselves. Similarly, we can use one pionic background – either the γ-rays or neutrinos – to constrain the others: synchrotron radio or IC X-rays from secondary $e^{\pm}$. Secondary $e^{\pm}$ are expected to dominate over primary electrons in starburst galaxies (e.g., Thompson, Quataert, & Waxman 2007), the inner regions of Milky Way-like galaxies (e.g., Porter et al. 2008), and possibly galaxy clusters (e.g., Dennison 1980), so this argument applies to backgrounds from these objects.

2. RATIO OF PIONIC γ RAYS TO SECONDARY EMISSION

Suppose a source injects CR protons with a luminosity dL_p/dE_p, so that the power in protons per log bin of energy is $E_p dL_p/dE_p$. During their propagation, CR protons above the energy threshold experience pionic losses which convert $F_{\rm cal}(E_p)$ of this energy into pions. About 1/3 of the energy lost to pionic interactions goes into neutral pions, which decay into γ-rays with a typical energy $\langle E_{\gamma} \rangle \approx 0.1 E_p$. The rest of the pionic losses go into charged pions; of this, 1/4 goes into secondary $e^{\pm}$ and the rest into neutrinos, so 1/6 of the pionic luminosity is in secondary $e^{\pm}$ while 1/2 is in neutrinos. The average energy of the neutrinos and $e^{\pm}$ is $\langle E_e \rangle \approx \langle E_{\nu} \rangle \approx 0.05 E_p \approx \langle E_{\gamma} \rangle /2$. Taking the ratio of the luminosity in pionic γ-rays to pionic secondary $e^{\pm}$, we have:

$$2 \langle E_e \rangle \frac{dL_e}{dE_e} \approx \langle E_{\gamma} \rangle \frac{dL_{\gamma}}{dE_{\gamma}}, \qquad (1)$$

and similarly, $3 \langle E_e \rangle \frac{dL_e}{dE_e} \approx \langle E_{\nu} \rangle \frac{dL_{\nu}}{dE_{\nu}}$ for neutrinos. In comparing $\langle E_{\gamma} \rangle$ to $\langle E_e \rangle$, we assume the pions are relativistic; we take $E_{\gamma} \geq 300 E_{300}$ MeV as a threshold for this. Far below this energy, few secondaries are expected and any emission must come from primary $e^{\pm}$.

The secondary $e^{\pm}$ then radiate synchrotron and IC emission, among other losses. The pitch-angle averaged rest-frame frequency of synchrotron emission is $\nu_C = (3E_e^2 eB)/(16 m_e^3 c^5)$, where e is the electron's charge, B is magnetic field strength.

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Since $\nu_C \propto E_e^2$, $d\ln\nu_C = 2d\ln E_e$: the synchrotron emission from one log bin in $e^\pm$ energy is spread over two log bins in synchrotron frequency. At most 100% of the CR $e^\pm$ emission can go into synchrotron, implying that $\nu_C L_\nu(\nu_C) = (E_e/2)dL_e/dE_e$, or

$$\nu_C L_\nu(\text{synch}) \lesssim (f/4)\nu L_\nu(\text{pionic } \gamma-\text{ray}) \tag{2}$$

evaluated for ν_C at $E_e = E_\gamma/2$, where $f \approx 1$ parameterizes uncertainties in this approximation and the backgrounds (Loeb & Waxman 2006). Higher f corresponds to greater γ-ray backgrounds, or smaller synchrotron or IC backgrounds. This uses the δ-function approximation for the synchrotron spectrum, which is generally valid for power law spectra (e.g., Felten & Morrison 1966).[3] Similarly, the average rest-frame energy of an IC upscattered photon of initial energy ϵ_0 is $E_{\rm IC} = (4E_e^2\epsilon_0)/(3m_e^2c^4)$ in the Thomson limit ($E_{\rm IC} \lesssim E_e$). Once again $E_{\rm IC} \propto E_e^2$, and the IC emission from one log bin in E_e is spread over two log bins in $E_{\rm IC}$. We therefore have

$$\nu_{\rm IC} L_\nu(\text{IC}) \lesssim (f/4)\nu L_\nu(\text{pionic } \gamma-\text{ray}) \tag{3}$$

evaluated for $E_e = E_\gamma/2$, again using the δ-function approximation (Felten & Morrison 1966). Note that eqs. 2 and 3 apply not just to the backgrounds as a whole, but to the pionic emission from *each* source and *each* population.

In what follows, we conservatively assume that *all* of the observed γ-ray background (Abdo et al. 2010b) is pionic in origin. Leptonic contributions to the γ-ray background only tighten the limits. The power-law fit to the Abdo et al. (2010b) background is:

$$\nu J_\nu(\gamma-\text{ray}) = 2.33\times 10^{-9}\left(\frac{E_\gamma}{100\ \text{MeV}}\right)^{-0.41} \tag{4}$$

in cgs units of erg cm^{-2} sec^{-1} sr^{-1}. At energies below *Fermi* observations, the observed γ-ray background is bounded by eq. 4 (Weidenspointner et al. 2000; Strong et al. 2004; see Fig. 1). Since the true γ-ray background is even smaller than eq. 4 at low energies, the true limits on synchrotron and IC backgrounds from secondary $e^\pm$ are stronger than what we find here. The Universe is transparent to γ-rays below 20 GeV, our maximum E_γ for limits on $z = 10$ sources, and to $z \approx 1$ for 100 GeV (e.g., Gilmore et al. 2009; Finke et al. 2010).

3. THE X-RAY AND SOFT γ-RAY BACKGROUNDS

Nonthermal emission in X-rays has been observed in galaxy clusters, and is believed to be IC-upscattered CMB photons (see the review by Rephaeli et al. 2008). Moran et al. (1999) suggested hard X-ray emission from IC upscattered ambient far-infrared (FIR) starlight in starburst galaxies contributes significantly ($\sim 5-10$%) to the X-ray background. Since pionic γ-rays accompany pionic secondary $e^\pm$ production, the observed γ-ray background limits the contribution of secondary $e^\pm$ in these sources to the X-ray background.

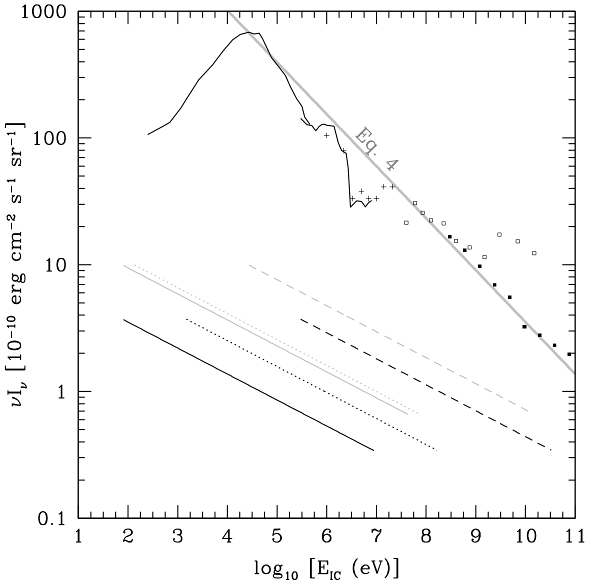

FIG. 1.— Limits on the X-ray and γ-ray backgrounds from IC upscattering ($f = 1$) by secondary $e^\pm$ on CMB photons (solid), FIR photons of $T = 50$ K (dotted), and UV/optical photons of $T = 10^4$ K (dashed), based on the observed γ-ray background. Black is $z = 0$ while grey is $z = 10$. The observed backgrounds are from Gilli et al. (2007) and references therein, Watanabe et al. (2000), Weidenspointner et al. (2000), Strong et al. (2004), and Abdo et al. (2010b).

In the observer-frame, and assuming a typical energy of $3kT_{\rm CMB}(z)$ for a CMB photon, the typical energy of upscattered CMB photons is $E_{\rm IC} \approx E_\gamma^2 k[T_{\rm CMB}(0)](1+z)^2/(m_e^2c^4)$. Plugging eq. 4 into eq. 3, we get:

$$\nu J_\nu \lesssim 2.2\times 10^{-10} f\left(\frac{E_{\rm IC}}{\text{keV}}\right)^{-0.205}(1+z)^{0.41}, \tag{5}$$

in cgs units. For our assumptions about pion kinematics to be valid, we impose the constraint that $E_\gamma \gtrsim 300(1+z)^{-1}$ MeV:

$$E_{\rm IC} \gtrsim 81E_{300}^2\ \text{eV}. \tag{6}$$

Since the γ-ray background is only observed for $E_\gamma \leq 100E_{100}$GeV Abdo et al. (2010b), we also require:

$$E_{\rm IC} \lesssim 9.0E_{100}^2(1+z)^2\ \text{MeV}, \tag{7}$$

where $E_{100} \to 0.2$ at high z because the Universe is opaque at energies above 20 GeV.

CRs may also upscatter ambient light in galaxies: either FIR from dust or UV/optical/NIR from stars. We proceed similarly, finding $E_{\rm IC} \approx E_\gamma^2 kT_{\rm amb}(1+z)/(m_e^2c^4)$. Applying eq. 3 to eq. 4 then gives us in cgs units:

$$\nu J_\nu \lesssim 9.8\times 10^{-11} f\left(\frac{E_{\rm IC}}{\text{MeV}}\right)^{-0.205}\left(\frac{T_{\rm amb}}{50\ \text{K}}\right)^{0.205}(1+z)^{0.205}, \tag{8}$$

valid for 1.5 keV$E_{300}^2(1+z)T_{50} \lesssim E_{\rm IC} \lesssim 165$ MeV$E_{100}^2(1+z)T_{50}$, where $T_{50} = T_{\rm amb}/(50\ \text{K})$.

Figure 1 shows that IC-upscattered CMB light from secondary $e^\pm$ is only a small fraction of the X-ray background, with greater contributions possible for sources at greater z. For $f = 1$ and sources at $z \approx 0$ (10), it makes up $\lesssim 2$% ($\lesssim 6$%) of the background below 0.5 keV, $\lesssim 1$% ($\lesssim 4$%) at 1 keV, $\lesssim 0.3$% ($\lesssim 0.7$%) at 10 keV, $\lesssim 0.4$% ($\lesssim 1$%) at 1 MeV, and $\lesssim 1$% ($\lesssim 3$%) at 10 MeV.

As seen in Figure 1, the bounds on the contribution of upscattered FIR light from secondary $e^\pm$ to the X-ray and γ-ray backgrounds are similar to those for upscattered CMB photons. IC upscattered FIR is $\sim 1f$% or less of the cosmic backgrounds at energies below 2 MeV, and up to $\sim 4f$% of the MeV background. Bounds on upscattered optical/UV light from young stars ($T_{\rm amb} = 10000$ K) follow similarly; these photons are scattered to higher energies. We find that such

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[3] This approximation is accurate to ~ 25% for an E^{-2} steady-state $e^\pm$ spectrum and is even better for an E^{-3} spectrum. Note that 70% of the synchrotron emission of electrons with E_e is in the 2 ln bins centered on ν_C.

IC emission from secondary $e^{\pm}$ is $\lesssim 14f$% of the actual γ-ray background for $z = 0$ sources ($\lesssim 3f$% below 2 MeV), but up to $5f - 10f$% of the MeV background and up to $\sim f/4$ of the GeV background for sources at $z = 10$.

These results imply that IC emission from secondary $e^{\pm}$ does not contribute significantly to the X-ray or soft γ-ray backgrounds. However, they do not apply to primary electrons or to secondary $e^{\pm}$ that have been reaccelerated.

4. THE RADIO BACKGROUND

Star-forming galaxies are expected to be a major source of the radio background. Many of the estimates of the cosmic radio background (such as Protheroe & Biermann 1996; Haarsma & Partridge 1998; Dwek & Barker 2002) use the FIR-radio correlation (FRC), a tight linear empirical relation between the far-infrared and GHz synchrotron luminosities of star-forming galaxies (e.g., Helou et al. 1985; Condon 1992; Yun et al. 2001). Recent measurements by ARCADE suggest that the GHz radio background is 6 times larger than expected from applying the FRC to the IR background (Fixsen et al. 2009; Seiffert et al. 2009). One way to explain this excess is if the FRC evolves with z (Singal et al. 2010). However, most bright galaxies out to $z \approx 2$ seem to lie on the FRC (e.g., Appleton et al. 2004; Sargent et al. 2010), or show only relatively moderate deviations (e.g., Ivison et al. 2010).

Recent work by Lacki et al. (2010b), supported by γ-ray detections of nearby starburst galaxies (Acciari et al. 2009; Acero et al. 2009; Abdo et al. 2010a; Lacki et al. 2010a), suggests that a conspiracy enforces the FRC in starburst galaxies: secondary $e^{\pm}$ dominate the primary electrons, increasing the radio emission by a factor of ~ 10 when combined with spectral effects; while bremsstrahlung, ionization, and IC losses suppress the radio emission by a similar amount at 1 GHz. In principle, an unbalanced conspiracy could enhance radio emission from starbursts (Lacki & Thompson 2010), but such "extra" radio emission comes from pionic secondary $e^{\pm}$, which are accompanied by pionic γ-rays. The pionic γ-ray background sets a hard limit on the synchrotron background from pionic $e^{\pm}$.

Based on the FRC, Loeb & Waxman (2006) and Thompson, Quataert, & Waxman (2007) predicted that starbursts contribute significantly to the neutrino and γ-ray backgrounds. With eq. 2, we *invert* these arguments: the γ-ray background sets upper limits on the radio background from starbursts. These limits also apply to other sources of the radio background as long as secondary $e^{\pm}$ dominate the radio emission.

If pion production creates secondary $e^{\pm}$ with source-frame energy E_e radiating synchrotron at observer-frame frequency ν_C, it also creates pionic γ-rays with source-frame energy $E'_{\gamma} \approx 2E_e$. The observed γ-ray background at $E_{\gamma} = E'_{\gamma}(1+z)^{-1}$ therefore limits the synchrotron background from secondary $e^{\pm}$ at

$$\nu_C \approx 3.2\left(\frac{E_{\gamma}}{\mathrm{GeV}}\right)^2 \tilde{B}_{\mu\mathrm{G}}\mathrm{MHz}, \tag{9}$$

where $\tilde{B}_{\mu\mathrm{G}} = (B/\mu\mathrm{G})(1+z)$.

The ARCADE fit to the radio background in cgs units is

$$\nu J_{\nu} = 3.7 \times 10^{-10}\nu_{\mathrm{GHz}}^{0.4}. \tag{10}$$

where ν_{GHz} is the observed frequency in GHz (Fixsen et al. 2009). The ARCADE data suggest that eq. 10 applies to $\nu_{\mathrm{GHz}} \lesssim 3.4$; at higher frequencies, the errors become too large to determine for sure whether the background spectrum steepens. If the background is entirely from secondaries, equations 2 and 4 give us a lower limit on $\tilde{B}_{\mu\mathrm{G}}$:

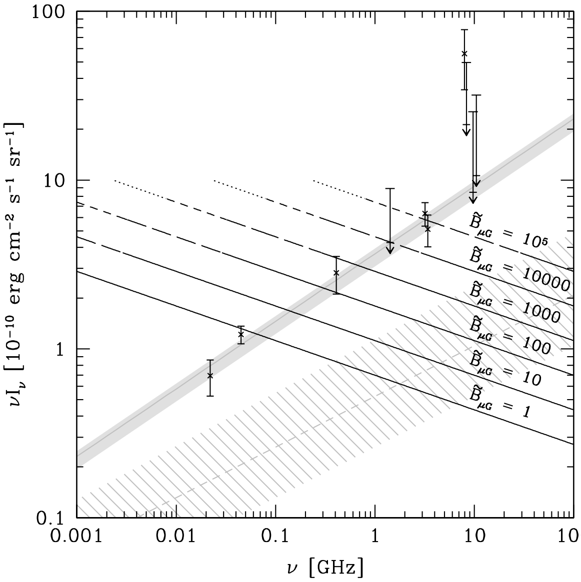

FIG. 2.— Limits on the radio background ($f = 1$) from secondary $e^{\pm}$ at a single redshift. The constraints apply for source populations at $z = 0$ (*solid*), $z = 2$ (*long-dashed*), $z = 5$ (*short-dashed*), and $z = 10$ (*dotted*). The ARCADE fit is the solid grey line, with uncertainties represented by the shading. The predicted radio background from Dwek & Barker (2002) (for a spectral slope $\alpha = 0.7$) is the dashed grey line, with uncertainies represented by the grey cross-hatched area.

$$3.4(1+z)^{-1}f^{-4.9}\nu_{\mathrm{GHz}}^{2.95}\mathrm{mG} \lesssim B. \tag{11}$$

Limits on the radio background are shown in Figure 2. At low frequencies, the ARCADE data is easily consistent with the γ-ray background (below the limits for all $\tilde{B}_{\mu\mathrm{G}}$ in Figure 2). At higher frequencies, large $\tilde{B}_{\mu\mathrm{G}}$ are required: with higher B, lower energy $e^{\pm}$ are responsible for the emission at a given frequency, and eq. 4 allows more power at lower $e^{\pm}$ energies. The limits on J_{ν} are constant in electron energy, but slowly shift in frequency (horizontally in Fig. 2) with different B.

Our limit only applies if $E'_{\gamma} \geq 300E_{300}$ MeV. This combined with eq. 9 implies that eq. 11 is only valid for $\nu_{\mathrm{GHz}} \lesssim 1.01(1+z)^{1.03}f^{2.50}E_{300}^{-1.03}$ and

$$B_{\mathrm{lim}} \approx 3.6f^{2.50}(1+z)^{2.03}E_{300}^{-3.0}\mathrm{mG} \tag{12}$$

is the best lower limit on B that can be derived even if the ARCADE best-fit radio background extends to $\nu \to \infty$. For very high B this means low energy primary electrons must be the source of the background.

The ARCADE background is marginally inconsistent with a secondary origin in most star-forming galaxies. When $f = 1.0$, a secondary origin for the ARCADE excess is difficult to reconcile with the γ-ray background. Eq. 12 rules out the IGM and clusters ($B \lesssim \mu$G), as well as Milky Way-like galaxies (~ 10 μG), and even M82-like starbursts (~ 200 μG) at low redshifts. Only the densest ULIRGs like Arp 220 and AGNs have the milliGauss magnetic fields needed (Condon et al. 1991; Thompson et al. 2006; Robishaw et al. 2008). ULIRGs tend to be the *brightest* (and therefore individually detected) galaxies, and cannot make up most of the ARCADE background (Seiffert et al. 2009). For a $z = 2$ population, $B \gtrsim 34 f^{-4.9}$ mG, but the magnetic field energy density of a galaxy is expected to be less than the hydrostatic pressure of a galactic disk, generally implying $B \lesssim 20-40$ mG (Thompson et al. 2006). For a source population at $z \gtrsim 2$, eq. 12 no longer is the main restriction, and the minimum allowed B decreases (eq. 11). Still, even at $z = 10$, a secondary origin for the ARCADE background requires $B \gtrsim 11 f^{-4.9}$ mG in its sources. Furthermore, there is very little cumulative star-formation at such high z; since eq. 2 applies to each individual source population, the ARCADE sources would have to be extremely efficient at accelerating CR protons and contribute most of the γ-ray background. Otherwise, the small fraction of the γ-ray background from such high-z galaxies would set even tighter limits. Observations at 10 GHz can further constrain the possibility of a $z \approx 10$ source: at higher frequencies, there is more power in the radio background, but at higher energies, there is less power in the γ-ray background.

The steep f dependence means that uncertainties in the γ-ray background and kinematics weaken the constraints on B considerably. However, greater f implies lower B, shifting the minimum allowed electron energy (150 E_{300} MeV) to lower frequency; this relaxes the constraint in eq. 12. Even for $f = 2$, the 3.4 GHz detections requires milliGauss magnetic fields in the sources except at the highest redshifts.[4] Furthermore, the strong f dependence works in reverse: if future observations find that even half of the γ-ray background is not pionic, or not from the sources of the ARCADE excess, then the limits on B strengthen by a factor ~ 30.

Could the ARCADE excess be from primary electrons? Any radio background from primary electrons can be accounted for if all of the protons escape ($F_{\rm cal} \approx 0$). However CR proton escape has to be quite efficient; in the Milky Way, the luminosity of primary electrons is only $1-2\%$ that of CR protons at $\sim$ GeV energies (Schlickeiser 2002). Previous modeling indicates that secondaries are important in starbursts and even the inner Galaxy, but become unimportant for low density regions like the Milky Way at the Solar Circle (Porter et al. 2008; Lacki et al. 2010b). The ARCADE excess could arise from very low density star-forming galaxies. However, galaxies have more gas at high z, making pionic losses more efficient. Another possibility is that primary CR electron (but not proton) acceleration efficiency is much higher in some population of galaxies or starbursts, producing much more synchrotron than expected from secondaries. IC upscattered starlight and bremsstrahlung in such galaxies would be a sign of these extra electrons.

5. CONCLUSION

The observed γ-ray background limits the luminosity of pionic secondary $e^{\pm}$ in the Universe. These secondary $e^{\pm}$ may be important in galaxy clusters and starburst galaxies. We show that simple ratios place bounds on the contribution of IC and synchrotron emission to the radio, X-ray, and γ-ray backgrounds from these secondary $e^{\pm}$. The IC upscattered optical/UV light from these secondaries contributes less than $1/4$ of the MeV γ-ray background; upscattered FIR and CMB from secondaries is ~ 1 % or less of the X-ray background.

We consider the ARCADE-measured radio background in light of these bounds. Secondary $e^{\pm}$ are expected to dominate in starbursts that make up most of the star-formation at $z \gtrsim 1$ (Dole et al. 2006; Caputi et al. 2007; Magnelli et al. 2009). The γ-ray background is marginally inconsistent with a secondary $e^{\pm}$ origin, unless the sources have very strong (milliGauss) magnetic fields, although with considerable uncertainty. However, we cannot rule out primary electrons in some population of low density galaxies or other sources (where pionic losses are minimal) as the cause of the ARCADE measurement.

These constraints can be improved by measuring the leptonic contribution to the γ-ray background, which may be substantial (Prodanović & Fields 2004). Resolving out the contribution of each class of sources to the γ-ray background would tighten the limits on their contribution to the other backgrounds. Note that this holds for the sources of the ARCADE excess specifically: even if most of the γ-ray background is star-formation, the sources of the ARCADE excess may contribute only a fraction of it. Finally, future pionic neutrino background measurements above 100 GeV, such as with IceCube (e.g., DeYoung et al. 2009), would help limit the IC and synchrotron backgrounds from the highest energy secondary $e^{\pm}$.

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[4] If half of the ARCADE background is from secondary $e^{\pm}$ and our other approximations are exact, $f = 2$.

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