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A New Way to Measure How Much Light Has Been Produced Since the Universe was Born

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Abstract. The extragalactic background light (EBL) that permeates the Universe in the optical-IR is very closely connected to the galaxy/ large scale structure formation in our Universe. Unfortunately, measuring the EBL has been proven very difficult, for very simple reasons that I will discuss in the first part of my talk. Luckily, we found a parameter-free way to break the deadlock of measuring the EBL with Fermi, NASA's new Gamma-ray satellite, observations of the lobes of nearby radio galaxies. Our method measures the energy density of the Cosmic Infrared Background at the location of radio galaxies by using *Fermi* Gamma-ray and multiwavelength observations of their radio lobes. We present an application of our method for the well-studied radio galaxy Fornax A, showing that *Fermi* observations will provide us with a direct, model independent measurement of the Cosmic Infrared Background.

1. Introduction

The extragalactic background light (EBL) is essentially the time-integral of the light production and re-processing in the Universe. Unfortunately, the EBL is very difficult to measure, due to the dominance of the foreground interplanetary dust. Although ingenious methods have been developed to estimate and subtract these backgrounds, the level of the EBL emission remains purely constrained (Hauser & Dwek 2001; Kashlinsky 2005). Robust lower limits to the EBL level have been set by galaxy counts (Dole, et al. 2006).

We propose to measure the EBL by detecting the high energy emission produced when EBL photons IC-scatter off the relativistic electrons of extragalactic sources. Inverse Compton (IC) scattering of the cosmic microwave background (CMB) has already been detected in the X-rays from the lobes of a handful of radio galaxies (e.g. Erlund, Fabian, & Blundell (2008)). The idea we propose is based on the fact that, although the EBL energy density is $\sim$ only a few percent that of the CMB, ($U_{EBL} = k\,U_{CMB},\ k \sim$ few $\times\,10^{-2}$), the CIB and COB photons have energies correspondingly $\sim$ 10 and 1000 times higher than those of the CMB. For a source with a given electron energy distribution (EED), its electrons will IC-scatter the CMB and EBL photons, and the IC emission will have a spectral shape related to that of the CMB and EBL, shifted in frequency by $\gamma^2_{\rm max}$, where $\gamma_{\rm max}$ is the maximum Lorentz factor of the EED (in practice, the Lorentz factor where the EED becomes steeper than γ^{-3}).

Therefore, the IC emission from such a source will consist of a powerful component due to CMB seed photons and two weaker components with powers of a few percent that of the up-scattered CMB, but shifted in energy by factors $\sim$ 10 and 1000. The cleanest spectral separation of these IC components results from a power-law EED characterized by a clear high energy cutoff.

If this IC emission can be detected, we will observe the high energy imprint of the CMB+EBL at the location of our source. This imprint will provide us with the level and spectral shape of the CIB+COB at the source. Here we show that the lobes of radio galaxies, if characterized by an EED with a suitably located high energy cutoff, can be used to measure the EBL at their location through *Fermi* observations, and we demonstrate our method on the radio lobes of the nearby bright radio galaxy Fornax A.

2. Source requirements

We discuss now the requirements that candidate sources need to satisfy. We exclude blazars and radio quasars, whose GeV emission is dominated by their pc-scale jet IC emission. The favored sources are the extended lobes of radio galaxies with weak active galactic nuclei (AGN) that are not expected to be significant GeV emitters. Moreover weak AGN will not contribute optical-IR seed photons to the radio lobes, beyond those contributed by the host galaxy. In addition to the lobe synchrotron radio emission, the lobe IC emission off the CMB must also be detected, to determine the lobe magnetic field and the EED normalization, *without resorting to the equipartition assumption. This parameter-free determination of the EED is necessary for a one-to-one mapping of the EBL to its IC emission.* The only cases for which IC off the CMB has been unambiguously identified is the X-ray emission of the lobes of a handful of radio galaxies. Given that in these sources the X-ray spectral index $\alpha_x < 1$, the peak of the IC emission off the CMB is at energies than X-rays, and the peak of the IC emission of the CIB and COB is at energies $\sim$ 10 and 1000 times higher correspondingly. The peak energy of the three IC components $\propto \gamma^2_{\rm max}$. This means that the only energy range at which we could expect to detect the IC emission off the CIB and COB is the GeV energy range covered by *Fermi*, and this for a relatively narrow range of $\gamma_{\rm max} \sim 10^5$ that keeps the IC off the CMB below the 100 MeV lower energy threshold of *Fermi*. Larger values would dominate the *Fermi* band by IC off the CMB, and smaller values would shift part or all of the IC off the EBL below the 100 MeV threshold. Sources that

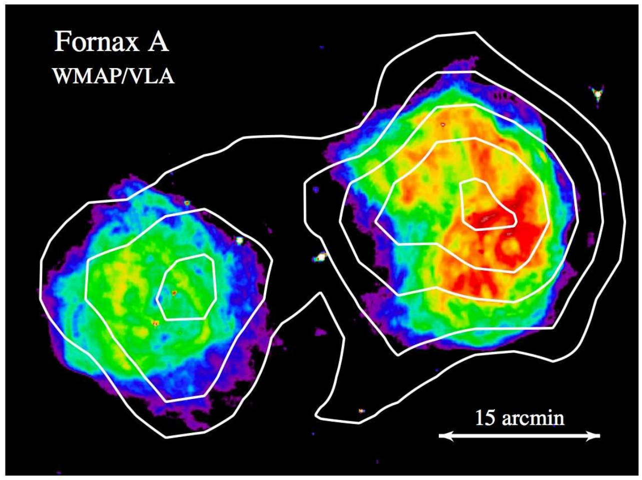

Figure 1. The 1.5 GHz VLA (gray scale; Fomalont et al. (1989)) and 61 GHz WMAP (contours; Hinsaw et al. (2007)) images of Fornax A.

satisfy the $\gamma_{\max}$ constraint are required to have no other γ-ray source within *Fermi*'s angular resolution ($\sim$ 0.8 deg at 1 GeV). A high Galactic latitude is desirable, because it reduces contamination from Galactic sources. Finally, high frequency radio observations and existing EGRET limits of the γ-ray flux are needed to constrain the critical quantity $\gamma_{\max}$. Satisfying all these constraints is challenging. We now show that at least one source, Fornax A, does.

3. EBL γ-ray imprints: the case of Fornax A

Fornax A is a high Galactic latitude ($-57°$) bright radio galaxy at a distance of 18.6 Mpc (5.41 kpc arcmin^{-1}), hosted by the massive elliptical NGC 1316 that shows a LINER core (Isobe, et al. 2006). Fig. 1 shows the 1.5 GHz VLA map (Fomalont et al. 1989) with the 61 GHz 3-yr WMAP (Hinsaw et al. 2007) contours superimposed. In the radio it shows two relaxed lobes of $\sim 20'$ diameter separated by $\sim 30'$. We use radio data Isobe, et al. (2006), replacing the extrapolated 100 MHz data point Finley & Jones (1973) with an 86 MHz measurement (Mills, Slee, & Hill 1960).

We also use the integrated 3-yr WMAP fluxes Hinsaw et al. (2007) from 23 to 61 GHz, which are larger than the 1-yr WMAP fluxes quoted by Cheung et al. (2007). The total radio spectrum has a spectral index of $\alpha_{\rm r} = 0.68 \pm 0.1$ Isobe, et al. (2006), increasing to $\sim$0.8 in the WMAP band Hinsaw et al. (2007). The western lobe is $\sim$1.9 times brighter than the eastern in the VLA 1.5 GHz map, but this ratio is only $\sim$1.3 in the WMAP 41 GHz and 61 GHz maps. The lobes are not well separated by WMAP at 23 and 33 GHz, and the source is not well detected in 91 GHz. The lobes have been detected in X-rays by ROSAT (Feigelson et al. 1995) and XMM (only the eastern lobe was observed) with $\alpha_X = 0.62^{+0.24}_{-0.15}$ (Isobe, et al. 2006), consistent with the radio index α_r (here we assume $\alpha_r = \alpha_X = \alpha = 0.65$). The lobe X-ray emission is due to IC-scattered

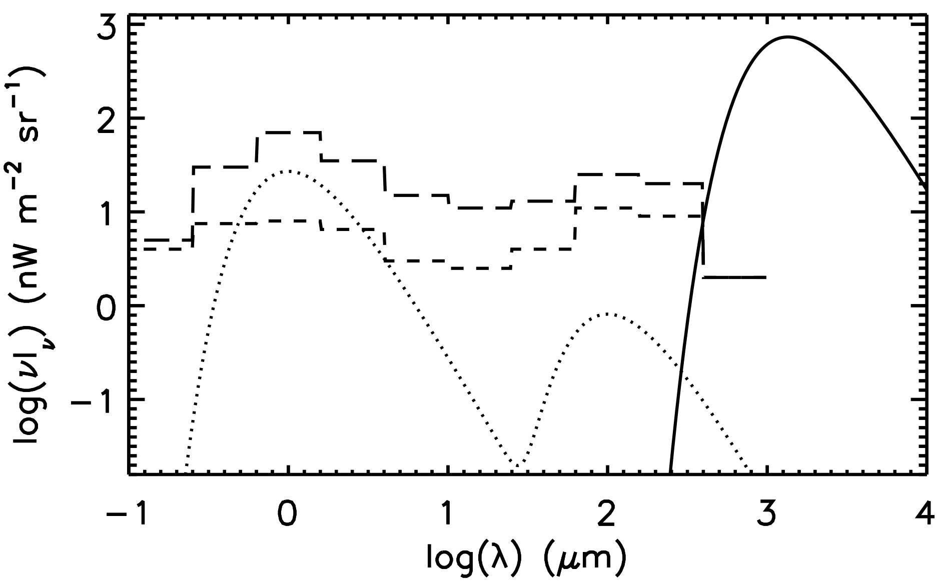

Figure 2. The seed photons at the lobes of Fornax A. CMB: solid line. Host Galaxy: dotted line. Short dashed line: Low estimate of the EBL. Long-dashed line: High estimate of the EBL.

CMB photons (the synchrotron-self Compton level is much below the observed flux). Because the CMB energy density is given, the X-ray flux and spectral index uniquely define the EED slope and normalization. With this at hand, the magnetic field required to produce the radio emission is uniquely determined to $B = 1.7\ \mu$G, close to the equipartition field of $B = 1.55\mu$G (Isobe et al. 2006).

4. The photon field at the lobes

The electrons in the lobes will also experience the directional photon field of the host galaxy. The unknown source orientation affects the IC level through the angle of IC scattering (Dermer, Schlickeiser, & Mastichiadis 1992) and by determining the distance of the lobes from the host galaxy. The combined effect results in a $\theta-$dependence of the total IC flux from both lobes due to galactic seed photons $f_{IC,gal} \propto [(1+\cos\theta)^2 + (1-\cos\theta)^2]\sin^2\theta$, that has a flat maximum at $\theta = \pi/2$, remaining within 10 % of the maximum for $\theta \sim 60^\circ$. We assume that the source axis forms an angle of $\theta = 60^\circ$ to the line of sight, using an average lobe projected distance of $15'$ from the galaxy. Given the flat θ-dependence of $f_{IC,gal}$ for $\theta \sim 60^\circ$, our choice represents the maximum IC emission of the lobes due to host galaxy seed photons. The SED of the host galaxy (Dale et al. 2007) is comprised of two components, the first one peaking at $\sim 1\mu$m, and the second one, ~ 30 times weaker, peaking at $\sim 100\mu$m. We approximate its SED as the sum of two black bodies and we plot in Fig. 2 with a dotted line the resulting isotropic equivalent photon field intensity at the lobes.

For the EBL we adopt a lower and an upper level (short and long dashed lines respectively in Fig. 2) of the expected background, by roughly following

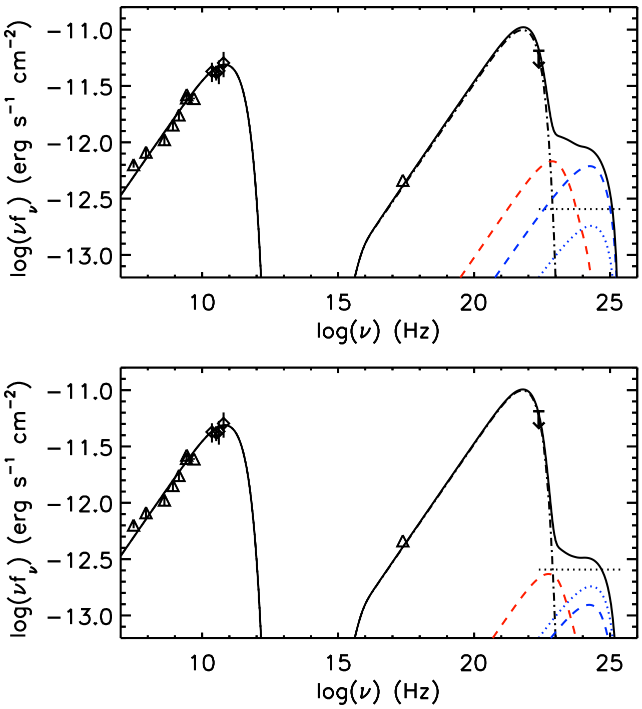

Figure 3. The radio, WMAP, and X-ray flux from both radio lobes, as well as the EGRET upper limit. The solid line is the model SED, resulting from a magnetic field of $B = 1.7\ \mu$G, and a power law EED with slope $p = 2.3$ and maximum Lorentz factor $\gamma_{\rm max} = 1.6 \times 10^5$. These parameters are strongly constrained by the data, and have a very small range in which they can vary. We also plot the IC due to the CMB (dot-dash line), the CIB and COB (red and blue broken line), as well as the maximum expected level of the IC emission due to the optical photons of the host galaxy (dotted blue line). The black dotted line marks the 2 year, 5σ *Fermi* sensitivity limit. The lower (upper) panel corresponds to the low (high) level EBL.

the range considered by Maxin & Raue (2007). This is meant to represent a plausible range of the yet unknown EBL. Without loss of generality, we choose to represent the EBL as a histogram. We note here that the lower limit is rather well established, because it relies on galaxy counts Dole, et al. (2006). As can be seen from Fig. 2, the lobe photon field at the $\lambda < 10\mu$m has comparable contributions from the galaxy and the COB for all plausible COB levels, while at $\lambda > 10\mu$m and up to $\sim 300\mu$m, the photon field is dominated by the CIB by more than a factor of ten, even for the lower EBL limit.

5. Anticipated Fermi GeV emission

We present the SED of the IC emission for the lower and higher EBL cases in Fig. 3. The black solid line is the total SED. The dotted blue line is the

IC emission due to the host galaxy optical photons. The IC emission due to the host galaxy IR photons is too weak to appear in the plots. To identify the contribution of the COB and CIB seed photons, we plot with broken blue and red lines the IC emission due to seed photons with $\lambda < 10\mu$m (five short-λ EBL bins in Fig. 2) and with $\lambda > 10\mu$m (five long-λ EBL bins in Fig. 2) respectively. We also plot the 2-year *Fermi* 5-σ sensitivity limit (dotted black line). We see that the IC of the EBL plus galaxy seed photons is detectable in both cases, although in the lower EBL case it is only somewhat above the 5-σ limit.

Note that, while the IC emission due to $\lambda > 10\mu$m seed photons is CIB dominated, the COB and galaxy IC contributions from the $\lambda < 10\mu$m seed photons are comparable for both low and high EBL cases. The IC emission from these seed photons dominates the flux at $\nu \sim 10^{24}$ Hz (corresponding to ~ 5 GeV), with no contribution from lower energy seed photons. Given that the $\lambda < 10\mu$m seed photons are an unspecified mixture of photons from the COB and the host galaxy, a measurement of the IC emission at ~ 5 GeV energies will provide us with an upper limit of the COB. The total emission at energies $\sim 1-$few GeV is due to comparable contributions of $\lambda < 10\mu$m and $\lambda > 10\mu$m seed photons. The key in disentangling the contribution of seed photons of different energies is to consider that as the seed photon energy increases, their IC radiation reaches higher energies: at a *Fermi* energy ϵ_γ, only seed photons with energy $\sim \epsilon_\gamma/\gamma^2_{\rm max}$ contribute. This can be used to reconstruct the seed photon SED starting from the optical, needed to model the high energy part of *Fermi* observations. Gradually, the lower energy IR seed photons will be incorporated at appropriately chosen levels, to model the emission at gradually lower *Fermi* energies. We anticipate that in the next two years we will finally have a parameter free measurement of the EBL.

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