Non-thermal emission in the lobes of Fornax A

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ABSTRACT

Current measurements of the spectral energy distribution in radio, X-and-γ-ray provide a sufficiently wide basis for determining basic properties of energetic electrons and protons in the extended lobes of the radio galaxy Fornax A. Of particular interest is establishing observationally, for the first time, the level of contribution of energetic protons to the extended emission observed by the Fermi satellite. Two recent studies concluded that the observed γ-ray emission is unlikely to result from Compton scattering of energetic electrons off the optical radiation field in the lobes, and therefore that the emission originates from decays of neutral pions produced in interactions of energetic protons with protons in the lobe plasma, implying an uncomfortably high proton energy density. However, our exact calculation of the emission by energetic electrons in the magnetized lobe plasma leads to the conclusion that all the observed emission can, in fact, be accounted for by energetic electrons scattering off the ambient optical radiation field, whose energy density (which, based on recent observations, is dominated by emission from the central galaxy NGC 1316) we calculate to be higher than previously estimated.

Key words: galaxies: cosmic rays – galaxies: active – galaxies: individual: Fornax A – gamma rays: galaxies – radiation mechanisms: non-thermal

1 INTRODUCTION

The spectral energy distributions (SED) of energetic particles outside their galactic sources are important for determining basic properties of the populations and for assessing the impact of the particle interactions in the magnetized plasma of galactic halos and galaxy clusters. Knowledge of these distributions is generally quite limited and is based largely on just radio observations. Measurements of non-thermal (NT) X-ray and more recently also γ-ray emission from the extended lobes of several nearby radio galaxies provide, for the first time, a tangible basis for detailed modeling of the spectral distributions of energetic electrons and protons in the lobes. Sampling the SED over these regions by itself, with only limited spatial information, yields important insight on the emitting electrons and possibly also on energetic protons whose interactions with the ambient plasma may dominate any observed ∼ 100 MeV emission (from the decay neutral pions).

The very luminous nearby radio galaxy Fornax A best exemplifies the level of spectral modeling currently feasible with supplementary X- and γ-ray measurements. This system, located at a luminosity distance \( D_L = 18.6\, \text{Mpc} \) (Madore et al. 1999) in the outer region of the Fornax cluster, consists of the elliptical galaxy NGC 1316 and two roughly circular (radius \( R \approx 11' \)) radio lobes centered (at a distance \( d \approx 17.5' \)) nearly symmetrically on its east and west sides (e.g., Ekers et al. 1983; Isobe et al. 2006; McKinley et al. 2015). The galaxy is at the center of a (sub-cluster) group of galaxies, thought to be falling towards the cluster center (Drinkwater et al. 2001), which includes the star-forming galaxies NGC 1310, NGC 1316C, and NGC 1317.

Detailed modeling of emission from the lobes of Fornax A was carried out by McKinley et al. (2015) and Ackermann et al. (2016); these included fitting radio, WMAP, Planck, NT emission at 1 keV, and Fermi measurements. Whereas the radio and X-ray data points can be fit with a truncated electron spectrum, the indication from both analyses was that Compton scattering of the (radio-emitting) electrons off the extragalactic background light (EBL) and some assumed level of the local optical radiation fields, are too weak to account for the emission observed by Fermi. This led to the conclusion that the γ emission could only be interpreted as \( \pi^0 \)-decay from \( pp \) interactions; if so, this would imply a very high proton energy density in the lobes.
Specifically, the deduced proton energy density was estimated to be \( \sim 10^2 \) higher than the gas thermal energy density, \( \sim 1 \text{ eV cm}^{-3} \) (assuming \( n_H = 3 \cdot 10^{-4} \text{ cm}^{-3} \), for \( k_B T = 1 \text{ keV} \); Seta et al. 2013). To ameliorate this clearly problematic result, McKinley et al. (2015) suggested that \( pp \) interactions occur mostly in filaments with very high gas over-density and enhanced magnetic field. This could very well be unrealistic given the implied enhancement also in thermal X-ray emission and the enhanced level of radio emission by secondary electrons and positrons produced in charged pion decays. Such enhancements would have likely been detected in both radio maps and X-ray images of the lobes (e.g., Tashiro et al. 2001, 2009; Isobe et al. 2006).

In an attempt to clarify and possibly remove some of the modeling uncertainty we re-assess key aspects of conditions in the Fornax A lobes, and repeat detailed calculations of the emission by energetic electrons and protons. We base our analysis on all the available radio, X-ray, and \( \gamma \)-ray measurements, and on newly-published detailed surface-brightness distribution of stellar emission from the central galaxy NGC 1316. The latter emission is sufficiently intense to constitute the most dominant optical radiation field in the lobes; consequently, the predicted level of \( \gamma \)-ray emission is significantly higher than in previous estimates. In Section 2 we briefly review the observations of NT emission in the various bands and the optical radiation field in the lobe region. In Section 3 we describe our calculations of the lobe SED model, which is fit to observations in Section 4. We conclude with a short discussion in Section 5.

2 OBSERVATIONS OF NT EMISSION FROM FORNAX A

Fornax A lobes have been extensively observed over a wide range of radio and microwave frequencies, in the (soft) X-ray band, and at high energies (\( \geq 100 \text{ MeV} \)) with the Fermi/LAT. We use the updated measurements of the lobes in all these spectral regions; the dataset used in our analysis is specified in Table 1 where the listed flux densities are the combined emission from both the east and west lobes. On sufficiently large scales the radio and X-ray emission appears smooth across the lobes, but with east lobe brightness \( \sim 1/2 \) that of the west lobe.

We briefly review the most relevant observations used in our analysis, avoiding many of the details that have already been presented in the two recent similar analyses by McKinley et al. (2015) and Ackermann et al. (2016). A reasonably accurate description of the optical and IR fields in the region of the lobes is important for a correct calculation of the predicted high energy X-and-\( \gamma \) emission from Compton scattering of energetic electrons (and positrons), a new aspect of our analysis that leads to a different conclusion on the possible origin of the emission observed by Fermi.

McKinley et al. (2015) compiled a comprehensive list of previously published radio measurements, supplemented by WMAP and Planck data in the 22-143 GHz band, and at 154 MHz (observed with the Murchison Widefield Array). When available, single-lobe flux densities were added up to obtain total lobe emission, implying a relatively low contribution from the central galaxy. The flux drops sharply at \( \nu > 30 \text{ GHz} \).

X-ray observations and spectral analyses were reported by several groups. Early on Feigelson et al. (1995), using spatially-unresolved ROSAT data, argued in favor of a diffuse NT origin of the X-ray emission. Kaneda et al. (1995), based on a spectral decomposition of ASCA 1.7-7 keV data, suggested that \( \sim 1/3 \) and \( \sim 1/2 \) of the west and east lobe 1 keV flux is NT, with a spectral index consistent with the radio index. This suggestion was confirmed by Tashiro et al. (2001) who, based on follow-up ASCA data, concluded that \( \sim 1/2 \) of the west lobe flux is NT; Tashiro et al. (2009), analyzing west-lobe Suzaku data with a multi-component spectral model, claimed the 0.5-20 keV spectrum to be fit by a power-law (PL) with an energy index consistent with the radio index. Similarly, Isobe et al. (2006) found that east-lobe XMM-Newton 0.3-6 keV data are well fit by a PL with an index consistent with the radio index. Following McKinley et al. (2015), we assume that the 1 keV flux densities (Tashiro et al. 2009, Isobe et al. 2006) are indeed NT.

Based on 6.1 yr of Pass 8 Fermi/LAT data, Ackermann et al. (2016) reported extended \( >100 \text{ MeV} \) lobe emission consistent with the radio lobes’ morphology, and point-like emission from the radio core. A similar level of emission, based on a smaller dataset and a point-source spatial model, had been previously reported by McKinley et al. (2015).

2.1 Optical radiation fields in the lobes

The superposed radiation field in the lobe region has cosmic and local components.

a) Cosmic Fields

i) The cosmic microwave background (CMB) is described as an undiluted Planckian with \( T_{\text{CMB}} = 2.735 \text{K} \) and integrated intensity \( \nu I_\nu = 960 \text{nW m}^{-2} \text{sr}^{-1} \) and energy density \( u_{\text{CMB}} = 0.25 \text{ eV cm}^{-3} \) (Cooray 2016);

ii) The cosmic IR background (CIB), originating from dust-reprocessed starlight integrated over the star formation history of galaxies, is described as a diluted Planckian with \( T_{\text{CIB}} = 290 \text{K} \) (from its 100 \( \mu \)m peak) and integrated intensity \( \nu I_\nu = 30 \text{nW m}^{-2} \text{sr}^{-1} \) and energy density \( u_{\text{CIB}} = 7.85 \cdot 10^{-5} \text{eV cm}^{-3} \) (Cooray 2016);

iii) The cosmic optical background (COB), originating from direct starlight integrated over all stars ever formed, is described as a diluted Planckian with \( T_{\text{COB}} = 2900 \text{K} \) (from its 1 \( \mu \)m peak) and integrated intensity \( \nu I_\nu = 24 \text{nW m}^{-2} \text{sr}^{-1} \), and \( u_{\text{COB}} = 6.28 \cdot 10^{-3} \text{eV cm}^{-3} \) (Cooray 2016).

The dilution factor, \( C_{\text{bb}} \), is the ratio of the actual energy density, \( u \), to the energy density of an undiluted blackbody at the same temperature \( T \), namely \( u = C_{\text{bb}} u_{\text{Planck}} \), where \( a \) is the Stefan-Boltzmann constant. The dilution factors of the cosmic fields are, \( C_{\text{CMB}} = 1 \), \( C_{\text{CIB}} = 10^{-5.629} \), and \( C_{\text{COB}} = 10^{-13.726} \).
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Table 1. Emission from the lobes.

| Frequency log(ν/Hz) | Energy Flux 10^{-12} erg cm^{-2} s^{-1} | Reference |
|---------------------|-----------------------------------------|-----------|
| 7.476               | 0.634 ± 0.063                           | Finlay & Jones 1973 |
| 7.933               | 0.814 ± 0.163                           | Mills et al. 1960 |
| 8.188               | 1.16 ± 0.220                            | McKinley et al. 2015 |
| 8.611               | 1.06 ± 0.106                            | Robertson 1973; Cameron 1971 |
| 8.778               | 1.86 ± 0.465                            | Piddington & Trent 1956 |
| 8.926               | 1.42 ± 0.128                            | Jones & McAdam 1972 |
| 9.151               | 1.77 ± 0.142                            | Ekers et al. 1983 |
| 9.179               | 1.77 ± 0.199                            | Fomalont et al. 1989 |
| 9.431               | 2.65 ± 0.265                            | Shimmings 1971 |
| 9.699               | 2.74 ± 0.411                            | Gardner & Whiteoak 1971 |
| 10.353              | 3.18 ± 0.159                            | McKinley et al. 2015 |
| 10.453              | 3.10 ± 0.217                            | McKinley et al. 2015 |

b) Local Fields

The local radiation fields are dominated by emission from the central galaxy, NGC1316, whose SED shows two thermal humps, IR and optical. The IR hump peaks at 100 μm and has a bolometric luminosity $L_{\text{IR}} \simeq 1.5 \cdot 10^{13}$ erg s^{-1}; its effective temperature is $T_{\text{gal,IR}} = 29$ K. The optical hump peaks at 1 μm, corresponding to an effective temperature $T_{\text{gal,OPT}} = 2900$ K, and has a bolometric luminosity $L_{\text{opt}} \sim 1.4 \cdot 10^{10}$ erg s^{-1} from the total r-band magnitude (Iodice et al. 2017), converted to bolometric magnitude, as detailed below.

The optical stellar surface-brightness distribution of NGC1316, with a half-light radius of 135″, can be decomposed into a (nearly) de Vaucouleurs spheroid plus an exponential envelope (Iodice et al. 2017). Its deprojection, i.e., the emissivity distribution, will be used to model the distribution of the photon energy density.

The de Vaucouleurs profile is given by $σ(R) = σ_0 \exp[-δ (R/R_e)]^α$, where $σ_0$ is the central surface brightness, $δ = 7.67$, $α = 1/4$, and $R_e$ is the radius encompassing half the (integrated) luminosity. The corresponding deprojected profile can be well approximated by the analytical expression $ρσ = ρ_0 x^{-β} \exp[-x^β]$ where $x = r δ^2/R_e$, $ρ_0 = σ_0 δ^2/(2 R_e) \Gamma(8)/\Gamma((3 - β)/α)$, and $β = 0.855$ (Mellier & Mathieu 1987). From r-band surface photometry measurements (Iodice et al. 2017) $R_e = 87″$ ($\sim 7.8$ kpc) and $R_e = 20.76$ mag arcsec^{-2}. The latter can be transformed into b-band magnitudes using $b = r + 1.33 (g - r) + 0.20$ (Jester et al. 2005), with $g - r = 0.74$ inside the half-light radius (Iodice et al. 2017): $μ_b = 21.94$ mag arcsec^{-2}. The b-band bolometric correction, needed to estimate the full-band magnitude, is $BC_b = -0.85 - (b - v)$ mag (Buzzoni et al. 2006); with $b - v = 0.84$ (within 2 $R_e$; Cantiello et al. 2010), $BC_b = -1.69$. Thus $μ_{b, bol} = 20.25$ mag arcsec^{-2}, which corresponds to $σ_{b, bol} = 264.9$ erg cm^{-2} pc^{-2}; from $σ_b = e^{−74} σ_e$ we finally derive $σ_{b, bol} = 228.3$ erg cm^{-2} s^{-1}. The resulting volume brightness distribution of the NGC 1316 stellar spheroid is

$$ρ_{\text{bol}}(r) = 4.7 \cdot 10^{-21} \left(\frac{r}{R_e}\right)^{-0.855} \exp\left[-7.67 \left(\frac{r}{R_e}\right)^{1/4}\right] \text{erg cm}^{-3}\text{s}^{-1}. \quad (1)$$

The deprojection of the exponential profile, $I(R) = I_0 \exp[-R/h]$, where $I_0$ is the central surface brightness and $h$ is a characteristic scale, is expressed in terms of a modified Bessel function of the second kind, $ρ(r) = I_0/(π h) K_0(r/h)$ (Baes & Gentile 2011). From Iodice et al. 2017 we get $μ_{o, r} = 22.79$ mag arcsec^{-2} and $h_e = 317″$ ($\sim 28.6$ kpc); however, the stellar envelope is measured to be considerably bluer at larger radii (see their Figs. 4, 6-left), implying $h_e \sim 360″$ ($\sim 32.5$ kpc). Following the same procedure adopted for the spheroid, $I_0, bol = 0.016$ erg cm^{-2} s^{-1}. The resulting emissivity distribution of the NGC 1316 stellar envelope is

$$ρ_{\text{env}}(r) = 5.2 \cdot 10^{-26} K_0(r) \text{erg cm}^{-3}\text{s}^{-1}. \quad (2)$$

We can now calculate the galaxy optical photon energy density, $u_{\text{gal,OPT}}$, in the lobes. Given that the current X- and γ-ray data are not spatially resolved, we take a volume average as a nominal value. The exact calculation accounting for the full light distribution and averaging over the volume of the lobes requires a 6D integration, but given the approximate nature of our treatment, we compute $u_{\text{gal,OPT}}$ as a line average along the nearest-to-farthest–boundary lobe diameter of the stellar spheroid and envelope components

$$u_j = \frac{ρ_0 λ_j}{8πcρ_p} \int_0^{2π} \int_0^{∞} \int_0^{2π} \int_0^{π} f_j \left(\sqrt{\rho \sin(θ) \sin(φ) + d + ξ^2} + [ρ \cos(θ)]^2 + [ρ \sin(θ) \cos(φ)]^2\right) \sin(θ) \, dθ \, dφ \, dρ \, dξ \text{erg cm}^{-3} \quad (3)$$

1. The total-IR flux is computed from the IRAS flux densities at 12, 25, 60 and 100μm (Golombek et al. 1988) using $f_{IR} = 1.8 \cdot 10^{-11}$ (13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100}) erg cm^{-2} s^{-1} (Helou et al. 1988).
2. $μ(\text{mag arcsec}^{-2}) = M_{\text{bol,⊙}} + 21.572 - 2.5 \log (L_{\text{bol,⊙}}/\text{pc}^{-2})$, with $M_{\text{bol,⊙}} = 4.74$ mag and $L_{\text{bol,⊙}} = 3.83 \cdot 10^{33}$ erg s^{-1}.
where $j$ denotes either component, $\lambda_j = R_{e,j}$, and $f_j(R/\lambda)$ is given by Eqs. (1) and (2). The resulting $u_j$ values are $7.500 \times 10^{-14}$ erg cm$^{-3}$ (disk) and $4.556 \times 10^{-14}$ erg cm$^{-3}$ (envelope).

Finally, $C_{\text{gal OPT}} = 10^{-12.65}$. A similar calculation yields $C_{\text{gal IR}} = 10^{-7.00}$. Thus, $n(\epsilon)$ includes the CMB, cosmic and local (NGC 1316) IR/optical radiation fields.

Further contributions to the local optical radiation field should also be assessed. The star-forming galaxies NGC 1310, NGC 1316C, and NGC 1317, members of the subcluster that contains Fornax A, lie close to NGC 1316. As their estimated projected separations from NGC 1316 ($\sim 20'$, $30'$, $6'$) are comparable to the Fornax A size, they are likely located within the lobe region. Their cumulative luminosity is relatively modest, $\lesssim 15\%$ of the NGC 1316 luminosity (Iodice et al. 2017).

## 3 NT EMISSION IN THE LOBES

Radio emission in the lobes is by electron synchrotron in a disordered magnetic field whose mean value $B$ is taken to be spatially uniform, and X-$\gamma$ emission is by Compton scattering of the electrons by the CMB and optical radiations fields. A significant energetic proton component could yield additional radio emission by secondary electrons and positrons produced by $\pi^\pm$ decays, and $\gamma$-ray emission from $\pi^0$ decay. The calculations of the emissivities from all these processes are well known and, need not be specified here. We will limit our brief treatment here to features in the calculations that result from the observational need to explicitly assume (at the outset) that the particle spectral distributions are truncated.

Given the lack of any information about temporal evolution of the lobe emission, it is appropriate to represent the spectral electron and proton numbers by time-independent, truncated PL distributions in the Lorentz factor $\gamma$ and energy $E$. The spectral (in $\gamma$) number of electrons in a lobe is then

$$N_e(\gamma) = N_{e,0} \gamma^{-\nu_e} \quad \text{in the interval } [\gamma_{\min}, \gamma_{\max}],$$

(4)

where $\nu_e = \nu_0 \gamma^2 \sin \theta$ (with $\nu_0 = \frac{2\pi B}{c} \frac{m_e}{e}$) is the cyclotron frequency). The modified Bessel function of the second kind, $K_{\nu/3}(\xi)$, has the integral representation

$$K_{\nu/3}(\xi) = \int_0^\infty e^{-\xi \cosh(t)} \cosh \left( \frac{\nu}{3} t \right) dt.$$  

(7)

With $x = \nu/\nu_c = \nu/\nu_0 \gamma^2 \sin \theta$ Eq. (6) transforms into

$$j_s(\nu) = N_{e,0} \frac{\sqrt{3}}{4} \frac{e^3}{m_e c^2} \left( \frac{\nu}{\nu_0} \right)^{-\frac{\nu-1}{3}} \int_0^x \sin \theta^{\frac{\nu-1}{3}} \cosh \left( \frac{\nu}{3} \theta \cosh t \right) dt ds d\theta.$$  

(8)

This 4D integral can be readily reduced to a 3D integral

$$j_s(\nu) = N_{e,0} \frac{\sqrt{3}}{4} \frac{e^3}{m_e c^2} \left( \frac{\nu}{\nu_0} \right)^{-\frac{\nu-1}{3}} \int_0^x \sin \theta^{\frac{\nu-1}{3}} \cosh \left( \frac{\nu}{3} \theta \cosh t \right) dt ds d\theta.$$  

(9)

The (differential) number of scattered photons in Compton scattering of electrons from the above distribution by a diluted (dilution factor $C_{\text{dil}}$) Planckian (temperature $T$) radiation field,

$$n(\epsilon) = C_{\text{dil}} \frac{8\pi}{h^3 c^3} \frac{\epsilon^2}{e^{\epsilon/k_B T} - 1} \text{ cm}^{-3} \text{ s}^{-1} \text{ erg}^{-1},$$

(10)

is (Blumenthal & Gould 1970)

$$\frac{d^2N_{e,\epsilon}}{dt d\epsilon} = \int_{\epsilon_{\min}}^{\epsilon_{\max}} \int_{\max}^{\max} \frac{N_e(\gamma) \pi r_0^2 c N(\epsilon)}{2\gamma^4 \epsilon^2} \left( 2\epsilon_1 \ln \frac{\epsilon_1}{4\gamma_1} + \epsilon_1 + 4\gamma_1 \epsilon - \frac{\epsilon_1^2}{2\gamma_1^2} \right) d\gamma d\epsilon \text{ cm}^{-3} \text{ s}^{-1} \text{ GeV}^{-1},$$

(11)

where $\epsilon$ and $\epsilon_1$ are the incident and scattered photon energies, and $r_0 = (e^2/m_e c^2)^{1/2}$ is the electron classical radius. In Eq. (11) we set $\epsilon_{\min} = 0$ and $\epsilon_{\max} = h/10^{12}$, $10^{13}$, and $10^{15}$ Hz for the CMB, IR, and optical components, respectively.
3.2 Pion decay yields

Interactions between energetic and (thermal) gas protons lead to the production of \( \pi^0 \) and \( \pi^\pm \), whose decays yield \( \gamma \) rays and \( e^\pm \), respectively.

The \( \pi^0 \)-decay \( \gamma \)-ray emissivity is (e.g., Stecker 1971)

\[
Q_\gamma(E_\gamma)|_{\pi^0} = 2 \int_{E_\pi^{\text{min}}}^{E_\pi^{\text{max}}} \frac{Q_\gamma(E_{\pi^0})}{\sqrt{E_{\pi^0} - m_{\pi^0}^2}} \, dE_{\pi^0} \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(12)

where the factor 2 accounts for the two photons emitted by the \( \pi^0 \) decay, \( E_{\pi^0}^{\text{max}} = E_\gamma + m_{\pi^0}^2/(4E_\gamma) \) GeV is the minimum \( \pi^0 \) energy required to produce a photon of energy \( E_\gamma \), \( E_{\pi^0}^{\text{max}} \) is the maximum energy of a neutral pion specified in terms of the above two masses and the maximum proton energy \( E_{p}^{\text{max}} \), and

\[
Q_\gamma(E_{\pi^0}) = \frac{4}{3} \pi n_H \int_{E_{p}^{\text{thr}}(E_{\pi^0})}^{E_{p}^{\text{max}}} J_p(E_p) \frac{d\sigma(E_{\pi^0}, E_p)}{dE_{\pi^0}} \, dE_p \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(13)

is the spectral distribution of the neutral pions. Here, \( n_H \) is the (thermal) gas proton density, \( J_p \) is the (isotropic) energetic proton flux, \( d\sigma(E_{\pi^0}, E_p)/dE_{\pi^0} \) is the differential cross-section for production of neutral pions with energy \( E_{\pi^0} \) from a collision of a proton with energy \( E_p \) with a proton (essentially at rest), and \( E_{p}^{\text{thr}} \approx 1.22 \) GeV is the threshold energy for production of a neutral pion with energy \( E_{\pi^0} \). We use a \( \delta \)-function approximation (Aharonian & Atoyan 2000) to the differential cross-section by assuming that a fixed average fraction, \( \kappa_{\pi^0} \), of the proton kinetic energy, \( E_{p}^{\text{kin}} = E_p - m_p \), is transferred to the neutral pion, i.e., \( d\sigma(E_{\pi^0}, E_p)/dE_{\pi^0} \sim \delta(E_{\pi^0} - \kappa_{\pi^0} E_{p}^{\text{kin}}) \sigma_{pp}(E_p) \) with \( \sigma_{pp} \) the total cross-section for inelastic \( p-p \) collisions. Then

\[
Q_\gamma(E_{\pi^0}) = \frac{c n_H}{3 \kappa_{\pi^0}} N_p \left\{ \frac{m_p + E_{\pi^0}}{E_{\pi^0} - m_{\pi^0}} \right\} \sigma_{pp} \left\{ \frac{m_p + E_{\pi^0}}{E_{\pi^0} - m_{\pi^0}} \right\} \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(14)

(in \( \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1} \)) where \( \kappa_{\pi^0} \approx 0.17 \) in the GeV-TeV region, and \( \sigma_{pp}(E_p) \) can be analytically approximated (see Eq. (79) of Kelner et al. 2006). Noting that in the range \( 5 \lesssim E_p/\text{GeV} \lesssim 50 \) (relevant to our analysis), \( \sigma_{pp} \) is roughly constant, \( \sigma_{pp,0} \approx 30 \) mbarn, we set \( \sigma_{pp} = \sigma_{pp,0} \). The resulting \( \gamma \)-ray photon emissivity (in \( \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1} \); energies are in GeV) is

\[
Q_\gamma(E_\gamma)|_{\pi^\pm} = \frac{2}{3} \frac{c}{\kappa_{\pi^\pm}} n_H N_p \sigma_{pp,0} \int_{E_{\pi^0}^{\text{min}}}^{E_{\pi^0}^{\text{max}}} \frac{(m_p + E_{\pi^0}/\kappa_{\pi^\pm})^{-q_p}}{\sqrt{E_{\pi^0}^2 - m_{\pi^0}^2}} \, dE_{\pi^0} \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(15)

The production rate of electrons and positrons is calculated from the \( \pi^\pm \) decay rate density (e.g., Stecker 1971),

\[
Q_{\pi^\pm}(E_{\pi^\pm}) = \frac{2}{3} \frac{c}{\kappa_{\pi^\pm}} n_H \int_{E_{\text{thr}}}^{E_{\pi^\pm}} N_p(E_p) f_{\pi^\pm,p}(E_p, E_{\pi^\pm}) \, dE_p \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(16)

where \( f_{\pi^\pm,p}(E_p, E_{\pi^\pm}) \) is the \( \pi^\pm \) energy distribution for an incident proton energy \( E_p \). The \( \pi^\pm \) energy distribution can be well approximated by assuming that a constant fraction, \( \kappa_{\pi^\pm} \), of the proton kinetic energy is transferred to charged pions, so that

\[
f_{\pi^\pm,p}(E_p, E_{\pi^\pm}) = \sigma_{pp}(E_p) \delta(E_{\pi^\pm} - \kappa_{\pi^\pm} E_{p}^{\text{kin}}) \quad \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(17)

For the range of \( q_p \) values of interest here, \( \kappa_{\pi^\pm} = 0.25 \) (Kelner et al. 2006). Substituting Eq. (17) in Eq. (16) we obtain

\[
Q_{\pi^\pm}(E_{\pi^\pm}) = \frac{2}{3} \frac{c}{\kappa_{\pi^\pm}} n_H N_p \sigma_{pp,0} \left( \frac{m_p + E_{\pi^\pm}/\kappa_{\pi^\pm}}{E_{\pi^\pm}} \right)^{-q_p} \, \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(18)

The above equation for the \( \pi^\pm \)-decay rate density, Eq. (18), allows calculation (e.g., Ramaty & Lingenfelter 1966) of the source rate density of the secondary \( e^\pm \) produced in charged-pion decays,

\[
Q_{e^\pm}(E_e) \approx \frac{8}{3} \frac{c}{\kappa_{e^\pm}} n_H N_p \sigma_{pp,0} \left( 4E_e + m_{e^\pm} + m_p \right)^{-q_p} \, \text{cm}^{-3} \text{s}^{-1} \text{GeV}^{-1}
\]

(19)

The corresponding steady-state distribution, \( N_{e^\pm}(\gamma) \), can be calculated via \( d[b(\gamma)N_{e^\pm}(\gamma)]/d\gamma = Q_{e^\pm}(\gamma) \) – where, assuming transport losses to be negligible, \( b(\gamma) \) is the radiative energy loss term (e.g., Rephaeli 1979). The latter is written as \( b(\gamma) = b_0 + b_1(\gamma) + b_2(\gamma) \) (in \( \text{s}^{-1} \)), where \( b_0(\gamma) = 1.2 \times 10^{-12} n_e [1 + \ln(\gamma/n_e)/84] \) is the loss rate by electronic excitations in ionized gas, \( b_1(\gamma) \approx 10^{-15} \gamma n_e \) is the loss rate by electron bremsstrahlung in ionized gas, and \( b_2(\gamma) = 1.3 \times 10^{-9} \gamma^2 (B^2 + 8\pi p_c) \) is the Compton-synchrotron loss rate. In these expressions \( n_e \) is the thermal electron density and \( p_c \) is the ambient radiation field energy density. The secondary electron density is then

\[
N_{e^\pm}(\gamma) = \frac{Q_{e^\pm}(\gamma) d\gamma}{b(\gamma)} \quad \text{cm}^{-3}
\]

(20)

where

\[
\int Q_{e^\pm}(\gamma) d\gamma \approx \frac{2}{3} \frac{c}{q_p - 1} n_H N_p \sigma_{pp,0} m_e \left( \frac{4}{\kappa_{e^\pm} \gamma} + \frac{m_{e^\pm} + \kappa_{e^\pm} m_p}{\kappa_{e^\pm} m_e} \right)^{-q_p + 1} \, \text{cm}^{-3} \text{s}^{-1}
\]

(21)
Figure 1. Left: broad-band SED of the Fornax A lobes. Data points (Table 1) are shown by dots. Emission components are: synchrotron, black short/long-dashed curves; Compton/CMB, black dotted–long-dashed curves; Compton/IR, red long-dashed curves; Compton/OPT, blue solid curves; pionic, green dotted curve. Thinner curves depict secondary-electron emissions. Right: dashed curves bracket the 95% confidence level of the predicted Compton/OPT emission.

The resulting \( N_{\text{se}}(\gamma) \) can be approximated by

\[
N_{\text{se}}^{\text{fit}}(\gamma) = N_{\text{se},0} \left[ 1 + \left( \frac{\gamma}{\gamma_f} \right)^{\tau-(q_e+1)} \right].
\]

where \( \tau \) is a (fit) parameter specified below (see section 5).

4 MODELLING THE LOBE SED

As has already been deduced in previous analyses (McKinley et al. 2015; Ackermann et al. 2016), the energy range of electrons emitting the observed radio and X-ray radiation is relatively narrow, as is clear from the steep drop of the flux at high radio frequencies, and from the level and spectral shape of the emission around \( \sim 1 \) keV. The exact emission level near this energy is pivotal to our analysis. X-ray observations were reported by several groups, starting with spatially-unresolved ROSAT measurements by Feigelson et al. (1995). From spectral analysis of ASCA 1.7 – 7 keV data Kaneda et al. (1995) deduced that the emission had a NT component (with a PL index similar to the radio index); specifically, they estimated that \( \sim 1/3 \) and \( \sim 1/2 \) of 1 keV flux from the west and east lobes, respectively, was NT; this was later confirmed by Tashiro et al. (2001). Similarly, Isobe et al. (2006) found that east-lobe XMM-Newton 0.3 – 6 keV data are well fit by a PL with an index consistent with the radio index. Additionally, from analysis of Suzaku data Tashiro et al. (2009) estimated that \( \sim 1/2 \) of the west lobe flux to be NT. Assuming all the measured flux at 1 keV originates in Compton scattering off the CMB yields the overall normalization factor, \( N_{e,0} \approx 8 \times 10^{64} \), and the lower energy limit, \( \gamma_{\text{min}} \approx 200 \).

Fitting the predicted synchrotron flux to measurements in the 0.03 – 143 GHz yields the spectral index of the electron distribution, \( q_e = 2.43 \), and the upper energy cutoff, \( \gamma_{\text{max}} = 7.10^4 \). The mean magnetic field strength in the lobes is computed using (e.g., Eq. 4.53 in Tucker 1975)

\[
B = \left[ 2.47 \times 10^{-19} (5.25 \times 10^3)^{(q_e-1)/2} T_{\text{CMB}}^{(q_e+5)/2} \frac{b(q_e)}{a(q_e)} \left[ \frac{F_c}{F_s} \left( \frac{\nu_c}{\nu_s} \right)^{(q_e-1)/2} \right]^{-1} \right]^{2/(q_e+1)} \text{gauss}.
\]

Eq. (23) applies when the synchrotron and Compton fluxes are emitted from the same region by electrons with untruncated PL spectrum. Substituting the measured 5 GHz and 1 keV flux densities for \( F_s \) and \( F_c \), respectively, Eq. (23) returns \( B = 2.64 \mu G \). The value we find is only slightly different, \( B = 2.9 \mu G \); the \( \sim 10\% \) discrepancy mostly stems from the scatter of radio data points about the synchrotron curve.

With the electron distribution fully determined, the Compton yields from scattering off the above specified IR and OPT radiation fields can now be calculated; the results for the full SED are shown in Fig. (1) together with the radio, X-ray, and
\(\gamma\)-ray measurements. The main current interest in the predicted Compton yields is the emission in the range 0.1–100 GeV probed by Fermi-LAT; the fact that our predicted emission in this range matches well the measurements is an important outcome of our analysis that is essentially a direct consequence of our full accounting for the optical radiation field in the lobes which yielded a higher energy density than estimated by Ackermann et al. (2016). As specified in the previous section, in our detailed estimate of the optical radiation field in the lobes we determined that this field is dominated by the stellar emission of the central galaxy, NGC 1316. This conclusion is based on recent mapping of the extended surface brightness distribution of this galaxy by Iodice et al. (2017).

The energetic proton density in the lobes is likely to be quite significant and the energy density higher than that of the electrons; however, this does not necessarily imply that the associated \(\pi^0\)-decay yield can exceed the above estimated level from Compton scattering of primary electrons off the local optical radiation field. Assuming a proton energy distribution, with \(q_p = 2.2\) and a theoretically-motivated nominal proton-to-electron energy-density ratio \(\zeta = \rho_p/\rho_e = 50\) (see below), we can calculate the secondary electron and \(\pi^0\)-decay yields in all the above spectral bands. These emissions are all well below the corresponding levels by primary electrons. Thus, we can only place a \(\sim 30\%\) nominal upper limit on the pionic contribution to the flux in the Fermi-LAT band, a limit that roughly reflects the modeling uncertainties in our analysis and the level of precision of the current Fermi-LAT data.

5 DISCUSSION

Detailed modeling of emission in radio lobes is clearly needed in order to determine key properties of energetic particles, magnetic and radiation fields, and for assessing the impact of AGN jets on their intergalactic or intracluster environment. In particular, fitting model predictions to measurements of the lobe SED is critical for a robust determination of the relative significance of energetic protons when gauged by their radiative yields from interactions with ambient gas. By virtue of proximity, brightness of its lobes, and adequate multi-spectral observations, Fornax A is one of the most suitable for such a study.

In our analysis of the broad-band SED of the Fornax A lobes we use the simplest truncated-PL spectral distribution, the most constraining SED dataset currently available, and a recently published, sufficiently precise NGC 1316 light distribution. Assuming the X-ray flux originates from electron Compton scattering off the CMB, our main result is that the related flux from Compton scattering off the optical radiation field, which is dominated by the central galaxy, is consistent with the Fermi-LAT measurements. Thus, there is no apparent need for an additional pionic component (at a level comparable to current observations). This conclusion would only be strengthened if account is taken of the estimated \(\lesssim 15\%\) contribution to the observed emission by NGC 1316 (Ackermann et al. 2016), and an additional \(\lesssim 15\%\) enhancement of the intra-lobe optical light by emission from nearby star-forming galaxies. In light of this, only an upper limit can be set on a (likely) pionic component, in contrast with the conclusion reached by McKinley et al. (2015) and Ackermann et al. (2016).

Limits on the ambient proton spectral parameters can be set by selecting the proton distribution’s spectral index and maximum energy to be close to the values that would be implied from fitting a pionic component to the Fermi-LAT data; this yields \(q_p = 2.2\) and \(E_p^{max} = 50\) GeV, respectively. The value of the index is in the range of what is theoretically predicted. Assuming a nominal p/e energy density ratio of 50, as appropriate for an electrically neutral NT plasma for the deduced value of \(q_e\), and assumed \(q_p\) (Persic & Rephaeli 2014), then \(N_p = 1.7 \cdot 10^{32}\). This would imply a total NT proton energy of \(7.2 \cdot 10^{38}\) erg, roughly two orders of magnitude lower than what would be required if the measured \(\gamma\)-ray emission were of pionic origin (McKinley et al. 2015; Ackermann et al. 2016).

This low-level normalization implies also a correspondingly low secondary electron (and positron) contribution to the observed emission; thus, the exact values of the proton and secondary-\(e^\pm\) spectral indices are of little practical interest. More relevant is the fact that the deduced spectral index, \(q_e \sim 2.4\), is significantly lower than the expected value for a population that had aged as result of efficient Compton-synchrotron energy losses – whose characteristic time, \(t_{CS} = \gamma/b_2(\gamma) \sim 0.08\) Gyr (estimated using the relevant photon and magnetic field energy densities and \(\gamma = 1.35 \cdot 10^4\), i.e., the likely Lorentz factor of an electron emitting at \(\nu_e = 1.4\) GHz in the deduced lobe magnetic field, derived from the expression for \(\nu_e\) with \(<\sin\theta> = 2/\pi\), is shorter than the estimated age of the lobes, \(t_{lobo} \sim 0.4\) Gyr (Lanz et al. 2010). This is perhaps due to lack of information on the particle injection (by the jet) and propagation mode and related spectro-spatial aspects, or perhaps a consequence of efficient re-acceleration that can flatten pre-existing NT particle spectra (e.g., Bell 1978; Wandel et al. 1987; Seo & Ptuskin 1994) within the lobes. Given these uncertainties, taking \(\tau = 3/4\) in Eq. (22) effectively implies a steady-state secondary \(e^\pm\) index of (asymptotically) 2.4, same as that of the primary electron spectrum. The secondary electron maximum energy, \(\sim 1.4E_p^{max}\) corresponds to \(\gamma_{max} \sim 2.5 \cdot 10^3\).

To assess the accuracy of our quantitative results we focus on the impact of the main observational and modeling uncertainties. Key parameters are the electron number normalization and endpoints of the energy range which were determined from the radio and X-ray data. Specifically, the values of \(N_{e,0}\) and \(\gamma_{min}\) were deduced from the measured 1 keV flux, interpreted to be a consequence of Compton scattering off the CMB. While there is appreciable uncertainty in the level of the NT emission at this energy, which was determined by Tashiro et al. (2009) and Isobe et al. (2006), it largely impacts the modeled level of the radio spectrum, whose fit to the radio data yields the value of the mean magnetic field. Therefore, the resulting uncertainty is essentially reflected in the latter quantity whose exact value (in the range \(B \sim 1 \sim 3\) \(\mu G\) in all previous analyses) is clearly not that important (also because it constitutes a nominal volume-averaged value across the lobes). The substantial uncertainty in the spectral shape of the X-ray data results in some level of parameter degeneracy; e.g., the combination \(N_{e,0} = 1.1 \cdot 10^{55}\).
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γ_{\text{min}} = 700 is consistent with the 1 keV flux density, but this higher γ_{\text{min}} causes a steeper rise of the predicted flux than suggested by the data. Also, the value of γ_{\text{max}}, constrained by the high-frequency turnover of the radio spectrum, is affected by the observational error in the value of q_e, whose relative level (at 1 σ confidence level) is estimated to be ∼ 4%.

A source of (mostly) modeling uncertainty results from monochromatic to bolometric flux conversion required in order to compute the dilution factor of the optical radiation field sourced by NGC1316. This involves converting r to b and (then) to bolometric magnitudes based on the adopted stellar population synthesis model. The CIB and COB intensities are known with a ∼ 30% uncertainty (see Cooray 2016).

Important are also the relatively large error intervals of the Fermi-LAT data (below ∼ 20 GeV). With the best-fit value of the spectral index determined from the radio data, α ≃ 0.71 ± 0.04 (1 σ uncertainty), the propagated uncertainty in the predicted Compton flux in the Fermi-LAT range is ∼ 15%.

A similar joint analysis of the multi-spectral emission from the giant radio lobes of the nearby radiogalaxy Centaurus A, the first extended extragalactic regions detected by Fermi-LAT (Abdo et al. 2010; Yang et al. 2012), is clearly of much interest. The lack of unambiguous evidence for NT X-ray emission from the lobes, perhaps due to their large angular size and complex X-ray morphology (e.g., Schreier et al. 1979; Hardcastle et al. 2009 and references therein), does not allow a definite conclusion on the origin of the measured γ-ray emission. Assuming that the observed low energy (≳ 60 MeV) emission originates mostly from Compton scattering off the CMB and EBL, allows calibration of the electron spectrum in a purely leptonic model (Abdo et al. 2010 3 ). However, the improved spatial resolution attained in more recent radio measurements (Sun et al. 2016) indicates a possible magnetic enhancement at the edge of the south lobe, and thus leads to a lower electron number normalization that lowers the likelihood of the leptonic origin of the γ-ray emission. As previously suggested for Fornax A, a combined lepto-hadronic model seems to require an unrealistically high proton energy density (Sun et al. 2016).

Unequivocal observational evidence for energetic protons in the lobes of radio galaxies is of great interest also for an improved understanding of the origin of extended radio halos in clusters. In a first detailed assessment of galactic energetic proton and electrons sources in clusters (Rephaeli & Sadeh 2016), it was assumed that electrons diffuse out of radio and star-forming galaxies, and because of the lack of clear evidence for an appreciable proton component in the lobes of radio galaxies, their (secondary electron) contribution to the radio halo emission was conservatively ignored. The extended distribution of star-forming galaxies, whose relative fraction increases with distance from the cluster center, is important in order to account for the large size of radio halos. This approach was applied to conditions in the Coma cluster, where the number of star-forming galaxies was estimated from the total blue luminosity of the cluster, and only the two central powerful radio galaxies were included as electron sources. It was found that for reasonable models of the gas density and magnetic field spatial profiles, the predicted profile of the combined radio emission from primary and secondary electrons is roughly consistent with that deduced from current measurements of the Coma halo. However, the level of radio emission was predicted to be appreciably lower than the measured emission, suggesting that there could be additional particle sources, such as AGN and (typically many) lower luminosity radio galaxies. Clearly, therefore, quantitative evidence for energetic protons in radio lobes would have important implications also on our understanding of the origin of cluster radio halos.

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3 The optical emission from the host galaxy, NGC5128, was estimated to negligibly contribute to the Compton yield.
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