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The Energetic Particle Population in Centaurus A

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Abstract. We report a significant hardening of the *Fermi*-LAT gamma-ray spectrum from the core of Cen A at E > 2.4 GeV, suggesting there is a source of high energy particles in the core of Cen A which is in addition to the jet component. We show that the observed gamma-ray spectrum is compatible with either a spike in the dark matter halo profile or a population of millisecond pulsars. This work gives a strong indication of new gamma-ray production mechanisms in active galactic nuclei and could even provide evidence for the clustering of heavy dark matter particles around black holes.

Keywords. gamma rays: observations, dark matter, galaxies: active, pulsars: general

1. Introduction

Cen A is the closest active galaxy to Earth (Rejkuba, 2004) and emits radiation at all wavelengths, including γ-rays (Sreekumar *et al.*, 1999; H.E.S.S. Collaboration, 2009, *Fermi*-LAT Collaboration, 2010a). Observations made with the Large Area Telescope (LAT) of the *Fermi Gamma-ray Space Telescope* confirmed the existence of a bright γ-ray core (*Fermi*-LAT Collaboration, 2010a) and extended emission spatially coincident with Cen A's giant radio lobes (*Fermi*-LAT Collaboration, 2010b). A possible hardening of the spectrum above 4 GeV was noted by Sahakyan *et al.* (2013), along with some evidence for variability on 45-day timescales, much less than other γ-ray bright radio galaxies such as M87 and NGC 1275 (H.E.S.S. Collaboration, 2006; Brown & Adams, 2011). This paper focuses on the core emission from Cen A, using the new Pass 8 data release from *Fermi*-LAT. After establishing the presence of a statistically significant hardening of the spectrum and assessing the evidence for variability, we consider possible interpretations of this result.

2. Analysis

All photons from within 10° of Centaurus A were extracted from 8 years of *Fermi*-LAT data since August 2008 and a summed likelihood analysis was performed using the *Fermi*-LAT PSF classes. These apply instrument response functions which depend on the quality of the PSF reconstruction and enable better resolution of Cen A's radio lobes and γ-ray core at lower energies. A zenith cut of 90° was applied to each PSF quartile, using only `SOURCE` photons. The corresponding emission models and the Pass 8 corrected Galactic diffuse emission template `gll_iem_v06.fit` were used, with the *Fermi* 4-year point source catalog, 3FGL, being used to produce a preliminary sky model (*Fermi*-LAT collaboration, 2010c).

Model	Norm [MeV cm^{-2} s^{-1}]	Shape Parameters		Scale E [MeV]	$2\Delta\log(\mathcal{L})$[a]	DoF
PL	$(4.36 \pm 0.06) \times 10^{-9}$	$\gamma = 2.690 \pm 0.014$		$E_0 = 481.17$	0.0	2
BPL	$(4.21 \pm 1.38) \times 10^{-11}$	$\gamma_1 = 2.73 \pm 0.02$	$\gamma_2 = 2.29 \pm 0.07$	$E_b = 2593 \pm 314$	28.600	4[b]
LP	$(4.15 \pm 0.08) \times 10^{-11}$	$\alpha = 2.70 \pm 0.01$	$\beta = -0.04 \pm 0.01$	$E_0 = 481.17$	16.637	3

Table 1. Spectral fits using several models, the definitions of which can be found in Equations 3.1 and 3.2. [a] This is the maximum likelihood probability compared to that of the best-fit power-law model. [b] The broken power-law model does not satisfy Wilks' theorem as it is not nested with a power-law model.

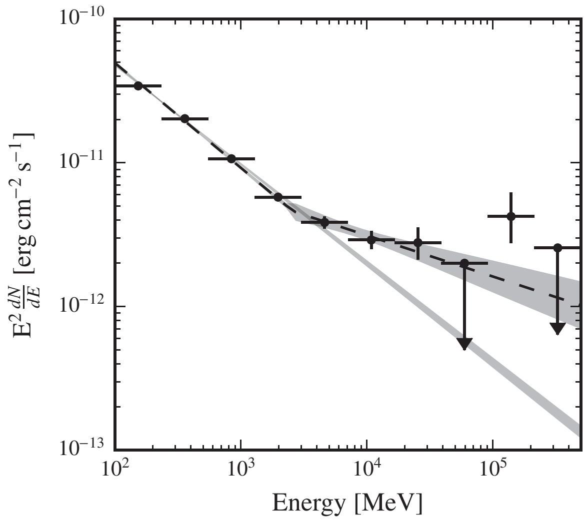

Figure 1. The spectrum of Centaurus A fitted with broken power-law and power-law models. The data are binned into 10 bins between 100 MeV and 500 GeV, with 95% upper limits plotted if the bin has a TS< 25.

3. The Spectrum

The spectrum of Cen A between 0.1 and 300 GeV was fitted with a power-law (PL), a broken power-law (BPL) spectrum:

$$\frac{dN(E)}{dE} = N \times \begin{cases} \left(\frac{E}{E_b}\right)^{-\gamma_1} & \text{if } E < E_b, \\ \left(\frac{E}{E_b}\right)^{-\gamma_2} & \text{otherwise,} \end{cases} \tag{3.1}$$

and a log-parabola (LP) model:

$$\frac{dN(E)}{dE} = N \left(\frac{E}{E_0}\right)^{-(\alpha + \beta \log(E/E_0))}, \tag{3.2}$$

The spectrum of Centaurus A, fitted with Equation 3.1 and a PL model, is shown in Figure 1; the best-fit parameters are in Table 1, including the fit to Equation 3.2. The BPL model is preferred over the PL fit, with a test statistic of over 28, a significance slightly greater than 5σ. This compares well with the HESS spectrum observed at higher energies; extrapolating the power law found at energies below 2.4 GeV to the HESS energies would under predict the flux above 250 GeV by a factor of 10 (see Figure 1).

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4. Variability

Binning the data on 15, 30 and 45-day timescales, as in Sahakyan *et al.* (2013), shows no significant variability using either a χ^2 comparison to a constant value or the TS_{var} (Nolan *et al.*, 2012). As our analysis suggests that there may be two separate emission components, we split the data at the best-fit break energy of 2.4 GeV and searched for variability above and below the break, binning the data on a 6-month timescale to retain sufficient statistics at high-energies. We find minimal evidence of variability (at the 95% level) in the data either above or below the break. When treating bins with a test statistic less than 16 as upper limits, which therefore do not contribute to the χ^2 value, no variability at all could be found in the high-energy component.

5. Implications

Petropoulou *et al.* (2014) noted a one-zone synchrotron self-Compton model cannot account for the emission of Cen A above a few GeV, and attributed the high-energy radiation to a relativistic proton component. Such a model predicts strong variability in the high energy component, which we have not found, although this lack of evidence could be due to the relatively low statistics in the high-energy regime. Nonetheless, we explore emission mechanisms in which the high-energy emission would be non-variable.

5.1. *Dark Matter*

To investigate whether the emission between 2.4 GeV and ~ 5 TeV could be produced by dark matter (DM), we allowed the DM mass and annihilation cross-section to be free parameters, as well as the normalisation and slope of the spectral emission below 2.4 GeV. We considered DM self-annihilations into leptons and quarks, and tested two DM density profiles, the NFW profile $\rho(r) \propto r^{-1}$ (Navarro, Frenk and White, 1996) and a 'spiky' profile, $\rho(r) \propto r^{-\frac{7}{3}}$ (Gondolo and Silk, 1999). Our best fit favours a DM candidate of mass 3 TeV, annihilating into a pair of top and anti-top quarks with cross-section $\sigma\mathrm{v} \approx 1.6 \times 10^{-32}\mathrm{cm}^3\mathrm{s}^{-1}$, and a 'spiky' density profile. The fit has a χ^2 of 1.7, or a χ^2/d.o.f. of 0.24, suggesting that the fit is dominated by statistical errors. The best-fit annihilation cross-section of $\sigma\mathrm{v} \approx 1.6 \times 10^{-32}\mathrm{cm}^3\mathrm{s}^{-1}$ is too small to explain the observed DM fraction in the Universe, but might suggest a rich DM sector with several (non thermal) DM particles (Boehm, Fayet and Silk, 2004; Zurek, 2009) or both velocity-independent and dependent terms in the annihilation cross-section.

5.2. *Millisecond Pulsars*

A further explanation for the high energy emission is the presence of millisecond pulsars (MSPs), which are a possible explanation for the low energy γ-ray excess observed in the central region of the Milky Way (e.g. Goodenough and Hooper, 2009). The important assumptions for modelling the expected emission from MSPs are the electron injection spectrum (which must extend to a few 10s of TeV) and a large enough ambient photon field for the inverse Compton losses to dominate over the synchrotron losses. For the magnetic field, we assume a constant value of 10 μG, and use a density profile for the MSPs consistent with the Galactic centre γ-ray excess of $\rho_{MSP} \propto r^{-1.2}$. The normalisation and slope of the jet contribution are kept as free parameters. Assuming MSPs are entirely responsible for the emission, this model leads to a fit with a $\chi^2 \sim 10$ or $\chi^2/dof \sim 1.4$.

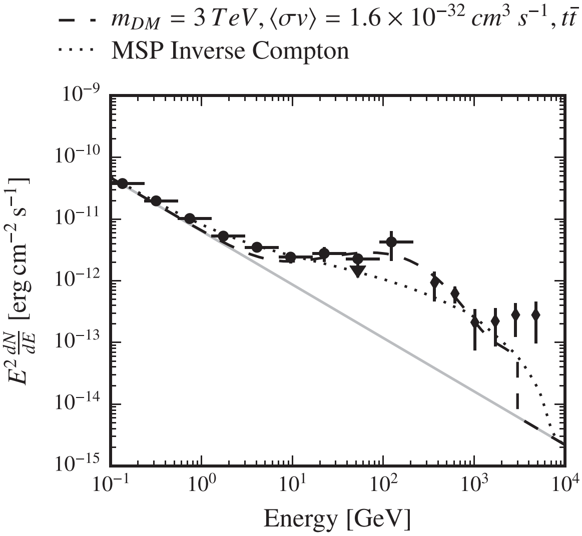

Figure 2. Dark matter and MSP fits to both Fermi and H.E.S.S. data. The dark matter fit finds $\chi^2/dof = 0.27$, and the MSP fit finds $\chi^2/dof = 1.4$. The sharp cutoff in the predictions from the dark matter model is a result of the mass of the dark matter particle, as no DM particle acceleration is considered.

6. Conclusions

We have shown evidence at the 5σ level for the existence of a hardening in the *Fermi*-LAT spectrum from Cen A, and that either heavy DM particles or a population of MSPs could explain this spectral feature. We cannot exclude the possibility that the jet is the origin of the spectral hardening, but the absence of variability above 2.4 GeV argues against jet-induced leptonic models. To understand better the nature of the high-energy component requires more data. In particular, the forthcoming Cherenkov Telescope Array, together with more *Fermi* data will be important in this respect. The detection of variability in either component, for example, would significantly constrain the models.

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