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Gamma rays from Fast Black-Hole Winds

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Massive black holes at the centers of galaxies can launch powerful wide-angle winds that, if sustained over time, can unbind the gas from the stellar bulges of galaxies. These winds may be responsible for the observed scaling relation between the masses of the central black holes and the velocity dispersion of stars in galactic bulges. Propagating through the galaxy, the wind should interact with the interstellar medium creating a strong shock, similar to those observed in supernovae explosions, which is able to accelerate charged particles to high energies. In this work we use data from the *Fermi* Large Area Telescope to search for the γ-ray emission from galaxies with an ultra-fast outflow (UFO): a fast ($v \sim 0.1$c), highly ionized outflow, detected in absorption at hard X-rays in several nearby active galactic nuclei (AGN). Adopting a sensitive stacking analysis we are able to detect the average γ-ray emission from these galaxies and exclude that it is due to processes other than the UFOs. Moreover, our analysis shows that the γ-ray luminosity scales with the AGN bolometric luminosity and that these outflows transfer ~0.04 % of their mechanical power to γ rays. Interpreting the observed γ-ray emission as produced by cosmic rays (CRs) accelerated at the shock front, we find that the γ-ray emission may attest to the onset of the wind-host interaction and that these outflows can energize charged particles up to the transition region between galactic and extragalactic CRs. A preprint of the full analysis is available on the arXiv: 2105.11469.

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1. Introduction

A fraction of the energy accumulated in active galactic nuclei (AGN) during their accretion phase can be released via the ejection of powerful outflows driven by the AGN itself, i.e. black-hole winds. It is thought that these outflows may contribute significantly to galaxy evolution and feedback, namely, the evolution of the bulge, the star formation, and the black hole growth [1]. Among the different types of outflows, the most powerful non-collimated ones are the so-called ultra fast outflows (UFOs). Primarily identified through X-ray observations of blue-shifted Fe K-shell absorption lines [1–8], UFOs are characterized by highly ionized gas with large column densities and mildly relativistic velocities (mean velocity of ~0.1c). They are located at sub-parsec scales from the central black hole of the host galaxy, and they have a mass outflow rate of ~0.01–1 $M_\odot$ yr^{-1}, corresponding to a high kinetic power of $\log\dot{E}_{\rm k} \sim$ 42-45 erg s^{-1} [1]. It has been predicted that the outflowing gas of a UFO may generate shock waves through interactions with the surrounding interstellar medium [9–11]. Due to the large kinetic power involved, this process may accelerate electrons and protons to high energies, subsequently generating non-thermal γ-ray emission, similar to what occurs with supernova remnants. For this reason it has been predicted that UFOs may be γ-ray emitters [9–11].

In this work we search for the γ-ray emission from UFOs using data collected by the Large Area Telescope [LAT 12] on board the *Fermi Gamma-ray Space Telescope* [12]. Models of the γ-ray emission from AGN outflows [9, 11] show them to be weak emitters, with γ-ray luminosities of $\approx 10^{40}$ erg s^{-1}, which explains why UFOs have not yet been detected by the LAT. Here, we adopt a different strategy and search for the collective γ-ray emission from a sample of UFOs using a stacking technique.

2. Sample Selection and Stacking Technique

We start from a sample of 35 sources that have been identified as UFOs through X-ray observations [2–6]. We have verified that none of the objects are positionally coincident with any known γ-ray sources reported in the 4FGL [13]. From the initial sample we make the following cuts. First, we only keep the radio-quiet sources (as specified in the original references) to avoid contamination of the signal from the relativistic jet. Furthermore, we only select sources that are nearby ($z < 0.1$) with a mildly relativistic wind velocity ($v > 0.1c$). The former cut is motivated by the expected low luminosity of the UFO emission [9], and the latter cut is motivated by the fact that the γ-ray emission is predicted to scale with the kinetic power of the outflow [9, 11]. After making these cuts we are left with 11 sources, which we use as our benchmark sample.

The stacking technique we employ has been developed previously and has been successfully employed for multiple studies, i.e. upper limits on dark matter interactions [14], detection of the extragalactic background light [15], extreme blazars [16], and star-forming galaxies [17]. The main assumption that we make for the stacking technique is that the sample of UFOs we are considering can be characterized by average quantities like the average flux and the average photon index (when we model their spectra with a power law). There are then two steps to the method. In the first step the model components are optimized for each ROI using a maximum likelihood fit. We evaluate the significance of each source in the ROI using the TS, which is defined as $\mathrm{TS} = -2\log(\mathrm{L}_0/\mathrm{L})$, where

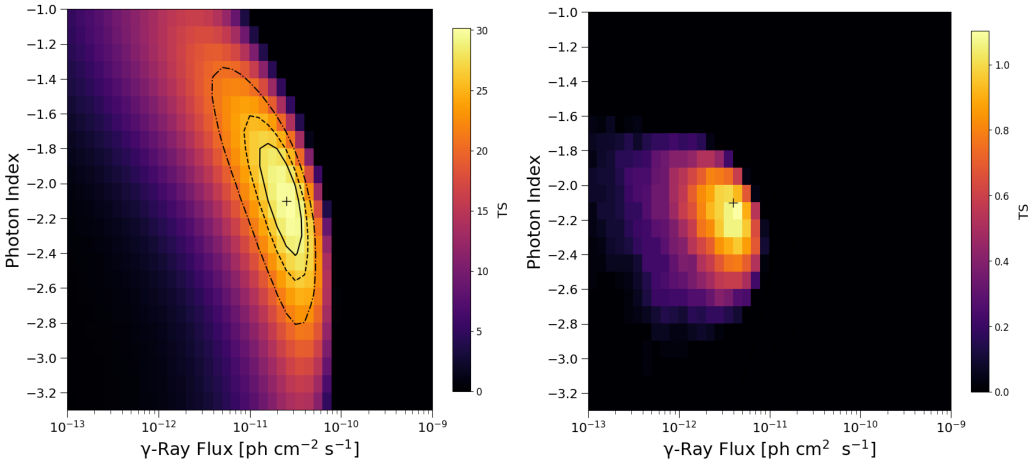

Figure 1: Left: Stacked TS profile for the sample of UFOs. The color scale indicates the TS, and the plus sign indicates the location of the maximum value, with a TS = 30.1 (5.1σ). Significance contours (for 2 degrees of freedom) are overlaid on the plot showing the 68%, 90%, and 99% confidence levels, corresponding to Δ TS = 2.30, 4.61, and 9.21, respectively. **Right:** Stacked profile for our control sample consisting of 20 nearby ($z < 0.1$) radio-quiet AGN with no UFOs (i.e. a UFO has been searched for but none has been detected). No signal is detected, with a maximum TS of 1.1.

L_0 is the likelihood for the null hypothesis, and L is the likelihood for the alternative hypothesis. For the first iteration of the fit, the spectral parameters of the Galactic diffuse component (index and normalization) and the isotropic component are freed. In addition, we free the normalizations of all 4FGL sources with TS≥25 that are within 5° of the ROI center, as well as sources with TS≥500 and within 7°. Lastly, the UFO source is fit with a power-law spectral model, and the spectral parameters (normalization and index) are also freed. In the first step we also find new point sources using the Fermipy function *find_sources*, which generates TS maps and identifies new sources based on peaks in the TS. The TS maps are generated using a power-law spectral model with an index of −2.0. The minimum separation between two point sources is set to 0.5°, and the minimum TS for including a source in the model is set to 16.

In the second step 2D TS profiles are generated for the spectral parameters of each UFO source. We scan photon indices from –1 to –3.3 with a spacing of 0.1 and total integrated photon flux (between 1–800 GeV) from 10^{-13} to 10^{-9} ph cm^{-2} s^{-1} with 40 logarithmically spaced bins, freeing just the parameters of the diffuse components. Lastly, the TS profiles for all sources are added to obtain the stacked profile. The TS is an additive quantity, and so the stacked profile gives the statistical significance for the combined signal.

3. Results

The stacked profile for our UFO sample is shown in the left panel of Figure 1. The maximum TS is 30.1 (5.1σ), corresponding to a best-fit index of -2.1 ± 0.3 and a best-fit photon flux (1−800 GeV) of $2.5^{+1.5}_{-0.9} \times 10^{-11}$ ph cm^{-2} s^{-1}. The 68%, 90%, and 99% significance contours are overlaid on the map, and as can be seen the spectral parameters are well constrained.

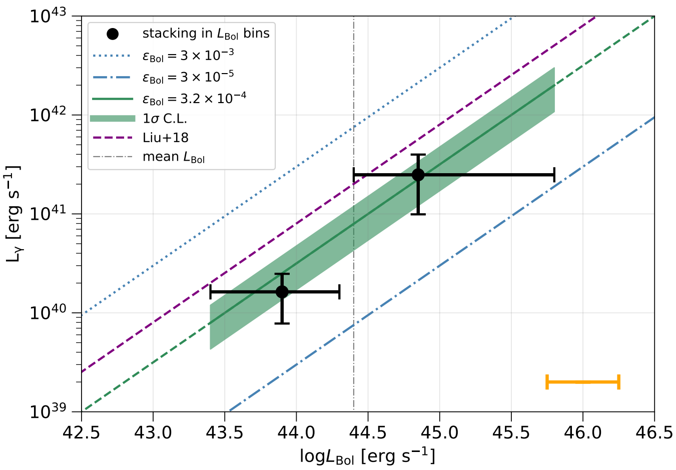

Figure 2: γ-ray luminosity versus bolometric luminosity. The black data points result from stacking in γ-ray luminosity, and the uncertainty in the x-axis corresponds to the bin widths. The grey dash-dot vertical lines show the value used to divide the bins. The solid green line shows the best-fit resulting from stacking in efficiency, with the green band showing the $1\,\sigma$ confidence level. For reference, the blue lines show a range of efficiencies within roughly an order of magnitude of the best fit. The orange bar shows the average one-sided uncertainty in individual measurements of AGN bolometric luminosity. We also overlay the predicted efficiency derived from [19, dashed purple line].

We repeat the analysis with a sample of 20 low redshift ($z < 0.1$) radio-quiet AGN that do not have UFOs. The sources were selected from the samples of [4] and [18] for which no UFO was found. The sample of [4] is based on absorption features, while the sample of [18] uses the excess variance method. Of the 20 sources in our control sample, there are 10 sources in common between the two studies, 4 additional sources from [4], and 6 additional sources from [18]. Results for the stacked profile are shown in the right panel of Figure 1. No signal is detected, with a maximum TS of 1.1. Using the profile likelihood method and a photon index of −2.0, the upper limit on the flux (1−800 GeV) at the 95% confidence level is 8.8×10^{-12} ph cm^{-2} s^{-1}. We have also shown that the γ-ray emission observed in the UFOs is a factor of ~40 larger than what we would expect for star-formation activity, and that it's highly unlikely the UFO emission results from weak jets. This supports the interpretation of the γ-ray emission being due to the outflow rather than other processes in AGN.

The γ-ray luminosity from UFOs is predicted to scale with the AGN bolometric luminosity. To test this relationship we calculate the stacked profile in bins of bolometric luminosity. Additionally, we calculated the stacked profile in terms of efficiency, defined as $\epsilon_{Bol} = L_\gamma / L_{Bol}$. Results for this are shown in Figure 2. Indeed, we do find a scaling relation, and we measure the best-fit efficiency to be $(3.2 \pm 1.5) \times 10^{-4}$.

4. Model

The physical model for the UFO SED is calculated by assuming that the γ-ray emission is dominated by hadronic processes resulting from diffusive shock acceleration. For typical UFO

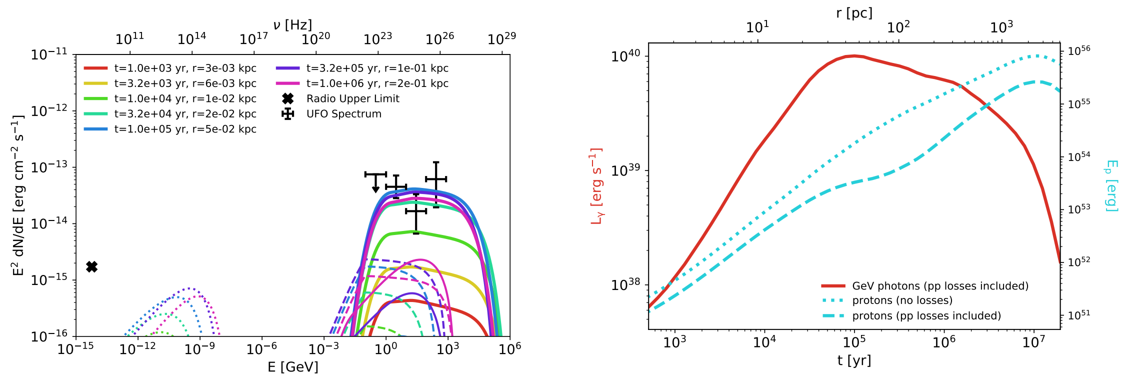

Figure 3: Left: Predicted multiwavelength SED of the UFO's nonthermal emission as a function of time. Synchrotron emission (dotted curves), bremsstrahlung emission (dashed curves), inverse-Compton emission (thin solid curves) and emission from π^0-decay (thick solid curves) are shown. The inverse-Compton emission remains subdominant despite assuming an artificially enhanced stellar radiation field of energy density 100 eV cm^{-3}. Also overlaid is the observed γ-ray flux and the average radio upper limit. Note that the leptonic emission produced at early times often does not appear as it falls below the plot range. **Right:** Light curve of a UFO-powered forward shock moving through a representative galaxy. The total energy in CRs is shown before and after proton-proton losses are included (blue dotted and dashed lines, respectively), as is the γ-ray luminosity at 1 GeV (red solid line).

shock velocities and densities, a leptonic origin of the γ-ray emission is disfavored, in that inverse-Compton scattering and bremsstrahlung of relativistic electrons would produce steeper γ-ray spectra with a lower normalization. The observed γ-ray SED indicates a firm detection of CR protons with energies reaching at least as high as $\approx 10^{12-13}$ eV.

Within our hadronic emission model we derive that on average the forward shock has traveled $\sim 20 - 300$ pc ($\sim 65 - 980$ light years) away from the SMBH and that the maximum energy of protons accelerated at the forward shock is $\approx 10^{17}$ eV. This makes AGN winds a potential source of CRs with energies beyond the 'knee' of the CR spectrum (i.e., 3×10^{15} eV) and also likely contributors to the IceCube neutrino flux [20].

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