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Prospects for very high energy observations of Starburst/Seyfert galaxies

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Andrew Chen[*]
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
E-mail: `andrew.chen@wits.ac.za`

Nebiha Shafi
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Hartebeesthoek Radio Astronomy Observatory, Krugersdorp 1740, South Africa
E-mail: `nebiha.shafi@wits.ac.za`

Sergio Colafrancesco
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
E-mail: `sergio.colafrancesco@wits.ac.za`

A handful of non-blazar galaxies, including both Seyfert and starburst galaxies, have been observed to emit gamma-rays by the *Fermi Gamma-ray Space Telescope*. For one of these objects, NGC 1068, a starburst galaxy which is also the brightest and closest Seyfert 2, a galactic outflow driven by the active nucleus is a likely source of both the radio and gamma-ray spectra, and we compare this case to other possible explanations including starburst activity and blazar-like jet emission. Other galaxies with both starburst and Seyfert characteristics, including NGC 4945, NGC 253, Circinus, and NGC 3256, show varying degrees of evidence of starburst, AGN mini-jet and AGN-driven outflow. Given the existence of various possible emission mechanisms operating at high energies, we discuss prospects for observations of starburst/Seyfert galaxies with *Fermi*, HESS and the Cerenkov Telescope Array (CTA), as well as future neutrino telescopes such as KM3NeT.

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[*] Speaker.

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1. Introduction

Active galaxies comprise the majority of sources detected by space-borne gamma-ray observatories sensitive in the 20 MeV to 300 GeV energy band[1][2], as well as accounting for a significant fraction of sources detected by ground-based imaging Cerenkov telescope arrays sensitive in the 20 GeV to 200 TeV energy band (e.g., MAGIC, VERITAS, H.E.S.S.)[3][4]. It is known today that the vast majority of gamma-ray detected active galactic nuclei (AGN) are blazars powered by their jet emission[5]. In the case of Fermi sources, even non-blazar objects such as radio galaxies and steep spectrum radio quasars (considered to be misaligned blazars)[6] and narrow-line Seyfert 1 galaxies[7] are also most likely powered by jet emission. Only a handful of extragalactic sources, including starburst galaxies such as M82, NGC 4945, NGC 253, NGC 6814, and Circinus[8], are thought to emit gamma rays through interactions of cosmic rays accelerated in supernova remnants with the interstellar gas and low-energy photons. This is the same mechanism that produces the diffuse emission in the Milky Way[9]. One interesting source detected by Fermi, NGC 1068, is both known as a starburst galaxy and a Seyfert 2 galaxy, and therefore an AGN. In this paper we compare some AGN and starburst models which can plausibly fit the spectrum of NGC 1068 and introduce a third alternative, the emission through AGN-driven galactic outflows. We briefly summarize the evidence for or against AGN-driven galactic outflow in other starburst/Seyfert galaxies including NGC 4945, NGC 253, and Circinus. We then explore the prospects for observations of starburst/Seyfert galaxies with current and future gamma-ray and neutrino telescopes under different models of the broadband emission.

2. Gamma-Ray Emission Mechanisms

2.1 Jet emission

The current understanding of AGNs is that they are supermassive black holes at the center of the host galaxy whose emission is powered by the conversion of gravitational potential into electromagnetic energy, when the nearby material accretes onto the black hole[10]. A fraction of AGNs are observed to produce jets, collimated beams of plasma exhibiting bulk relativistic motion. When the jet is aligned with the line of sight, the Doppler boosted radiation of the jet dominates the emission and the AGN is classified as a blazar[11].

Blazars exhibit a non-thermal spectral energy distribution (SED) which spans from radio to gamma-ray with two broad peaks. The low-energy peak is thought to be produced by synchrotron emission from high-energy electrons interacting with the magnetic field within the jet. In leptonic models, the high-energy peak is produced by inverse Compton emission, where the high-energy electrons up-scatter photons produced either through synchrotron emission from those same electrons (synchrotron self-Compton or *SSC*) or external seed photons coming from the disk, broad-line region, cosmic microwave background, or other radiation backgrounds[12].

In hadronic models, proton acceleration produces synchrotron, photo-hadronic and/or proton-proton cascade emission. The broad high energy hump yields a power law, broken power law, or log-parabola spectrum in gamma-rays[13].

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2.2 Star formation

In galaxies undergoing active star formation, massive stars exhaust their nuclear fuel, collapse, and undergo supernova explosion. The remnant produces an expanding shell whose shock front can produce high energy cosmic rays through diffusive shock acceleration. If hadrons are accelerated, they interact with the interstellar medium of the host galaxy and produce charged and neutral pions. The main neutral pion decay mode yields two gamma rays producing hence a spectrum with a characteristic pion bump at ≥ 70 MeV in the galaxy rest frame[8].

2.3 AGN-driven outflow models

In some starburst/Seyfert galaxies (such as NGC 1068), sub-mm interferometry of molecular lines in the circumnuclear disk (CND) suggests the existence of a giant, AGN-driven outflow which extends to ~ 100 pc scale with a velocity of 100-200 km/s [14][15]. This outflow can induce shocks in the CND, which, in turn, can accelerate relativistic particles with an efficiency that may exceed that in Supernova remnants (SNR) and could leave observational signatures in different electromagnetic bands [16][17]. In addition to primary accelerated electrons, the decay of neutral pions created by collisions between relativistic protons accelerated by the AGN shocks with ambient protons may produce a significant gamma-ray emission. Such hadronic gamma-ray emission can be favored as the dominant component of the gamma-ray spectrum at energies above 100 MeV. At lower energies leptonic processes like inverse Compton (IC) scattering and non-thermal bremsstrahlung can significantly contribute to the gamma-ray emission. Finally, the same electrons responsible for IC and bremsstrahlung emission spiraling in interstellar magnetic fields radiate synchrotron emission in the radio continuum. In this picture, the gamma-ray and radio luminosities are determined by the energy supplied to relativistic protons and electrons at the shock.

3. The case of NGC 1068

NGC 1068 is the closest AGN, at a distance of 14.4 Mpc. Like many Seyfert 2 galaxies, a Seyfert 1-like spectrum with broad lines is revealed when viewed in polarized light; according to the AGN unification scenarios, this is evidence that the nucleus is obscured by a clumpy torus of gas and dust[18]. NGC 1068 is also undergoing active star formation in its central region. NGC 1068 is a gamma-ray emitter, with a flux according to the *Fermi-LAT* Third Source Catalog (3FGL)[1] of $(6 \pm 1) \times 10^{-9}$ph cm^{-2}s^{-1} for 1-100 GeV. The H.E.S.S. collaboration reported an upper limit of 5.76×10^{-12}ph cm^{-2}s^{-1} for $E_{th} > 330$ GeV [19]. We examine whether the gamma-ray emission observed by Fermi is primarily due to a blazar-like AGN jet, starburst activity, or some other origin, and the implications of different models for TeV observations.

3.1 Jet emission hypothesis

Lenain et al. (2010) [20] first reported the detection of Seyfert 2 galaxies NGC 1068 and NGC 4945 by *Fermi* and showed that the broadband SED of NGC 1068 could derive from a leptonic jet scenario. Interestingly, their model includes an external inverse Compton component whose seed photons are infrared photons due to dust re-emission of absorbed starlight being up-scattered by relativistic electrons at a few tenths of parsecs from the central source within the misaligned

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jet, which provides the bulk of the gamma-ray emission compared to a negligible synchrotron self-Compton (SSC) component. This indirect dependence on active star formation may explain why comparable obscured Seyfert 2 galaxies have gamma-ray luminosity upper limits lower than that of NGC 1068.

3.2 Starburst hypothesis

Yoast-Hull et al. (2014)[21] and Eichmann & Becker Tjus (2016)[22] have developed models for the gamma-ray emission and broadband SED from interaction of high energy cosmic rays produced in supernovae with interstellar matter and radiation from starburst galaxies based on their star formation rate. They have shown that diffuse cosmic ray models which successfully fit the gamma-ray spectrum of other starburst galaxies are unable to explain the gamma-ray emission of NGC 1068. The star formation rate of NGC 1068 would need to be higher by a factor of from at least a few to several orders of magnitude in order to fit the observed gamma-ray flux. Moreover, using the parameters for fitting the gamma-ray flux significantly overestimates the radio synchrotron emission compared to the observed radio flux.

3.3 Giant AGN-driven outflow

Radio continuum observations have spatially resolved a number of nuclear structures - a 2 kpc starburst disk, a kpc-scale radio jet, a pc-scale jet surrounded by a circumnuclear disk (CND)[23][24][25], and a sub-arcsecond jet-cloud interaction (around 20 pc)[26]. More recently, sub-mm interferometry observations have illuminated the distribution and kinematics molecular gas in the central $r \sim 2$ kpc region of NGC 1068 with $\sim 10-100$ pc spatial resolution[14][15]. The ALMA CO (6-5) map fully resolved the CND and revealed a highly-structured asymmetric ring of 350×200 pc size which is noticeably off-centered relative to the AGN.

Perhaps the most interesting result of these high resolution observations is the gas kinematics revealing evidence of a giant nuclear ($r \sim 50-400$ pc) outflow extending up to ~ 100 pc with a velocity of 100 - 200 km s^{-1} in several molecular line tracers probed by ALMA[14][15][27]. Gallimore et al. (2016)[28] further detected a higher velocity CO (6 -5) emission (~ 400 km s^{-1}) with a sign of non-circular rotation that is consistent with a bipolar outflow along the axis of the AGN accretion disk. The tight spatial correlation between the AGN ionized gas outflow, the radio jet, and the molecular outflow, strongly suggests that the molecular outflow is AGN-driven[27]. These observations also provide strong support for the dynamic disk-wind scenario for the AGN obscuring torus.

GarcÃ■a-Burillo et al. (2014)[15] estimated the molecular outflow rate in the CND, $\dot{M} \sim 63 M_{\odot} \mathrm{yr}^{-1}$, assuming a multi-conical outflow geometry, with a corresponding kinetic luminosity outflow of $L_{kin} \sim 5 \times 10^{41}\,\mathrm{erg\,s^{-1}}$. Comparison of the kinetic energies associated with AGN activity and nuclear starburst shows that AGN activity is the more likely source powering the outflow. In fact either the radio jet and/or AGN radiation pressure are found to be capable of driving the molecular outflow (e.g. [15][29]).

On the other hand, this AGN-driven outflow in the CND can induce shocks that lead to the acceleration of cosmic rays (e.g. [30][31]). Several molecular line abundance ratio studies provide an intriguing evidence for a connection between the CND and cosmic rays. Chemical analysis of

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ALMA full resolution molecular line studies revealed significant chemical difference across the CND. Their studies show that a high cosmic ray ionization rate (possibly combined with X-ray activity), and a component of shocked gas are present in every subregion of the CND[30][32][33].

3.4 Comparison of models for the gamma-ray emission of NGC 1068

In Figure 1, we plot the *Fermi-LAT* gamma-ray data from 3FGL[1] and the H.E.S.S. upper limit[19]. We compare these data to three models; a simple SSC jet model, a starburst model[22], and an AGN outflow-driven model[29]. We also show predicted thresholds for CTA-South for 50 and 100 hours of observation. The starburst model fails to fit the observed gamma-ray spectrum, while both the jet model and the AGN outflow-driven model are able to fit the data, albeit with slightly unrealistic parameters. While continued *Fermi* observations may be able to discriminate between the two models at the lowest and highest energies (see [29] for further details), TeV telescopes such as H.E.S.S. and CTA are the most promising avenue for clearly showing which model is correct. A H.E.S.S. detection would support the AGN outflow-driven model, while CTA will be able to reveal the TeV spectrum in detail.

Note that using commonly assumed proton and electron acceleration efficiencies, AGN-driven outflows would produce a gamma-ray flux $\approx 4-10$ times lower than observed. The evidence for strong coupling between the molecular medium in the CND and the outflow shock-produced CR from molecular line survey abundances discussed in the previous section could boost the efficiencies to the required level.

4. Prospects for CTA and other gamma-ray observations of starburst/Seyfert galaxies

We consider in this section a few more examples of starburst/Seyfert galaxies in order to assess their observability with the future very high-energy observatories: these are NGC 253, Circinus, NGC 4945 and NGC 3256.

NGC 253 is a well-studied nearby (d $\sim$ 3.9 Mpc) prototype starburst galaxy. It is hosts several compact objects including a possible AGN [35][36]. NGC 253 is also known to host a superwind - with multiphase structure - believed to be driven by the starburst (e.g. [37][38][39]). The starburst galaxy is one of the two starburst galaxies observed in γ-rays at both GeV and TeV energies [40][8][41].

The Circinus spiral galaxy (d $\sim$ 4.2 Mpc) is one of the most extensively studied nearby galaxies, situated behind the intense foreground of the Galactic plane. Circinus hosts a Seyfert 2 nucleus [42] surrounded by a circumnuclear starburst [43]. Radio observations have shown bipolar radio lobes perpendicular to the disk, as well as kpc-scale jet-like structures [44]. Gamma-ray emission has also been detected with the Fermi-LAT [45].

NGC 4945 is another nearby spiral galaxy (d $\sim$ 3.9 Mpc) that exhibits both starburst and Seyfert characteristics (e.g.[46]). It also harbours a powerful nuclear wind forming a conical plume orthogonal to the disk of the galaxy, believed to be starburst-driven wind [47][48], that is similar to NGC 253. At high energies NGC 4945 is one of the few starburst/Seyfert systems which have been detected in γ-rays [8].

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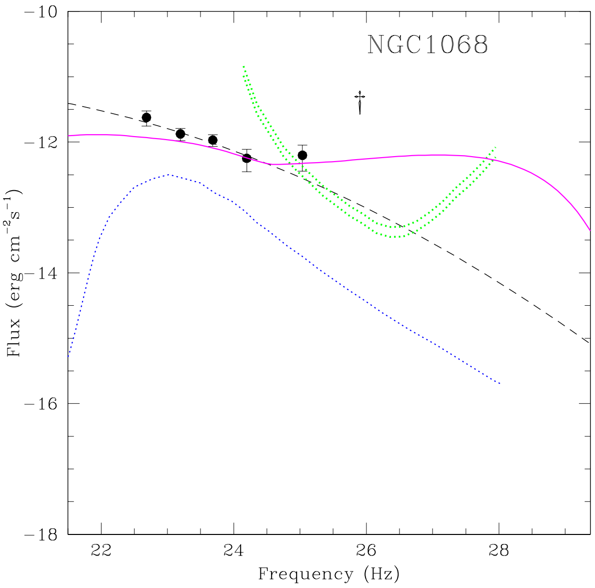

Figure 1: Black dashed: a simple SSC model with main parameters spectral index $\alpha_1 = 0, \alpha_2 = 3, \log(\Gamma_{break}) = 3.5$, indicative of an AGN-like jet. Blue dotted curve: model from starbursts of Eichmann and J. Becker Tjus (2016; see their Fig. 7)[22]. Magenta solid curve: model from Lamastra et al. (2016; see their Fig. 2 magenta curve, model-1, AGN outflow)[29]. Black dots are Fermi-LAT data from 3FGL[1] and the dagger symbol is the H.E.S.S. upper limit[19]. The CTA-South sensitivity for 50 and 100 hours is shown by the green curves (https://www.cta-observatory.org/science/cta-performance ; see also [34]).

NGC 3256 is one of the most luminous galaxies beyond the local group. The system is a merger of two galaxies and contains two nuclei separated by 850 pc [49][50] and known for its two bright, extended tidal tails [51]. Two molecular outflows associated with each of the two nuclei have been observed by ALMA – a southern outflow that is believed to be driven by an AGN bipolar jet and a northern outflow suggested to be part of a starburst-driven superwind [52]. Some similarities between NGC 3256 and Arp 220, the first ultra-luminous infrared galaxy (ULIRG) to be detected in GeV γ-rays [53], have been observed [52]: they are both late stage mergers with large infrared luminosities; outflows from both of the two merger nuclei are present (e.g, [54][52]); and the two nuclei with less than 1 kpc separation still have their own nuclear gas disks with misaligned rotational axes [55].

In order to estimate the prospects of observations of a list of starburst/Seyfert galaxies with CTA and other gamma-ray observatories, we first calculate the total energy budget of each galaxy according to the procedure listed below. We then scale the three NGC 1068 model spectra (jet, starburst, and AGN outflow-driven emission) by energy budget and distance and we compare the

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resulting spectra with the sensitivity of CTA. Note that we have not attempted to predict the spectrum of each source based on its own physical characteristics, but rather performed a simple scaling of the NGC 1068 model spectra based on the calculated total energy budget. Consequently, the comparisons made below should be understood to have large uncertainties.

4.1 Energy budget calculation

In order to get a rough estimate of the energy budget available to each galaxy, we use a simple pion emission model based on the following basic assumptions: uniform ISM particle distributions, equilibrium for particle injection and losses due only to cosmic ray interactions with the ISM (ignoring escape), a power law cosmic ray proton injection spectrum with spectral index of p, and supernovae as the assumed drivers of cosmic ray acceleration. Therefore, we adopt a source function spectrum $Q(E) \propto E^{-p}$ such that

$$\int_{E_{min}}^{E_{max}} Q(E) E dE = \frac{\varepsilon_{cr} \nu E_{51}}{V}, \tag{4.1}$$

where ε_{cr} is the particle acceleration efficiency, ν is the supernova rate, V is the volume of the starburst region, and $E_{51} = 1$ is 10^{51} ergs, the typical energy from a supernova explosion. In an equilibrium condition the particle spectrum then becomes $N(E) = Q(E)\tau(E)$ where $\tau(E)$ is the loss life time (due to radiative and collisional losses). Adopting [56] to calculate the pion source function from the proton spectrum and using the approach of [57] to get the cross sections for pion production, we calculate the gamma-ray emissivity from the starburst/Seyfert sources as

$$q_\gamma(E_\gamma) = 2 \int_{E_{min}}^{\infty} \frac{q_{\pi^0}(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}} dE_\pi \tag{4.2}$$

4.2 Results

We emphasize that the comparisons between the gamma-ray data and the simple scaled NGC 1068 models as applied to other galaxies should be understood to have large uncertainties, since we have not made any attempt to predict the spectrum of each source based on its own physical characteristics.

We notice that, in the case of NGC 253 (Fig. 2), the outflow model would be difficult to reconcile with the observed Fermi and HESS combined spectrum. More precise observations with CTA would be able to rule out certain outflow scenarios with greater confidence. The Fermi and HESS spectrum is roughly consistent with the SSC jet model, and more detailed starburst models can also fit the gamma-ray data well; see [41] for three examples.

In NGC 4945 (Fig. 2) the SSC model fits the Fermi-LAT data, while the starburst model would have to be refined along the lines of those used for NGC 253 [41] in order to be consistent with the spectral curvature. The AGN outflow-driven model is subdominant at GeV energies but provides a quite flat spectrum at TeV energies that lies well above the nominal CTA sensitivity limits. The SSC model would lie near the edge of the nominal CTA sensitivity limits while the starburst model would be more difficult to detect.

In the case of Circinus, the starburst model can reproduce quite well the GeV Fermi-LAT data including the spectral curvature at GeV energies, but with a steep high-energy spectrum which

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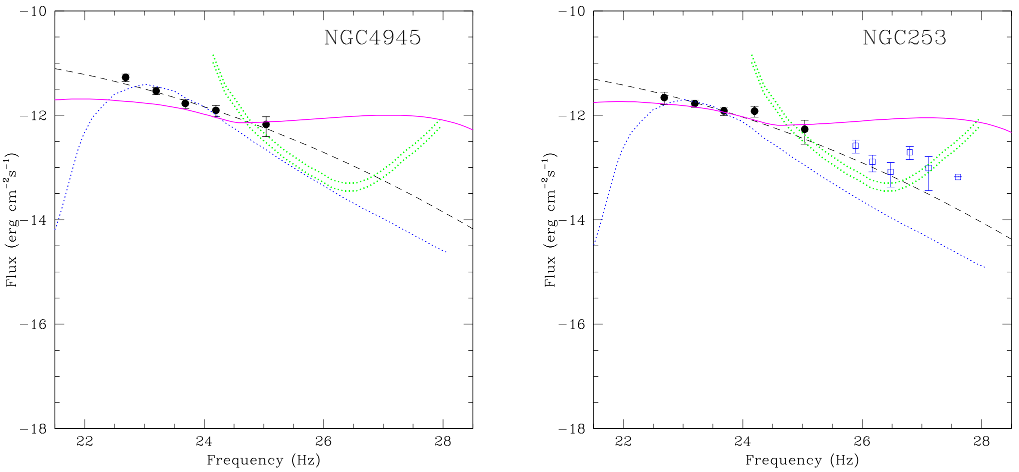

Figure 2: Same as Fig. 1 but for NGC 4945 and NGC 253. The HESS data for NGC 253 from [41] are shown as blue squares.

could make it more difficult to detect at CTA energies (Fig. 3). The other two models here considered (e.g., the SSC and the AGN outflow-driven models) predict spectra that lie above the nominal CTA sensitivity limits.

NGC 3256 (Fig. 3) has unfortunately only a Fermi upper limit of 3.47×10^{-10} ph cm^{-2} s^{-1} for 1 GeV $< E <$ 100 GeV, which is not able to constrain the models. No publicly available TeV upper limit exists for this source.

5. Prospects for neutrino observations of starburst/Seyfert galaxies

Any hadronic interactions which produce gamma rays through neutral pion decay will also produce neutrinos through charged pion decay. Detection of neutrino emission from a starburst/Seyfert galaxy would therefore provide conclusive evidence of hadron acceleration and interactions of cosmic-ray protons with interstellar matter and radiation. The neutrinos are a factor of 20 less energetic than the initial cosmic-ray protons, meaning that detection of 1 PeV neutrinos would indicate acceleration of protons up to $\approx$ 20 PeV. In NGC 1068, photo-hadronic cooling dominates proton-proton by a factor of (25-100). At lower energies, and in other galaxies, proton-proton cooling could become significant. While past and current detectors such as ANTARES and IceCube are not sensitive enough to detect the neutrino emission from these galaxies, future detectors such as KM3NeT may be sensitive enough. For a more detailed discussion see [29].

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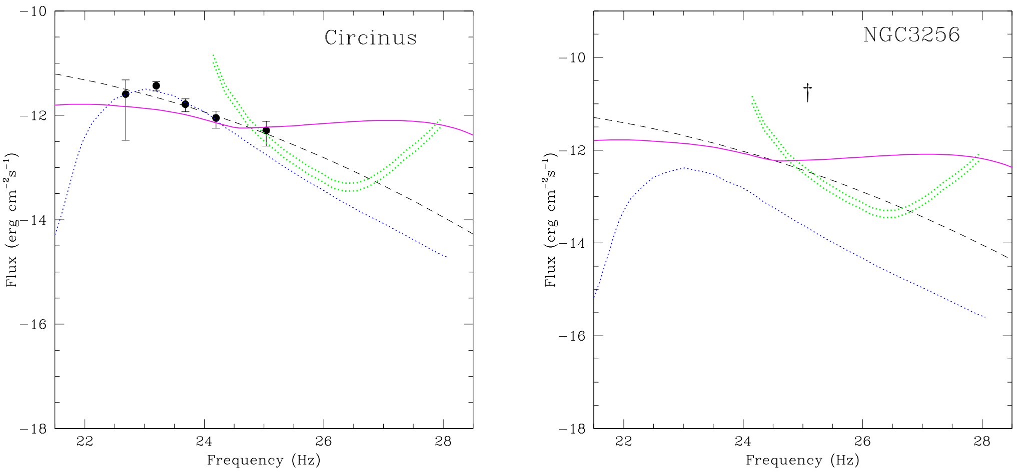

Figure 3: Same as Fig. 1 but for Circinus galaxy and NGC 3256.

6. Discussion and Future Work

NGC 1068 is an interesting case of a gamma-ray emitting AGN that exhibits characteristics of a misaligned jet, starburst activity, and AGN-driven outflow. We have argued that observations in the 100 GeV to TeV spectral range are the key to disentangling the source of the gamma-ray emission from both NGC 1068 and other starburst/Seyfert galaxies such as NGC 4945, NGC 253, Circinus, and NGC 3256. Ongoing observations by Fermi and H.E.S.S. may lead to a breakthrough, while CTA is ideally suited to measuring the spectrum in the relevant energy range and definitively resolving the ambiguity. The CTA spatial resolution of $\lesssim 3$ arcmin for $E \gtrsim 3$ TeV would also help distinguish between jet, starburst and outflow activity (https://www.cta-observatory.org/science/cta-performance ; see also [34]).

Our group is in the process of pursuing a number of lines of enquiry. We are investigating jet models which incorporate an external Compton component with seed photons from dust re-emission of absorbed starlight along the lines of [20] to complement the simple SSC model used in this paper. We are also investigating these and other starburst/Seyfert galaxies which may be detectable by CTA under different emission scenarios, starting with simple scaling of NGC 1068 models and progressing to models tailored to each starburst/Seyfert.

We are also beginning an optical observing campaign of starburst/Seyfert galaxies including these galaxies with the South African Large Telescope (SALT). Observations of the OVIII to OVII line ratio have been used to distinguish between supernova and AGN models of the gamma-ray emission from the Fermi bubbles within the Milky Way[58]; our observations will use this and other line ratios to distinguish between jet, starburst, and AGN-driven outflow models for NGC 1068 and other starburst/Seyferts.

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Another avenue of investigation involves neutrino observations. Observed neutrino flux would provide definitive evidence of hadronic interactions. Only the upper range of AGN-driven outflow models predict the PeV emission that would be required for detectable neutrino emission. Nevertheless, there is one neutrino detected by IceCube whose position is consistent with NGC 1068 [59][60]. Future neutrino telescopes such as KM3NeT[61] will provide sufficient sensitivity to begin to probe the hadronic cosmic ray acceleration of NGC 1068 and other galaxies with AGN-driven outflows.

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References

[1] F. Acero, M. Ackermann, M. Ajello, A. Albert, W. B. Atwood, M. Axelsson et al., *Fermi Large Area Telescope Third Source Catalog*, *ApJS* **218** (June, 2015) 23, [`1501.02003`].

[2] F. Verrecchia, C. Pittori, A. W. Chen, A. Bulgarelli, M. Tavani, F. Lucarelli et al., *An updated list of AGILE bright γ-ray sources and their variability in pointing mode*, *A&A* **558** (Oct., 2013) A137, [`1310.4029`].

[3] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, M. Beilicke, W. Benbow, D. Berge et al., *Observations of selected AGN with HESS*, *A&A* **441** (Oct., 2005) 465–472, [`astro-ph/0507207`].

[4] J. Aleksić, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, P. Bangale et al., *The major upgrade of the MAGIC telescopes, Part II: A performance study using observations of the Crab Nebula*, *Astroparticle Physics* **72** (Jan., 2016) 76–94, [`1409.5594`].

[5] M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini et al., *The Third Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope*, *ApJ* **810** (Sept., 2015) 14, [`1501.06054`].

[6] A. A. Abdo, M. Ackermann, M. Ajello, L. Baldini, J. Ballet, G. Barbiellini et al., *Fermi Large Area Telescope Observations of Misaligned Active Galactic Nuclei*, *ApJ* **720** (Sept., 2010) 912–922.

[7] A. A. Abdo, M. Ackermann, M. Ajello, L. Baldini, J. Ballet, G. Barbiellini et al., *Radio-Loud Narrow-Line Seyfert 1 as a New Class of Gamma-Ray Active Galactic Nuclei*, *ApJ* **707** (Dec., 2009) L142–L147, [`0911.3485`].

[8] M. Ackermann, M. Ajello, A. Allafort, L. Baldini, J. Ballet, D. Bastieri et al., *GeV Observations of Star-forming Galaxies with the Fermi Large Area Telescope*, *ApJ* **755** (Aug., 2012) 164, [`1206.1346`].

PoS(HEASA 2016)018

[9] M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini et al., *Fermi-LAT Observations of the Diffuse γ-Ray Emission: Implications for Cosmic Rays and the Interstellar Medium*, *ApJ* **750** (May, 2012) 3, [`1202.4039`].

[10] R. Antonucci, *Unified models for active galactic nuclei and quasars*, *ARA&A* **31** (1993) 473–521.

[11] G. Fossati, L. Maraschi, A. Celotti, A. Comastri and G. Ghisellini, *A unifying view of the spectral energy distributions of blazars*, *MNRAS* **299** (Sept., 1998) 433–448, [`astro-ph/9804103`].

[12] G. Ghisellini, A. Celotti, G. Fossati, L. Maraschi and A. Comastri, *A theoretical unifying scheme for gamma-ray bright blazars*, *MNRAS* **301** (Dec., 1998) 451–468, [`astro-ph/9807317`].

[13] M. Böttcher, A. Reimer, K. Sweeney and A. Prakash, *Leptonic and Hadronic Modeling of Fermi-detected Blazars*, *ApJ* **768** (May, 2013) 54, [`1304.0605`].

[14] M. Krips, S. Martín, A. Eckart, R. Neri, S. García-Burillo, S. Matsushita et al., *Submillimeter Array/Plateau de Bure Interferometer Multiple Line Observations of the Nearby Seyfert 2 Galaxy NGC 1068: Shock-related Gas Kinematics and Heating in the Central 100 pc?*, *ApJ* **736** (July, 2011) 37, [`1105.6089`].

[15] S. García-Burillo, F. Combes, A. Usero, S. Aalto, M. Krips, S. Viti et al., *Molecular line emission in NGC 1068 imaged with ALMA. I. An AGN-driven outflow in the dense molecular gas*, *A&A* **567** (July, 2014) A125, [`1405.7706`].

[16] C.-A. Faucher-Giguère and E. Quataert, *The physics of galactic winds driven by active galactic nuclei*, *MNRAS* **425** (Sept., 2012) 605–622, [`1204.2547`].

[17] J. Nims, E. Quataert and C.-A. Faucher-Giguère, *Observational signatures of galactic winds powered by active galactic nuclei*, *MNRAS* **447** (Mar., 2015) 3612–3622, [`1408.5141`].

[18] R. R. J. Antonucci and J. S. Miller, *Spectropolarimetry and the nature of NGC 1068*, *ApJ* **297** (Oct., 1985) 621–632.

[19] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, A. R. Bazer-Bachi, B. Behera, M. Beilicke et al., *Upper limits from HESS active galactic nuclei observations in 2005-2007*, *A&A* **478** (Feb., 2008) 387–393, [`0711.3196`].

[20] J.-P. Lenain, C. Ricci, M. Türler, D. Dorner and R. Walter, *Seyfert 2 galaxies in the GeV band: jets and starburst*, *A&A* **524** (Dec., 2010) A72, [`1008.5164`].

[21] T. M. Yoast-Hull, J. S. Gallagher, III, E. G. Zweibel and J. E. Everett, *Active Galactic Nuclei, Neutrinos, and Interacting Cosmic Rays in NGC 253 and NGC 1068*, *ApJ* **780** (Jan., 2014) 137, [`1311.5586`].

[22] B. Eichmann and J. Becker Tjus, *The Radio-Gamma Correlation in Starburst Galaxies*, *ApJ* **821** (Apr., 2016) 87, [`1510.03672`].

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[23] L. J. Tacconi, R. Genzel, M. Blietz, M. Cameron, A. I. Harris and S. Madden, *The nature of the dense obscuring material in the nucleus of NGC 1068*, *ApJ* **426** (May, 1994) 77–80.

[24] J. F. Gallimore, S. A. Baum, C. P. O'Dea and A. Pedlar, *The Subarcsecond Radio Structure in NGC 1068. I. Observations and Results*, *ApJ* **458** (Feb., 1996) 136.

[25] J. F. Gallimore, S. A. Baum and C. P. O'Dea, *The Parsec-Scale Radio Structure of NGC 1068 and the Nature of the Nuclear Radio Source*, *ApJ* **613** (Oct., 2004) 794–810, [`astro-ph/0406062`].

[26] J. F. Gallimore, C. Henkel, S. A. Baum, I. S. Glass, M. J. Claussen, M. A. Prieto et al., *The Nature of the Nuclear H_2O Masers of NGC 1068: Reverberation and Evidence for a Rotating Disk Geometry*, *ApJ* **556** (Aug., 2001) 694–715, [`astro-ph/0104083`].

[27] S. García-Burillo, F. Combes, C. Ramos Almeida, A. Usero, M. Krips, A. Alonso-Herrero et al., *ALMA Resolves the Torus of NGC 1068: Continuum and Molecular Line Emission*, *ApJ* **823** (May, 2016) L12, [`1604.00205`].

[28] J. F. Gallimore, M. Elitzur, R. Maiolino, A. Marconi, C. P. O'Dea, D. Lutz et al., *High-velocity Bipolar Molecular Emission from an AGN Torus*, *ApJ* **829** (Sept., 2016) L7, [`1608.02210`].

[29] A. Lamastra, F. Fiore, D. Guetta, L. A. Antonelli, S. Colafrancesco, N. Menci et al., *Galactic outflow driven by the active nucleus and the origin of the gamma-ray emission in NGC 1068*, *A&A* **596** (Dec., 2016) A68, [`1609.09664`].

[30] S. García-Burillo, A. Usero, A. Fuente, J. Martín-Pintado, F. Boone, S. Aalto et al., *Molecular gas chemistry in AGN. II. High-resolution imaging of SiO emission in NGC 1068: shocks or XDR?*, *A&A* **519** (Sept., 2010) A2, [`1005.1263`].

[31] J. Kamenetzky, J. Glenn, P. R. Maloney, J. E. Aguirre, J. J. Bock, C. M. Bradford et al., *The Dense Molecular Gas in the Circumnuclear Disk of NGC 1068*, *ApJ* **731** (Apr., 2011) 83, [`1102.3915`].

[32] R. Aladro, S. Viti, E. Bayet, D. Riquelme, S. Martín, R. Mauersberger et al., *A λ = 3 mm molecular line survey of NGC 1068. Chemical signatures of an AGN environment*, *A&A* **549** (Jan., 2013) A39, [`1210.4571`].

[33] S. Viti, S. García-Burillo, A. Fuente, L. K. Hunt, A. Usero, C. Henkel et al., *Molecular line emission in NGC 1068 imaged with ALMA. II. The chemistry of the dense molecular gas*, *A&A* **570** (Oct., 2014) A28, [`1407.4940`].

[34] K. Bernlöhr, A. Barnacka, Y. Becherini, et al. and CTA Consortium, *Monte Carlo design studies for the Cherenkov Telescope Array*, *Astroparticle Physics* **43** (Mar., 2013) 171–188, [`1210.3503`].

[35] J. S. Ulvestad and R. R. J. Antonucci, *VLA Observations of NGC 253: Supernova Remnants and H II Regions at 1 Parsec Resolution*, *ApJ* **488** (Oct., 1997) 621–641.

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[36] F. Müller-Sánchez, O. González-Martín, J. A. Fernández-Ontiveros, J. A. Acosta-Pulido and M. A. Prieto, *The Stellar Kinematic Center and the True Galactic Nucleus of NGC 253*, *ApJ* **716** (June, 2010) 1166–1177, [`1005.1645`].

[37] M.-H. Ulrich, *Observations of the outflow of gas from the nucleus of NGC 253 and its implications for the stellar population of the nucleus*, *ApJ* **219** (Jan., 1978) 424–436.

[38] W. Pietsch, A. Vogler, U. Klein and H. Zinnecker, *X-ray observations of the starburst galaxy NGC 253 — II. Extended emission from hot gas in the nuclear area, disk, and halo*, *A&A* **360** (Aug., 2000) 24–48, [`astro-ph/0005335`].

[39] A. D. Bolatto, S. R. Warren, A. K. Leroy, F. Walter, S. Veilleux, E. C. Ostriker et al., *Suppression of star formation in the galaxy NGC 253 by a starburst-driven molecular wind*, *Nature* **499** (July, 2013) 450–453, [`1307.6259`].

[40] A. A. Abdo, M. Ackermann, M. Ajello, W. B. Atwood, M. Axelsson, L. Baldini et al., *Detection of Gamma-Ray Emission from the Starburst Galaxies M82 and NGC 253 with the Large Area Telescope on Fermi*, *ApJ* **709** (Feb., 2010) L152–L157, [`0911.5327`].

[41] A. Abramowski, F. Acero, F. Aharonian, A. G. Akhperjanian, G. Anton, A. Balzer et al., *Spectral Analysis and Interpretation of the γ-Ray Emission from the Starburst Galaxy NGC 253*, *ApJ* **757** (Oct., 2012) 158, [`1205.5485`].

[42] G. Matt, F. Fiore, G. C. Perola, L. Piro, H. H. Fink, P. Grandi et al., *A reflection-dominated X-ray spectrum discovered by ASCA in the Circinus galaxy*, *MNRAS* **281** (Aug., 1996) L69–L73.

[43] S. K. Ghosh, R. S. Bisht, K. V. K. Iyengar, T. N. Rengarajan, S. N. Tandon and R. P. Verma, *Far-infrared observations of NGC 4945 and the Circinus galaxy*, *ApJ* **391** (May, 1992) 111–120.

[44] M. Elmouttie, R. F. Haynes, K. L. Jones, E. M. Sadler and M. Ehle, *Radio continuum evidence for nuclear outflow in the Circinus galaxy*, *MNRAS* **297** (July, 1998) 1202–1218.

[45] M. Hayashida, Ł. Stawarz, C. C. Cheung, K. Bechtol, G. M. Madejski, M. Ajello et al., *Discovery of GeV Emission from the Circinus Galaxy with the Fermi Large Area Telescope*, *ApJ* **779** (Dec., 2013) 131, [`1310.1913`].

[46] J. B. Whiteoak, *NGC 4945 - A galaxy with a nucleus full of surprises*, *Proceedings of the Astronomical Society of Australia* **6** (1986) 467–471.

[47] J. S. Doane and W. G. Mathews, *Stellar Evolution in the Starburst Galaxy M82: Evidence for a Top-heavy Initial Mass Function*, *ApJ* **419** (Dec., 1993) 573.

[48] D. K. Strickland, *Winds from nuclear Starbursts: Old truths and recent progress on superwinds*, in *The Interplay Among Black Holes, Stars and ISM in Galactic Nuclei* (T. Storchi-Bergmann, L. C. Ho and H. R. Schmitt, eds.), vol. 222 of *IAU Symposium*, pp. 249–254, Nov., 2004. `astro-ph/0404316`. DOI.

PoS(HEASA 2016)018

[49] S. Zenner and R. Lenzen, *Near Infrared Images of IRAS Galaxies*, *A&AS* **101** (Oct., 1993) 363.

[50] R. P. Norris and D. A. Forbes, *Radio Detection of a Double Nucleus in the Merging Galaxy NGC 3256*, *ApJ* **446** (June, 1995) 594.

[51] J. English, R. P. Norris, K. C. Freeman and R. S. Booth, *NGC 3256: Kinematic Anatomy of a Merger*, *AJ* **125** (Mar., 2003) 1134–1149, [`astro-ph/0302192`].

[52] K. Sakamoto, S. Aalto, F. Combes, A. Evans and A. Peck, *An Infrared-luminous Merger with Two Bipolar Molecular Outflows: ALMA and SMA Observations of NGC 3256*, *ApJ* **797** (Dec., 2014) 90, [`1403.7117`].

[53] F.-K. Peng, X.-Y. Wang, R.-Y. Liu, Q.-W. Tang and J.-F. Wang, *First Detection of GeV Emission from an Ultraluminous Infrared Galaxy: Arp 220 as Seen with the Fermi Large Area Telescope*, *ApJ* **821** (Apr., 2016) L20, [`1603.06355`].

[54] K. Sakamoto, S. Aalto, D. J. Wilner, J. H. Black, J. E. Conway, F. Costagliola et al., *P Cygni Profiles of Molecular Lines Toward Arp 220 Nuclei*, *ApJ* **700** (Aug., 2009) L104–L108, [`0906.5197`].

[55] K. Sakamoto, N. Z. Scoville, M. S. Yun, M. Crosas, R. Genzel and L. J. Tacconi, *Counterrotating Nuclear Disks in ARP 220*, *ApJ* **514** (Mar., 1999) 68–76, [`astro-ph/9810325`].

[56] T. M. Yoast-Hull, J. E. Everett, J. S. Gallagher, III and E. G. Zweibel, *Winds, Clumps, and Interacting Cosmic Rays in M82*, *ApJ* **768** (May, 2013) 53, [`1303.4305`].

[57] S. R. Kelner, F. A. Aharonian and V. V. Bugayov, *Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime*, *Phys.~Rev.~D* **74** (Aug., 2006) 034018, [`astro-ph/0606058`].

[58] K. C. Sarkar, B. B. Nath and P. Sharma, *Supernovae vs. AGN: Clues to the origin of Fermi Bubbles from OVIII/OVII line ratio*, *ArXiv e-prints* (Oct., 2016) , [`1610.00719`].

[59] M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens et al., *Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data*, *ApJ* **796** (Dec., 2014) 109, [`1406.6757`].

[60] S. Adrián-Martínez, A. Albert, M. André, G. Anton, M. Ardid, J.-J. Aubert et al., *The First Combined Search for Neutrino Point-sources in the Southern Hemisphere with the ANTARES and IceCube Neutrino Telescopes*, *ApJ* **823** (May, 2016) 65.

[61] S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli et al., *Letter of intent for KM3NeT 2.0*, *Journal of Physics G Nuclear Physics* **43** (Aug., 2016) 084001, [`1601.07459`].

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