



H.E.S.S. observations of Seyfert-starburst galaxies



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Overview

Composite Seyfert-starburst galaxies

Observations, data analyses, and results

Discussion

Conclusion





Composite Seyfert-starburst galaxies

Seyfert vs starburst galaxies

Seyfert galaxies

- Subclass of AGN
- Found in spiral galaxies
- Radio quiet - but some have large-scale radio bubbles resembling those emanating from the Milky Way
- Jet/lobes can produce γ -ray emission

Starburst galaxies

- Ongoing star formation
- Found in spiral galaxies
- Starburst phase lasts few hundred million years
- γ -ray emission from core-collapse supernovae & SNRs
- e.g. NGC 253 and M82 detected at VHE

Composite Seyfert-starburst galaxies

- NGC 1068, Circinus, and NGC 4945 have both strong starburst activity and a Seyfert nucleus
- All three show not only evidence of jet/lobe activity and star formation, but also circumnuclear superwind outflows which can accelerate charged particles
- Similar to scenarios for past activity creating Milky Way Fermi bubbles
- All three detected in GeV
 - Circinus and NGC 4945 similar to NGC 253
 - NGC 1068 one order of magnitude higher

NGC 1068

- Face-on, early type, barred spiral galaxy
- Brightest Seyfert 2 galaxy (Seyfert 1 nucleus visible in polarized light)
- $M_{\text{BH}} \sim 1.5 \times 10^7 M_{\odot}$
- Distance uncertain (10.1 - 16.7 Mpc)
- Circumnuclear disk, 200 pc + starburst ring, 2 kpc
- Reflection component from Compton thick layer seen in X-rays
- GeV luminosity one order of magnitude higher than NGC 253
- IceCube neutrino excess coincident with position

Circinus galaxy

- Gas-rich spiral galaxy, distance 4.2 ± 0.7 Mpc
- 4° below the Galactic plane
- Seyfert 2 nucleus
- Circumnuclear gas/dust rings 80 and 430 pc hosting immense starburst region
- Bipolar radio lobes inflated by kpc-scale outflows
- One-sided [O III] ionization cone
- Ionized filaments extending radially out to 1 kpc

NGC 4945

- Barred spiral galaxy, nearly edge-on, distance 3.8 ± 0.3 Mpc
- Located in Centaurus constellation
- Highly obscured Seyfert 2 nucleus, $M_{\text{BH}} \sim 10^6 M_{\odot}$
- Variable hard X-ray emission on hours timescale
- Very bright > 20 keV, only visible through reflected emission < 10 keV due to large column density ($\log[N_H / \text{cm}^{-2}] \sim 24.7$)
- Circumnuclear starburst disc 200 pc diameter
- Double conical ionized [N II] outflow



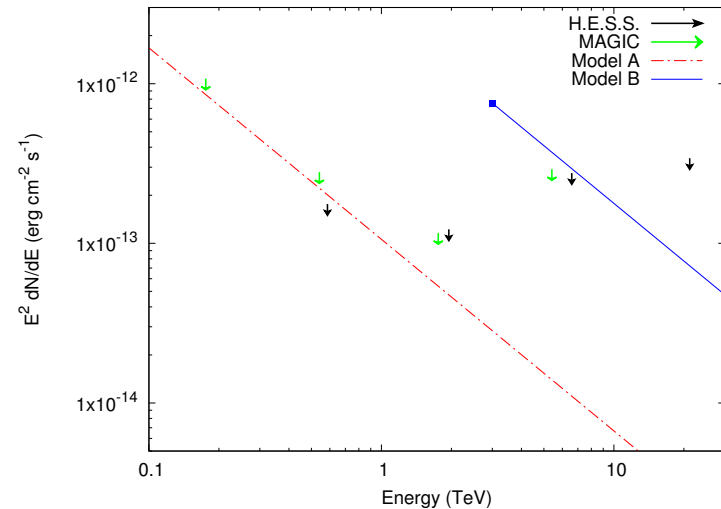
Observations, data analyses, and results

Observations: NGC 1068

- 431 observations performed from 2004 to 2016
- Total exposure 168.5 → Acceptance-corrected exposure 144.3 hours
- γ -ray excess = 157 counts above background → 2.0σ (no detection)
- Upper limit of $F(> 323 \text{ GeV}) < 3 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ (95% confidence)
- Consistent with extrapolation from Fermi-LAT spectrum

Results: NGC 1068

- H.E.S.S. upper limits comparable to MAGIC ULs
- Models A and B show γ -ray flux based on the IceCube ν flux for a $p - p(p - \gamma)$ neutrino source and further reduced by a factor of 4000 (8000) and 150 (300) due to absorption, respectively.
- Energy range for model B : IceCube scaled up $2\times$; for model A, extended to lower energies.
- Model A more tightly constrained



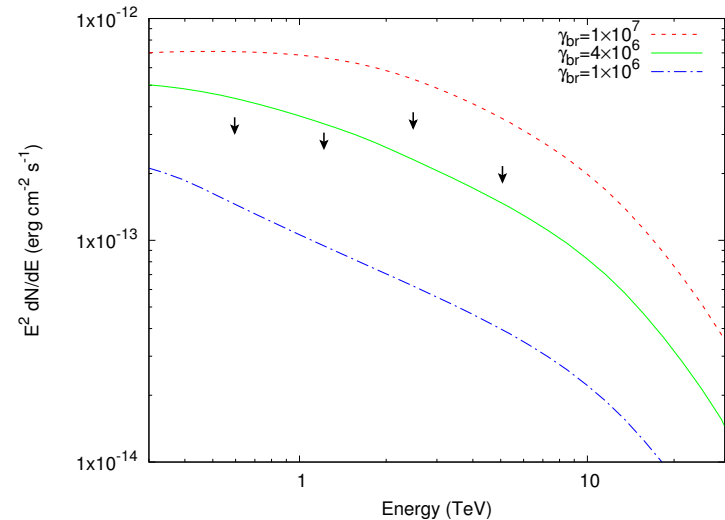
Flux upper limits obtained from H.E.S.S. observations shown along with those obtained from MAGIC. Models show the absorbed γ -ray flux.

H.E.S.S. Observations of Circinus

- March 1-4 2014; 26 good quality runs in wobble mode
- In addition, archival 12-m observations of nearby sources included
 - 12 in May 2006 of PSR J1537-6429
 - 6 in March 2007 of PWN HESS J1356-645
- Total exposure 18.4 hr → acceptance-corrected 13.2 hr
- $b = -3^{\circ}.80$ → Galactic diffuse γ -ray background subdominant component of particle background
- Exclusion region around HESS J1356-645

Results: Circinus

- 213 γ -ray-like events on-source, 2923 off-source
- $\alpha = 0.06075 \rightarrow 35.4$ excess counts $\rightarrow 2.5\sigma$ (no detection)
- Consistent with extrapolation from Fermi-LAT spectrum



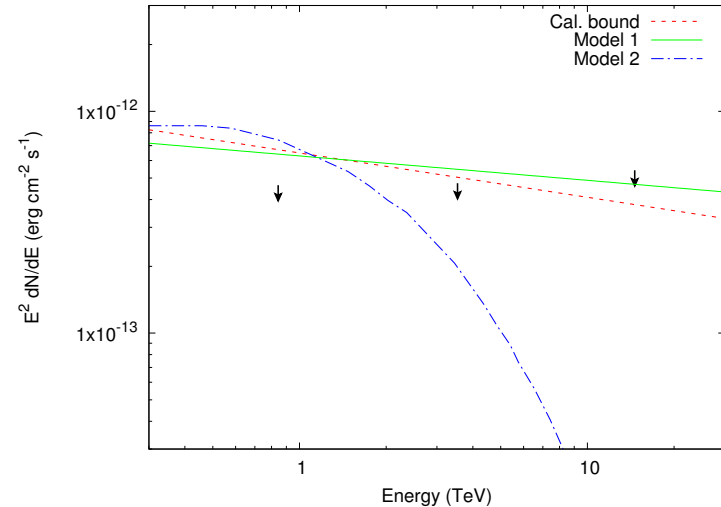
Flux upper limits obtained from H.E.S.S. observations of the Circinus galaxy. A model involving gamma-ray emitting lobes is shown for different values of a spectral break

H.E.S.S. Observations of NGC 4945

- 104 observations from 2012 to 2015
- Total exposure 42.7 hr → acceptance-corrected 37.2 hr
- 92% of 12-m and 63% of 28-m runs taken during Swift-BAT 15-50 keV high state ($> 1.71 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$)

Results: NGC 4945

- 622 γ -ray-like events on-source, 7460 off-source
- $\alpha = 0.0821 \rightarrow 55.8$ excess events $\rightarrow 0.4\sigma$ (no detection)
- $F(> 320 \text{ GeV}) < 5.8 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ (95% confidence)



Flux upper limits obtained from H.E.S.S. observations of NGC 4945 with 12-meter telescopes. A calorimetric bound is by Wang & Fields and models, 1 and 2, are by Wojaczyński & Niedźwiecki and by Xiang et al.



Discussion

Calorimeter model

- Requires energy injected in CR protons by SNe be lost to inelastic hadronic collisions before CR escape from starburst galaxies
- Neutral pion decay dominant γ -ray production mechanism
- Describes well NGC 253 and M82 γ -ray emission
- Wang & Fields found that GeV emission from NGC 1068 and NGC 4945 consistent with calorimetry assuming sufficiently high SN rates, but Circinus inconsistent
- Using W&F model, proton spectral index 2.2, H.E.S.S. limits imply 58% and 70% calorimetric efficiencies for NGC 1068 and NGC 4945 (assuming CR acceleration energy per SN of 3×10^{50} erg), higher than M82 (35%) and NGC 253 (39%), leaving room for contribution from other processes - viable explanation
- For Circinus, H.E.S.S. upper limits imply calorimetric efficiency upper limit above calorimetric bound (i.e. $> 100\%$) due to low infrared luminosity and predicted VHE flux.

γ -ray emission due to AGN outflows

- Spectral curvature and/or variability
- TeV flux can be higher or lower than extrapolated GeV spectra
- According to Lenain et al. (2010) EIC model, VHE emission detectable by H.E.S.S. only if maximum electron energy $\gamma_{\max} > 5 \times 10^6$
- For NGC 1068, characteristic frequency of a soft (external) photon field 1×10^{14} Hz \rightarrow upscattering to TeV in Klein-Nishina regime and therefore suppressed wrt calorimeter model
- Adding additional hard ($\gamma \simeq 2.0$) component to account for CR protons accelerated by AGN-driven shocks can exceed TeV flux produced by calorimeter model (Lamastra et al. 2016)
 - However, requires CR acceleration efficiencies larger than commonly assumed for SNR shocks
 - Constraints from Acciari et al. (2019) show that AGN outflow model fails to reproduce broadband γ -ray spectrum from NGC 1068.

Jet-driven bubbles: NGC 1068 and the Circinus galaxy

- Structures similar to Fermi bubbles
- kpc-scale lobes present in NGC 1068 and Circinus
- Kataoka et al. (2013) model + ISRF in addition to CMB
 - Bubbles closer to galactic disks than in Milky Way
 - NGC 1068 has higher infrared luminosity
 - ISRF upscattered to higher energies than CMB
 - ISRF model adopted from GALPROP and scaled according to galactic infrared luminosity
 - In this leptonic model, γ -ray emission luminous at TeV but faint in GeV band (similar to young shell-type TeV-bright SNRs)
 - Assumes CR electrons and B fields in an approximate energy equilibrium
- Using radio band flux densities, for Circinus: $\sim 3.5\mu G$ while for NGC1068: NE lobe $87\mu G$, SW lobe $44\mu G$
- Broken power law electron spectra, index 2.2 below and 3.2 above γ_{brk}
- Maximum electron Lorentz factor 10^8
- Break energy only free parameter

Jet-driven bubbles: NGC 1068 and the Circinus galaxy

- Comparing to H.E.S.S. limits, break energy must be lower than $\gamma_{\text{brk}} \simeq 4 \times 10^6$ in NGC 1068 and Circinus, compared to 10^6 for Fermi bubbles from Kataoka et al. (2013)
- Therefore less constrained than Fermi bubbles, possibly detectable by further VHE observations
- Hadronic bubble emission can also contribute, which would further constrain electron energy break

Temporal characteristics of NGC 4945

- VHE flux variability can be caused by SNe or AGN jets
- Wojaczyński & Niedźwiecki (2017) reported evidence for
 - Anti-correlation between daily hard X-ray fluxes from Swift and γ -ray flux from Fermi-LAT
 - Correlation between hard X-ray flux and γ -ray spectral hardness ($\Delta\Gamma = 0.36 \pm 0.11$)
 - Indication of AGN contribution to the HE γ -ray emission
 - Extrapolation of subdominant hard component to TeV energies would be substantial
- $\sim 80\%$ of H.E.S.S. exposure during strong hard X-ray flux state
 $\rightarrow F(> 1 \text{ TeV}) = (4.3 \pm 0.8) \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$
- Suggestive of cutoff during strong hard X-ray state

Spectral characteristics of NGC 4945

- Two-state behavior can lead to spectral hardening of HE γ -ray spectrum under assumption of broken power-law spectrum
- Low-energy part dominated by soft γ -ray component produced during weak hard X-ray state, high-energy part by hard γ -ray during strong hard X-ray state.
- Broken power law can also result from two different spectral components e.g. Centaurus A
- Xiang et al. (2021): spectral hardening in Fermi-LAT 11 year spectrum
- With two hadronic components, high- E component has very hard proton power law spectral index of $\alpha = 1.12_{-0.19}^{+0.13}$, harder than diffusive shock accel. $\alpha = 1.5$
- H.E.S.S. differential flux UL at 0.84 TeV is $E^2 dN/dE < 4.7 \times 10^{-13}$ erg $\text{cm}^{-2} \text{s}^{-1}$ which is less than the Xiang et al. two-zone model $E^2 dN/dE = 7.4_{-3.4}^{+1.0} \times 10^{-13}$ erg $\text{cm}^{-2} \text{s}^{-1}$
- Sufficient to constrain, but to fully test, flux UL must be lowered by a factor of two.

Multi-messenger channels: Astrophysical neutrinos

- pp or $p\gamma$ interactions produce both charged pions which decay into muons and neutrinos and neutral pions which decay into γ rays.
- The neutrino channel can be used to constrain the VHE γ ray production and absorption

$$\frac{dN_i}{dE_i} = k_i \left(\frac{E_i}{\text{TeV}} \right)^{-\Gamma}, i = \{\nu_\mu + \tilde{\nu}_\mu, \gamma\}$$

where $k_{\nu_\mu + \tilde{\nu}_\mu} \approx (0.71 - 0.16\Gamma)k_\gamma$ for pp interactions and $k_{\nu_\mu + \tilde{\nu}_\mu} \approx 2^{-\Gamma}k_\gamma$ for $p\gamma$ interactions

- Neutrinos interact extremely weakly and travel to Earth without attenuation, while γ rays can be heavily absorbed by photon fields within the source.

IceCube neutrino excess and NGC 1068

- Refined analysis of IceCube data from 2008/4/6 to 2018/7/10 showed an excess of 79_{-20}^{+22} neutrinos associated with NGC 1068 at a significance of 4.2σ .
- Reported averaged best-fit at $E_\nu = 1$ TeV is $\Phi_{\nu_\mu + \tilde{\nu}_\mu}^{1\text{TeV}} = (5.0 \pm 1.5_{\text{stat}} \pm 0.6_{\text{sys}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ with power law index $\Gamma = 3.2_{-0.2}^{+0.2}$.
- Too high to be explained by starburst scenarios
- Given H.E.S.S. integral flux UL above 0.33 TeV of $I_\gamma = 3 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$, the optical depth for internal $\gamma\gamma$ absorption is $\gtrsim 4000$ for pp neutrino sources and $\gtrsim 8000$ for $p\gamma$ neutrino sources

Multi-messenger channels: UHECR channel

- Observed correlation between starburst galaxies and UHECR arrival directions as seen by Pierre Auger Observatory (PAO), suggesting CRs accelerated to $> 3.9 \times 10^{19}$ eV
- Favored model with 9.7% of UHECR flux above 3.9×10^{19} eV from nearby starburst galaxies (remaining 90.3% isotropic)
- UHECR hotspot in Centaurus A/M83 group which contains NGC 4945
- UHECR excess close to south Galactic pole \rightarrow contributions from NGC 253 and NGC 1068
- Assuming CR power-law with spectral index s harder than 2.7 below $> 3.9 \times 10^{19}$ eV, CR luminosities above proton energy 10 GeV compared with those by SNRs - strongly depends on spectral index

Auger excesses and NGC 4945 + NGC 253

- For NGC 4945 and NGC 253, corresponding to 39% and 36% of possible UHECR flux from SBGs, CR power comparable with CR power produced by SNRs if $s = 2.2$ and $> 10\times$ the CR power produced by SNRs if s is 2.4 or softer.
- Therefore, calorimetry limits from H.E.S.S. and Fermi-LAT observations of NGC 4945 and NGC 253 are violated if CR-UHECR sources have soft spectra $s \gtrsim 2.2$.
- Potential CR-UHECR sources in Seyfert/starbursts include starburst superwinds, hypernova remnants, and kpc-scale jets.



Conclusion

Summary

- Composite Seyfert/starburst galaxies NGC 1068, Circinus, and NGC4945 were observed in VHE γ rays by H.E.S.S.
- Only flux upper limits obtained, constraining
 - fraction of SN explosion KE converted into CR energy in NGC 1068 and NGC 4945
 - electron populations inside the kpc-scale bubbles in NGC 1068 and Circinus
 - temporal and spectral properties of NGC 4945 previously suggested from Fermi-LAT observations
 - propagation of VHE γ rays produced via hadronic interactions and expected to accompany neutrinos seen with IceCube, for a SMBH surrounded by gas or photons in NGC 1068, and
 - spectral hardness of hypothetical CR-UHECR sources in NGC 4945 producing both CRs interacting with gas in NGC 4945 and UHECRs observed on Earth.

Summary

- These ULs are among the most stringent constraints to date.
- In conclusion, VHE γ -ray observations of composite Seyfert/starburst galaxies probe a broad range of phenomena.
- CTA will be able to reach comparable sensitivities in one tenth the exposure time, with the possibility of detecting differential fluxes at 1 TeV greater than $1 \times 10^{-13} \text{ erg cm}^{-2}\text{s}^{-2}$.



**Thanks for
your attention!**



Backup

H.E.S.S. Analysis

- Model analysis - semi analytical air shower model
- Better angular resolution and sensitivity compared to Hillas parameter-based
- Combined3 Standard cut configuration
- Monoscopic vs stereoscopic chosen depending on reconstructed direction uncertainty for events where both possible
- $0^\circ.12$ on-source radius (corresponding to point-like source)
- Reflected region background method with multiple off-source regions
- 95% confidence level, spectral index $\Gamma = 2.4$ assumed
- Cross-check with `gammapy` analysis

H.E.S.S. Observations of NGC 1068

- 431 good quality runs taken in wobble mode
 - 310 with 4 12-m telescopes
 - 69 with between 1 and 3 telescopes (most only 12-m)
 - 23 with only the 28-m
 - 29 with 5 telescopes
- 279 (65%) prior to MAGIC observations
- Zenith angles range from 23° to 38°, mean zenith angle 26°
- Most taken with offset 0°.7
- 6077 γ -ray like events on-source
 - 77660 γ -ray like events off-source
 - on-source/off-source exposure

| Year | Start (mm/dd) | End (mm/dd) |
|------|------------------|----------------|
| 2004 | 10/09 | 10/17 |
| 2006 | 10/13 | 10/23 |
| 2008 | 08/27 | 09/08 |
| 2011 | 08/26 | 12/19 |
| 2012 | 10/13 | 12/11 |
| 2013 | 10/02 | 10/28 |
| 2014 | 08/23 | 10/16 |
| 2015 | 09/21 | 11/16 |
| 2016 | 07/05 | 10/29 |



ratio $\alpha = 0.0762$

Comparison with GeV emission

- Circinus and NGC 4945 are at similar distances to NGC 253 and M82, starburst galaxies detected by both Fermi-LAT and H.E.S.S.
- NGC 1068 is ~ 4 times more distant but significantly higher GeV luminosity
- NGC 1068 and NGC 4945: 4FGL-DR3 (Fermi-LAT 12-year) fluxes compatible with Lenain et al. (2010)
- Circinus: 4FGL-DR3 consistent with Ebrahim (2021) and Guo et al. (2019) but $2.5\times$ lower than Hayashida et al. (2013)
- Extrapolation of Fermi-LAT spectra to H.E.S.S. energy range yields expected statistical significances of:
 - NGC 1068: 2.2 to 4.8σ
 - Circinus: 1.0 to 3.6σ
 - NGC 4945: 2.0 to 3.7σ
- Lack of detection by H.E.S.S. consistent with extrapolation of Fermi-LAT spectra