Multi-wavelength study of large-scale outflows from the Circinus galaxy | ROZEENA EBRAHIM

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Circinus is a spiral galaxy located *4 Mpc* away featuring *kpc-scale lobes* along its minor axis. Circinus shows characteristics of both *Seyfert* and *starburst* galaxies.

AIMS. *Observe* kpc-scale radio lobes with MeerKAT. Study GeV emission of Circinus with Fermi-LAT. Investigate observational properties to study *lobe formation*. Compare these results to the *Fermi bubbles*.

WHY CIRCINUS? Facilitates the study of:

- Lobe emission models:
  - Active galactic nucleus (AGN) jet driven
  - Supernova (SN) wind driven
- The origin of the Fermi bubbles
- The interaction between *radio lobed spiral galaxies*[1] and their environments.

[1] *Radio lobes are rarely observed in spiral galaxies, such as Circinus, but mostly in elliptical ones.*

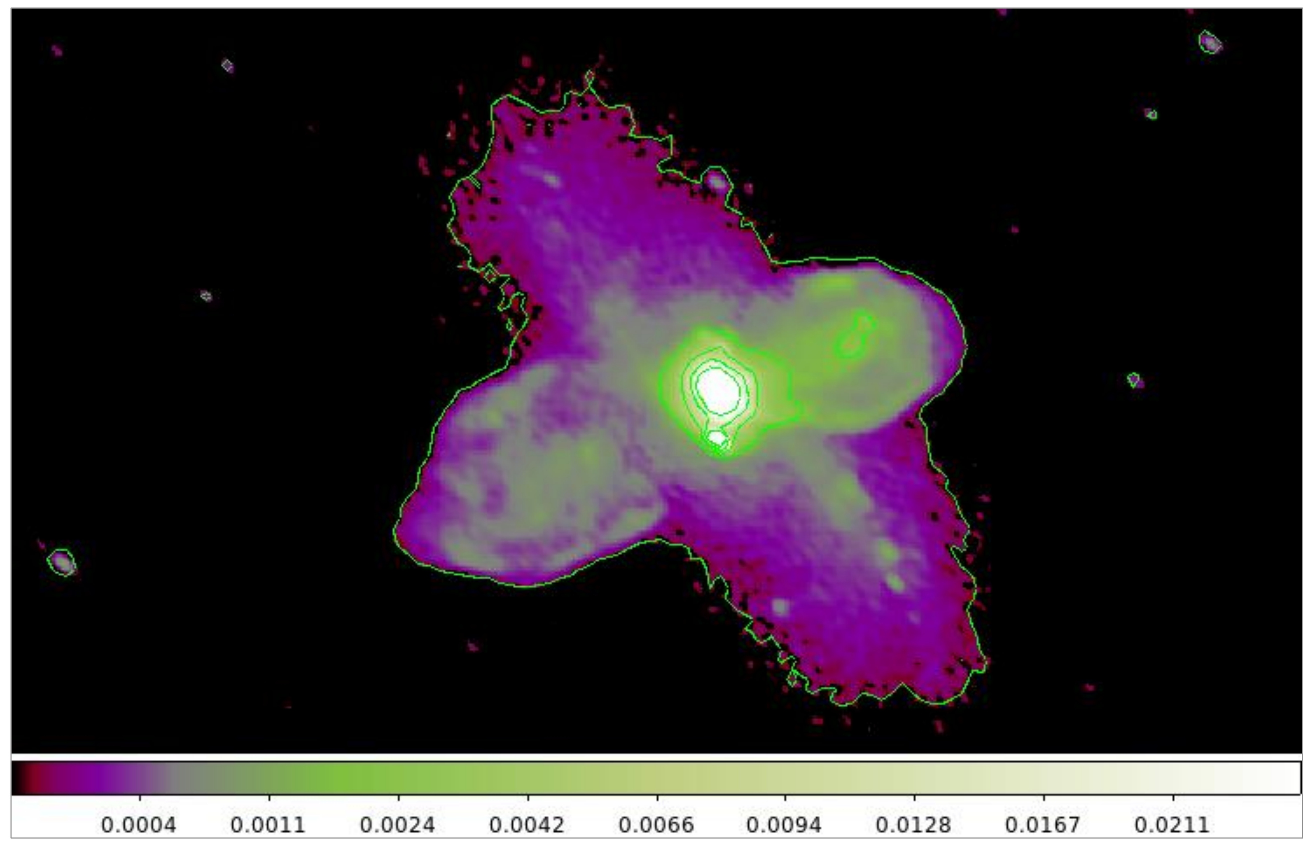

Fig.1: **MeerKAT radio map at 1.4 GHz of Circinus in Jy/beam with a 149 MHz bandwidth using a 7.6x4.4 arcsec² beam.**
Image provided by SARAO using the CARAcal pipeline (this work, Thorat et al, in prep)

RADIO EMISSION OF CIRCINUS.

- **CHALLENGING PREVIOUS CLAIMS AGAINST THE STARBURST MODEL:**
  The MeerKAT spectral index map **(Fig. 2)** shows *similar indices* for the lobe sub-structure. This spectral analysis questions ATCA observations which show *spectral flattening* towards hotspots used as evidence against the starburst wind-driven model [1].
- **ORIGIN OF EMISSION IN SHOCKED REGION/SHELL:**
  We computed the width of the shocked region (shell), that would be observed at a *MeerKAT characteristic frequency*, due to synchrotron losses. The predicted lobe *width-to-radius ratio is ~30x the observed ratio*. Hence, the width of shell cannot be explained by synchrotron cooling arguments - very strong magnetic fields are required to match observations. A *shock compression* scenario is more likely. This behaviour is typical of what is observed in *SNRs* (supernova remnants).
- **FEASIBILITY OF THE STARBURST MODEL:**
  We confirm the argument made by [1] in determining the feasibility of the starburst model. The age of the lobes is inferred to be $\sim 10^6$ years and the total energy needed to create the shocked regions is 2×10^{55} erg [1]. A single SN explosion at maximum efficiency releases 10^{51} erg. For a timescale of 10^6 years, this would require a SN rate of ~0.02/year. This is consistent with the SN rate derived by [1]. Thus, the compatibility of these timescales permits a superwind driven model.

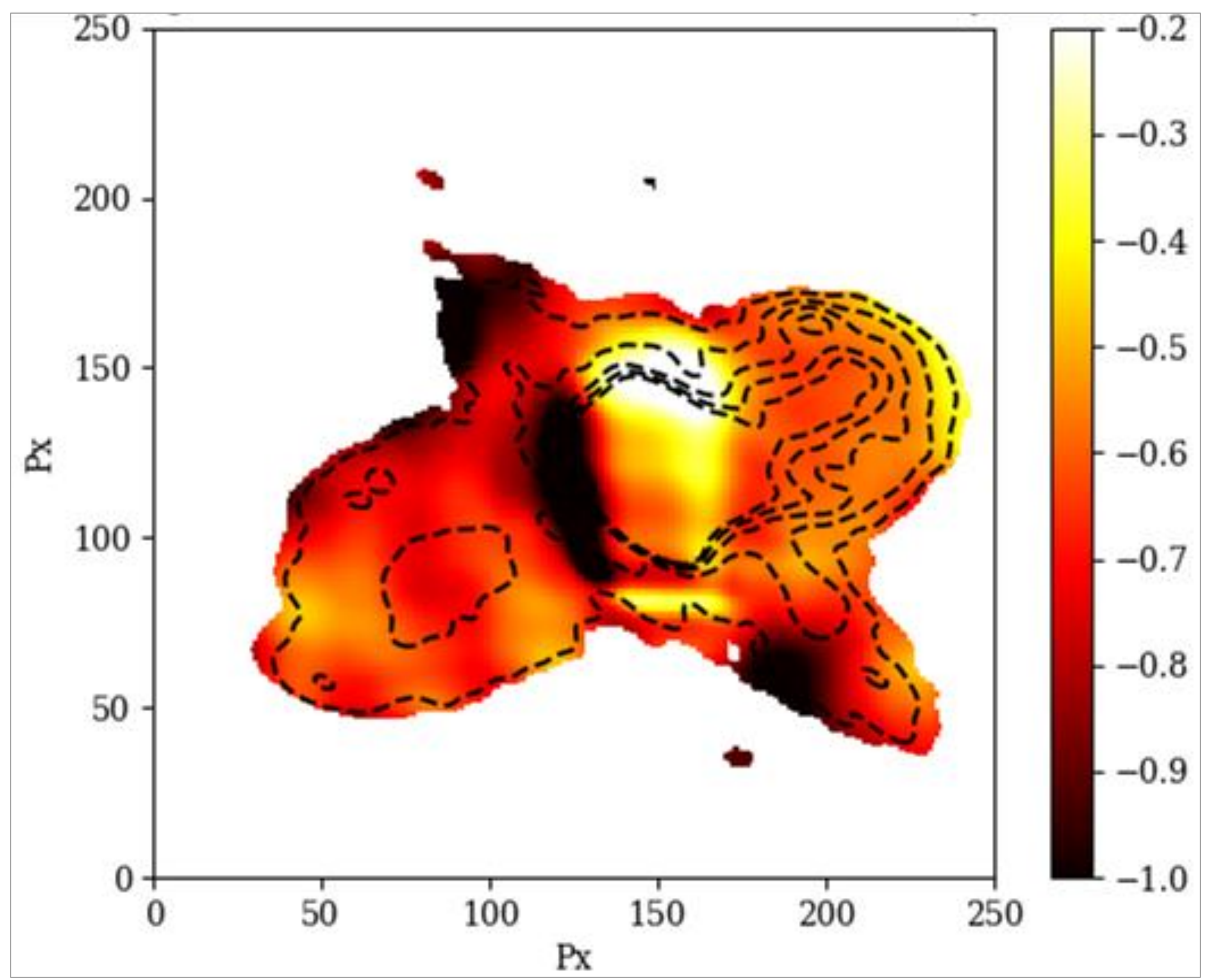

Fig.2: **MeerKAT spectral index map of Circinus (1020 MHz -1380 MHz) with beam correction & 2D box smoothing, and 1020 MHz contours.**

GEV EMISSION OF CIRCINUS.

- **COSMIC RAY - INTERSTELLAR MEDIUM (CR-ISM) INTERACTION:**
  The observed *GeV luminosity* from our 0.1-100.0 GeV *10-year* Fermi-LAT *likelihood analysis* is consistent with an *empirical relation* for *star-forming galaxies*, suggesting that the GeV emission of Circinus originates from the *CR-ISM interaction* (due to star-forming processes). This is contrary to the results from [2], who used the *first 4 years* of data and an *older source catalog* to find Circinus *incompatible* with the star-forming relation. Our results also provide evidence that Circinus is a *proton calorimeter*, consistent with [3].

Fermi-LAT γ-ray luminosity in the 0.1-100.0 GeV range for $L_{ir}=0.66\times10^{44}$ erg/s [2] at different photon indices

	Γ (photon index)	Lγ (γ-ray luminosity 0.1-100.0 GeV) [10^{40} erg/s]	L_γ/L_{ir} (ratio between 0.1-100.0 GeV γ-ray luminosity and 8.0-1000.0 μm infrared luminosity)
Our analysis - Γ free	2.06±0.11	1.02±0.40	0.00018
Our analysis - Γ fixed	2.26	1.12±0.16	0.00019
Guo et al. (2019) [3]	2.20	1.17±0.44	0.00020
Proton calorimeter limit	-	1.05	0.00018

- **FLUX DECLINE OF SN1996CR (Type IIn SN in Circinus):**
  A possible *decline* of the GeV flux is noted with time (as more Fermi-LAT data is included and the source models are updated to include more observations). We considered the case in which this flux decline is dominated by the *γ-ray emission of SN1996cr*. We tested for both a *constant* and a *decline* model **(Fig. 3)** and found *both models are plausible*. More *Fermi-LAT data* and *CTA-South* observations could be fruitful in understanding the origin of this GeV emission.

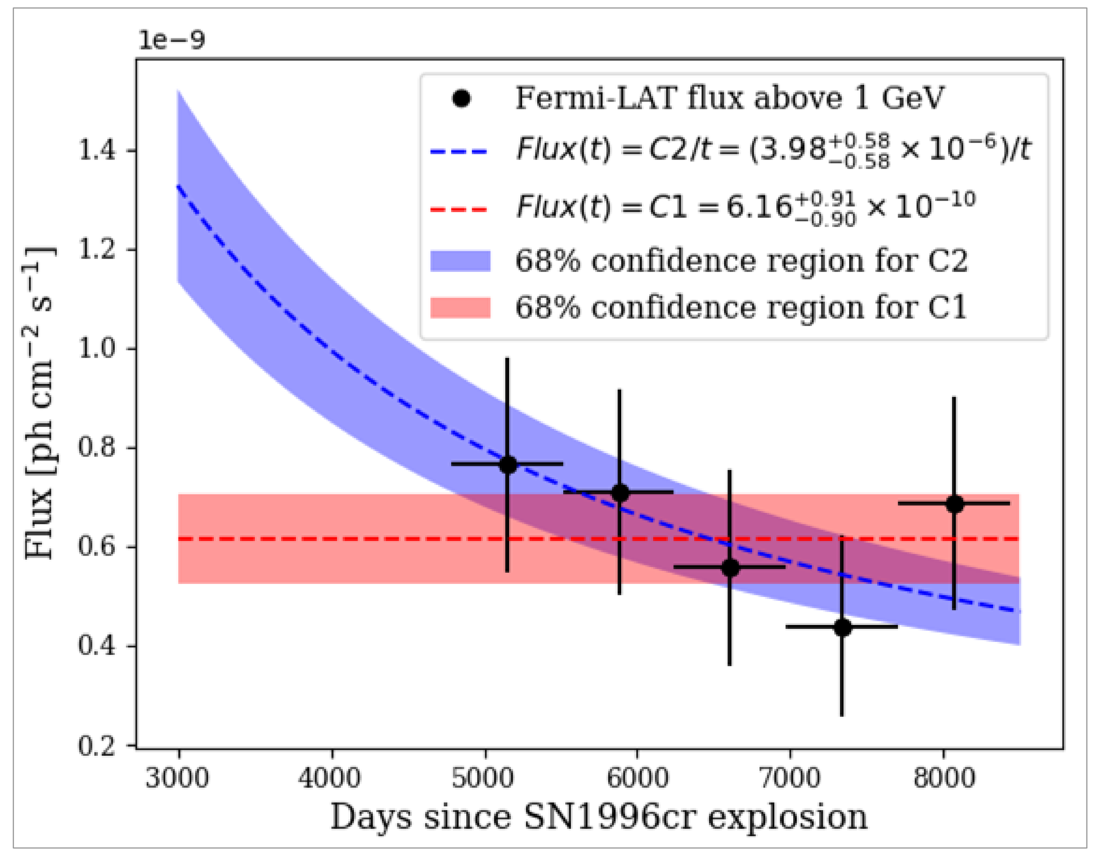

Fig.3: **Fermi-LAT GeV light curve of Circinus above 1 GeV fitted with two models.**

- **SCIENTIFIC CASE FOR H.E.S.S.:**
  Our estimates of the expected γ-ray emission from the radio lobes of Circinus (through our broadband emission modelling - **Fig. 4**) and the extrapolated SN1996cr GeV emission can be tested with *H.E.S.S. array*. Since the TeV flux is expected to *drop with time*, our estimates show that it makes sense to *re-analyse* archival H.E.S.S. data in order to search for a *brighter TeV signal*. This presents a new scientific case for Circinus with H.E.S.S. These H.E.S.S. observations can *constrain the lobe structures* in nearby galaxies and allow us to *probe models for transient events* with data collected *before the Fermi-LAT launch*.

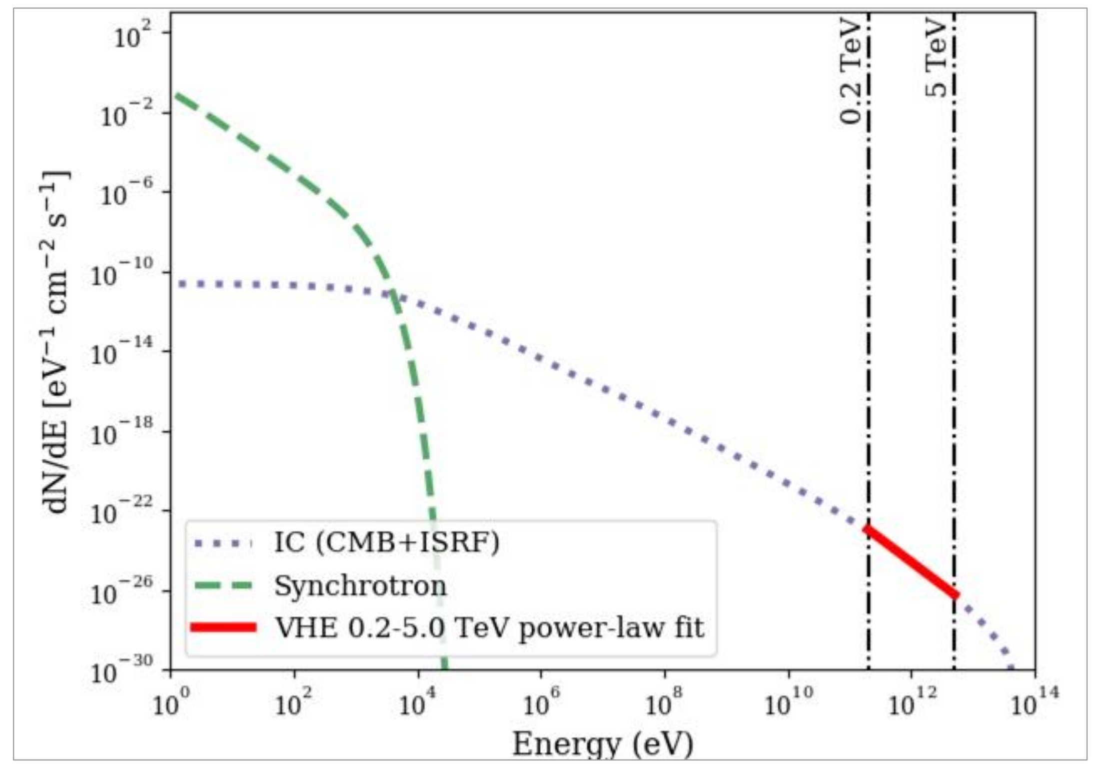

Fig.4: **Power-law fit of the modeled SED in the 0.2-5.0 TeV range shown in red.**

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[2] M. Hayashida, Ł. Stawarz, C. C. Cheung, K. Bechtol, G. M. Madejski, M. Ajello,F. Massaro, I. V. Moskalenko, A. Strong, and L. Tibaldo, *Discovery of GeV Emission from the Circinus Galaxy with the Fermi Large Area Telescope*,ApJ, vol. 779,p. 131, Dec. 2013.

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