Multi-Wavelength Study of the Large-Scale Outflows from the Circinus Galaxy

(Research in progress)

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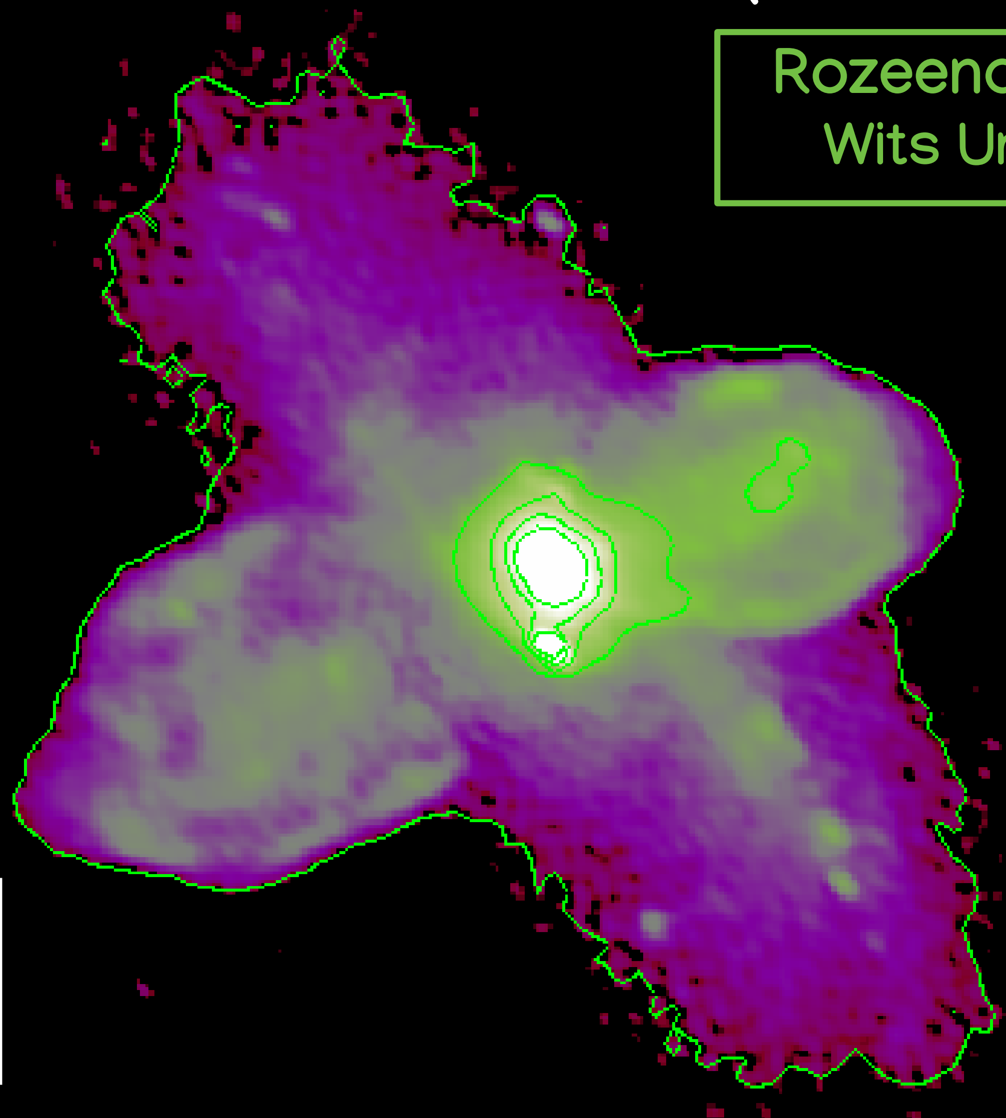

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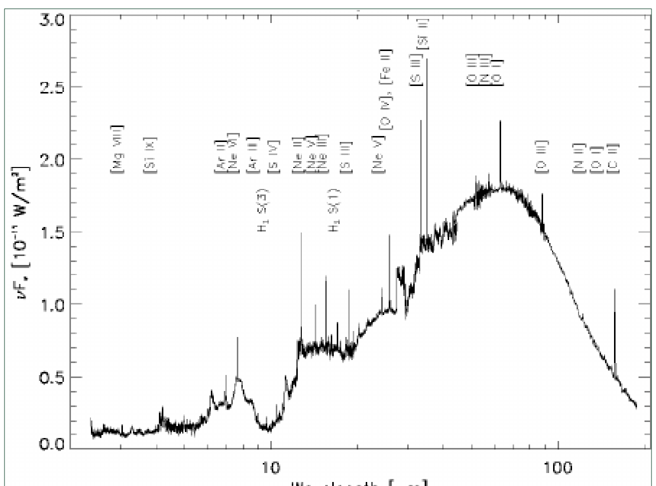
Image: Circinus Galaxy – MeerKAT Image Courtesy of SARAO

Circinus Galaxy

- Spiral galaxy
- 4 Mpc away
- Composite Seyfert/ starburst galaxy

Image: Circinus Galaxy – Judy Smith (Wikimedia Commons)

– <u>Seyfert Galaxies:</u>



Optical emission spectrum of Circinus
Image: Taken from Cesarsky & Sauvage (1999)

- Low luminosity nuclei
- Powered by massive blackholes
- Visible wavelengths: Appear as spiral galaxies
- Other wavelengths: Very luminous cores
- Circinus core classified as Seyfert II:
  - Massive compact core
  - Seyfert II characteristic emission lines (narrow emission lines only)

Circinus Galaxy

– Starburst Galaxies:
  - Closest starburst galaxies: Circinus, NGC 253, NGC 4945 and M82
  - Host supernovae (SNe)
    - SN 1996cr: Bright type II SN in Circinus which exploded in 1996
  - Very high star formation rates
  - Global Kennicutt-Schmidt Law:
    - Relation between gas density and disk-averaged star-formation rate
    - Circinus lies amongst the starburst galaxies
  - Starburst nature of Circinus:
    - Star-formation rate
    - Characteristic emission lines
    - Nuclear starburst ring

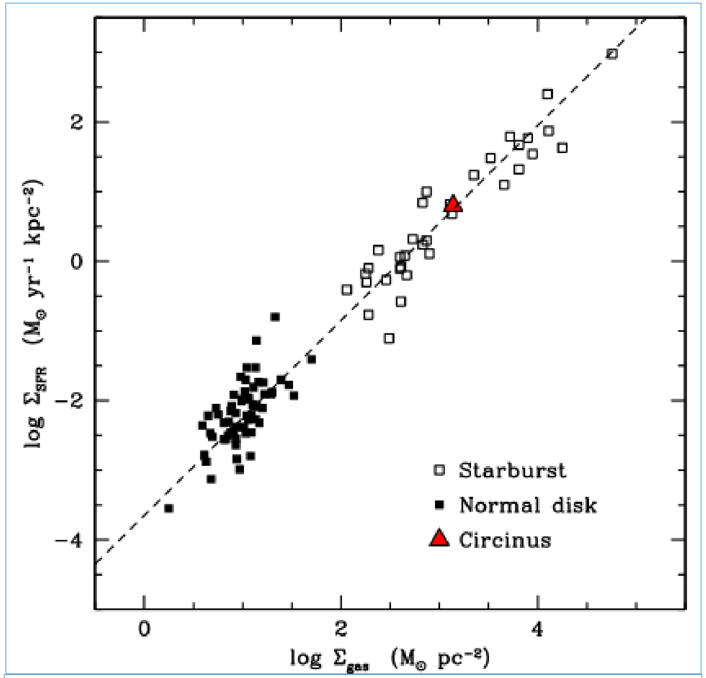


Image: Global Kennicutt-Schmidt Relation for a sample of nearby normal and starburst galaxies by For et al. (2012)

Why Circinus?

1. Studying the origin of radio lobes

- Circinus: kpc radio lobe outflows along minor axis
- Radio lobes
  - Strong radio emission from the centre of a galaxy
  - Length: Up to 1 Mpc
- Two commonly proposed models:
  - Starburst driven galactic winds
  - AGN driven jets

1. Starburst model:

- SN explosions in core
- Each SN produces stellar wind
- Winds combine to form a super-bubble

2. Supersonic jet model:

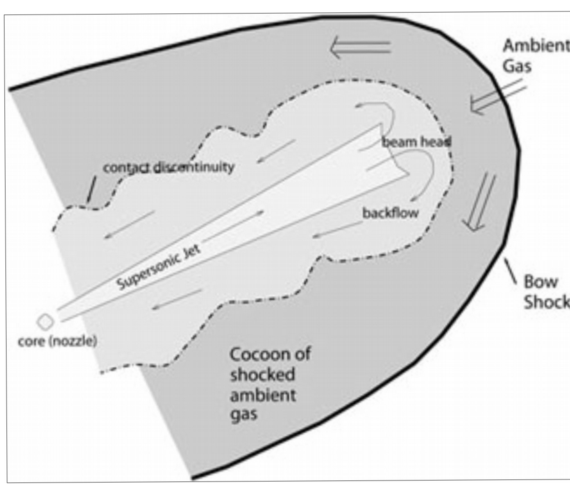


Image: D.M. Worrall (NASA/IPAC Extragalactic Database)

- Jet interacts with surroundings to produce shockwaves
- Termination of the jet = radio hotspot
- Jet's fluid flow produces a contact discontinuity containing the radio lobe emission
- Sufficient energy can drive a bow shock and the resultant shocked ambient gas is observed in the x-ray

Studying these radio lobes can provide a better understanding of the emission models

Why Circinus?

2. Studying Fermi Bubbles

- Kpc emission from the Milky Way
- Gamma-rays: 8 kpc bubble structures
- Radio: Two very large bi-conical lobes with ridges that wind along the cones
- Origin: AGN-driven bubbles or starburst-driven outflows?
  - Caretti et al. (2013) advocate a *cosmic ray* model
  - Bubbles have a narrow waist
    - Consistent with a central star-forming ring of gas
    - Support for *starburst* model

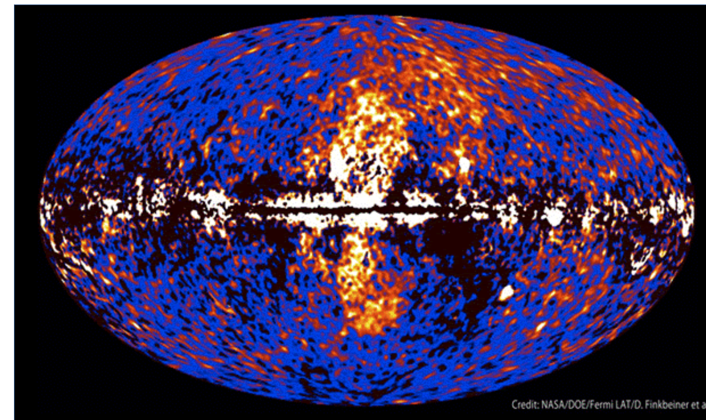
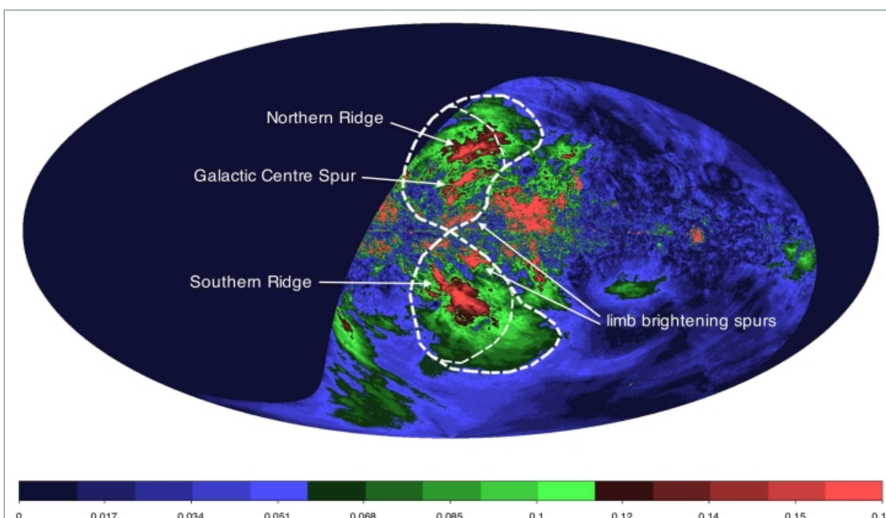


Image: Fermi Bubbles mapped in the gamma-rays by Fermi-LAT (NASA Images)



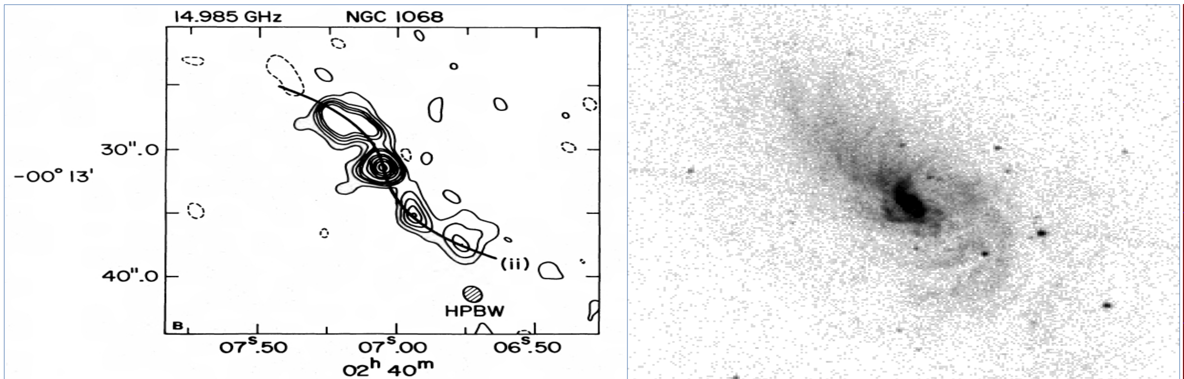
Fermi Bubbles spatial extent in radio (thick dashed line) and in gamma-rays (thin dashed lines)

Image: Linearly polarized intensity map at 2.3 GHz from S-PASS taken from Carretti et al. (2013)

Why Circinus?

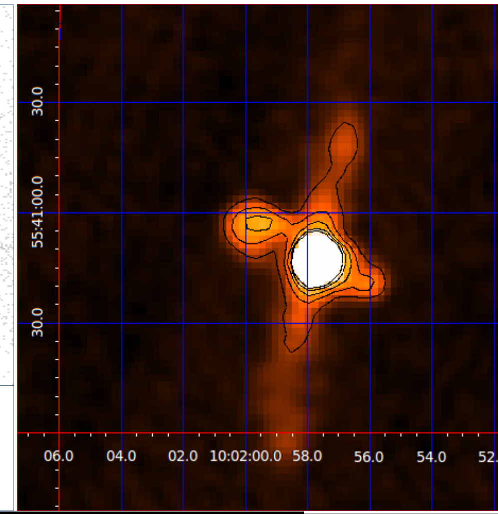
2. Studying Fermi Bubbles

- The study of its origins requires the study of galaxies featuring a similar emission



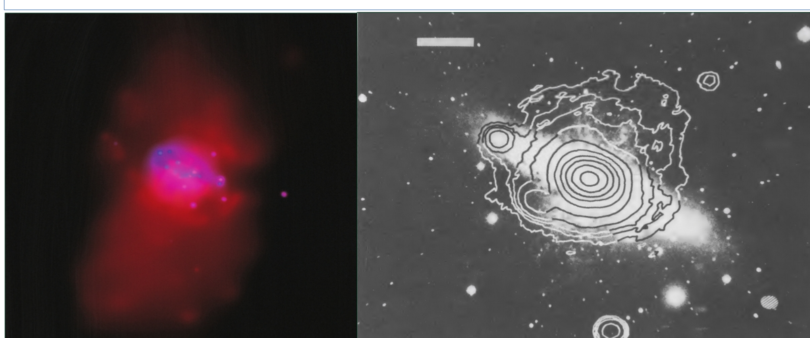
NGC 1068: Spiral galaxy, 15 Mpc away, AGN driven S-shaped lobe emission

Images: 15GHz VLA Radio Contour Map (LEFT) & 0.25-7.50 KeV Chandra X-ray map (RIGHT)



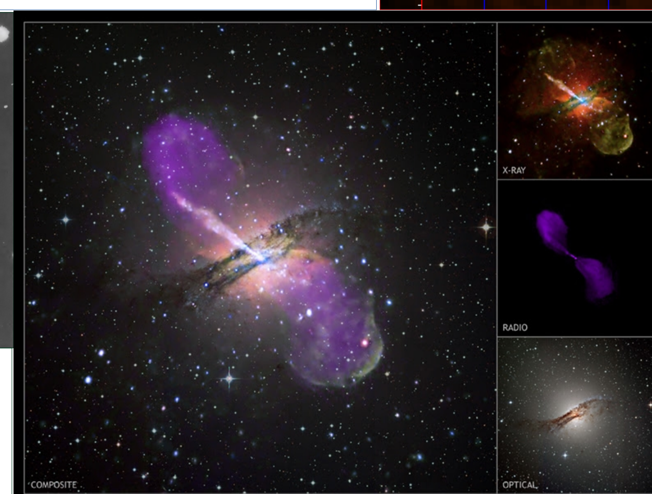
NGC 3079:
-Spiral AGN/ starburst galaxy
-16 Mpc away
-Giant radio lobes

Image: 20cm VLA FIRST Survey Radio Image



M82: Elliptical starburst galaxy, 3.6 Mpc away, 8 kpc starburst driven radio halo

Image: 0.5-10.0 keV Chandra X-ray Map (LEFT) & 1.4GHz VLA Radio Map on optical continuum photograph (RIGHT)



Centaurus A:
-Nearest AGN
-3.4 Mpc away
-Jets, radio lobes, diffuse emission
-Southern inner lobe has a shock similar to one found in Circinus

Image: Composite X-Ray, Radio and Optical image of Centaurus A (NASA Images)

Studying these radio lobes can provide a better understanding of the origin of Fermi Bubbles

Why Circinus?

3. Studying radio lobed spiral galaxies

- Radio lobes: usually observed in elliptical galaxies
- Spiral galaxies:
  - Dense interstellar medium (ISM)
  - Jets cannot travel far out into the ISM
  - Less energy fed into ISM
  - Higher star-formation rate
- Milky Way is a spiral galaxy with large outflows
  - Others: NGC 1068, NGC 3079 and Circinus
- Circinus is the best candidate:
  - Closest
  - Study the substructure of its lobes in better detail

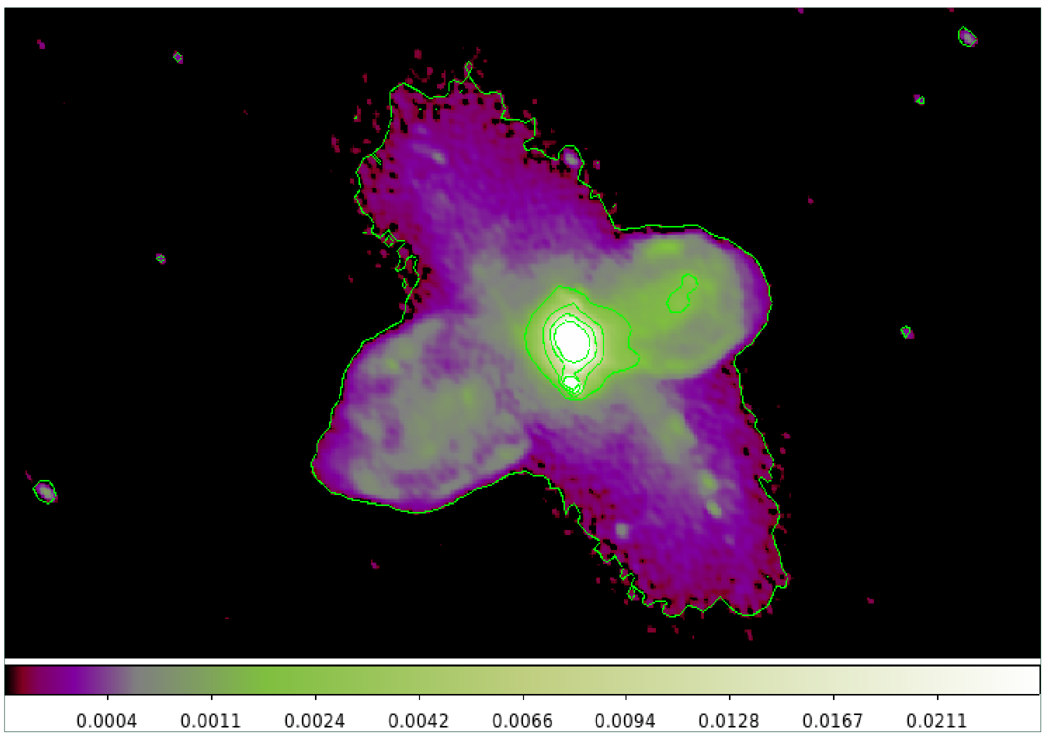
The study of Circinus which features both star-formation and jets facilitates the study of the substructure of radio lobes anomalously found in a spiral galaxy

Research Objective

- Study the radio lobes of Circinus in the context of Milky Way Fermi bubbles
- Investigate whether these structures originate from star-formation activity or jets
  - Multi-wavelength analysis of the radio lobes using MeerKAT and Fermi-LAT data
- Compare these results to Fermi bubbles

What have we done so far?
Spatial Structure of Radio Lobes

- MeerKAT: High resolution data to identify the regions of different brightness
- 4 hours of 1.4 GHz MeerKAT data of Circinus
  - Provided by SARAO
- MeerKAT resolution: Spatial structure of lobes are observable



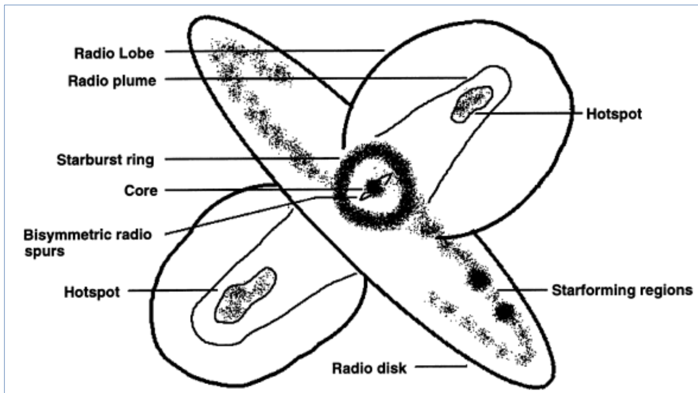
MeerKAT Radio Map of Circinus
–Central frequency: 1.375 GHz
–Bandwidth: 149 MHz
–Beam: 7.6x4.4 $arcsec^2$
–Pixel size: 1.3x1.3 $arcsec^2$
–Map units: Jy/beam
–60 Antennas

Image: Radio Map provided by SARAO

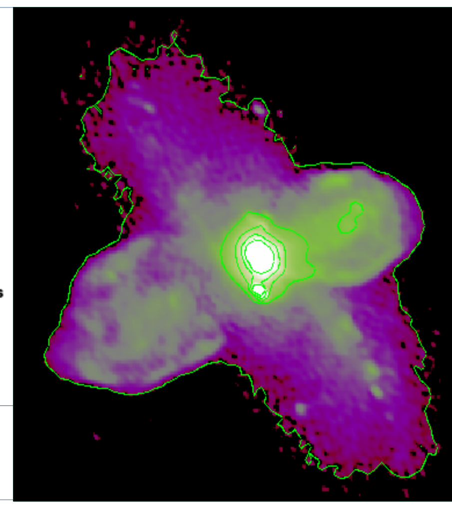
What have we done so far?

Spatial Structure of Radio Lobes

- Elmouttie et al. (1998):
  - Unresolved core
  - Diffuse radio nuclear starburst ring
  - 1.5 kpc radio lobes: Contains central plume and an edge brightened region



Proposed structure of Circinus from ATCA
Image: Taken from Elmouttie et al. (1998)

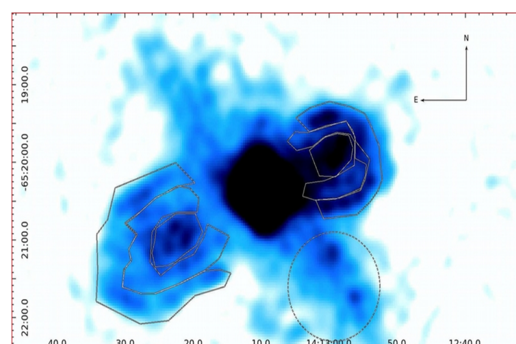


1.4 GHz MeerKAT Radio Map of Circinus

Image: Radio Map provided by SARAO

- MeerKAT & ATCA:
  - Bright core region
  - Galactic disk
  - Radio lobes (NW and SE)
  - Similar star forming regions in southern disk

- Mingo et al. (2012):
  - Similar morphology to MeerKAT and Elmouttie et al. (1998)
  - Edge-brightening within the shells



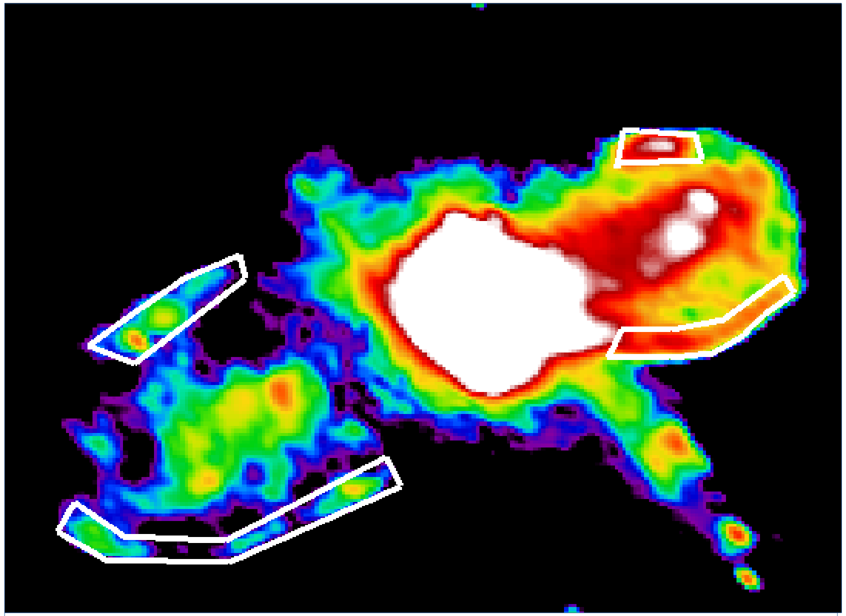
13cm ATCA Radio Map of Circinus

Image: Taken from Mingo et al. (2012)

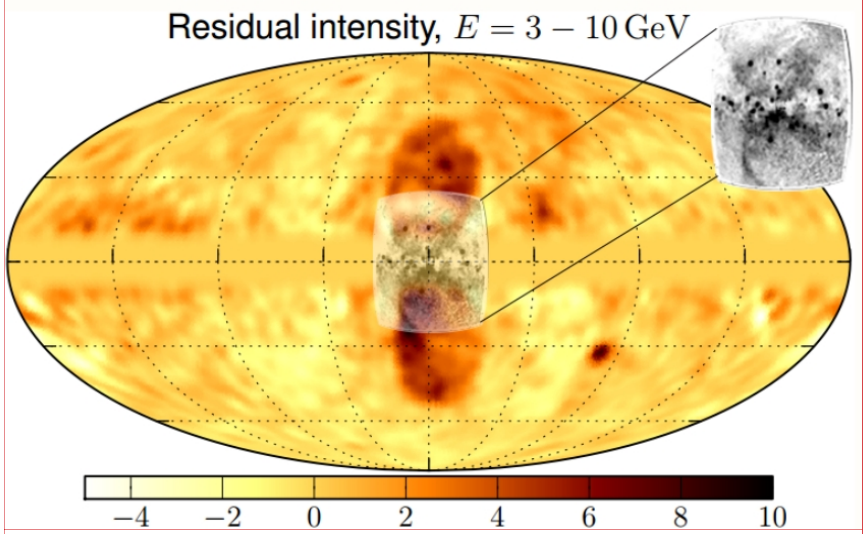
What have we done so far?

Circinus Lobes vs Fermi Bubbles

- MeerKAT: Finer angular resolution for edge-brightened region observations
- Edge-brightening effect: Identified the bright, thin regions along the edges of the lobes



1.4 GHz MeerKAT Radio image of Circinus with edge-brightened regions outlined

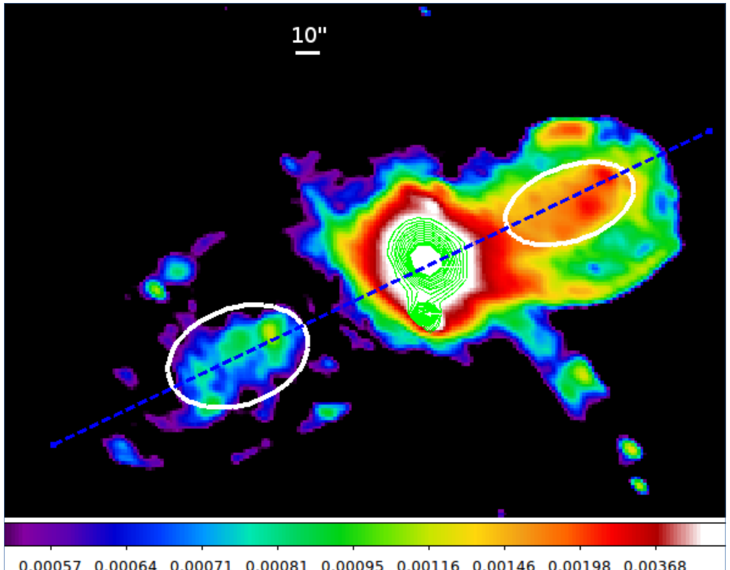


ROSAT X-Ray Image superimposed on the gamma-ray map featuring Fermi bubbles

- Intrepretation:
  - This effect is observed with Fermi Bubbles in the X-Rays
  - ROSAT: X-ray edges coincide with the edges of Fermi bubbles
  - Interpreted as shockwaves

What have we done so far?

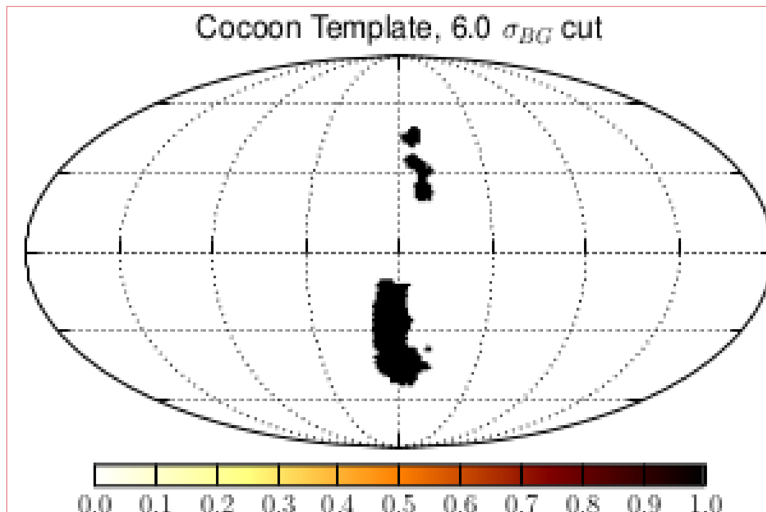
Circinus Lobes vs Fermi Bubbles



1.4 GHz MeerKAT Radio image of Circinus with plumes outlined

- Circinus features plumes
- MeerKAT: Plumes identified as the most intense outflow regions from the core contained inside each lobe

- Enhanced gamma-ray emission in Fermi bubbles:
  - Studied by Ackerman et al. (2014)
  - Known as 'Cocoons'
  - More pronounced in the south-east region
  - No evidence of a jet origin found



Cocoon template obtained from Fermi-LAT
Image: Taken from Ackermann et al. (2014)

What's next?

- *Spectral analysis* :
  - New information on the ageing of electrons along the flow
  - Better understand the structure and origin of the emission in each region
  - Observe the possible presence of hotspots

- *Compare lobes to Fermi bubbles* :
  - Using these observations we can conduct further comparisons between the two structures

What's next?

Gamma-ray observations

- Radio galaxies can be seen in gamma-rays
- Fermi-LAT:
  - Observable range cannot resolve the disk and lobes of Circinus
  - Search for variability in Circinus
- Hayashida et al. (2013):
  - Discovered gamma-ray emission from Circinus using Fermi-LAT
  - Energy range: 0.1-100 GeV
  - Time period: 4 years
  - Significance: 7.3σ
  - No variability or spatial structure seen
  - High luminosity observed:
    - Exceeds predictions for cosmic ray interactions with the ISM
    - Source of excess emission is unknown

What's next?

Gamma-ray observations

- Likelihood analysis:
  - Find the parameters which best fit the data to a source model
  - Parameters: Flux, position and spectrum of the emission
- Source model: 4th LAT catalog (4FGL)
  - First eight years of Fermi observations
  - Contains most data
  - Previous studies used the older catalog
  - Updated catalog: Higher likelihood of succesfully proving or disproving variability
- Variability observation = support for an AGN origin

All these results could then provide support for either a jet, starburst or composite model to explain the origin of radio lobes

Thank you for your attention

EXTRA SLIDE: Why MeerKAT?

- Consider the following 20cm wavelength (~1.5 GHz) ATCA radio contour maps of Circinus from Elmouttie et al. (1998):

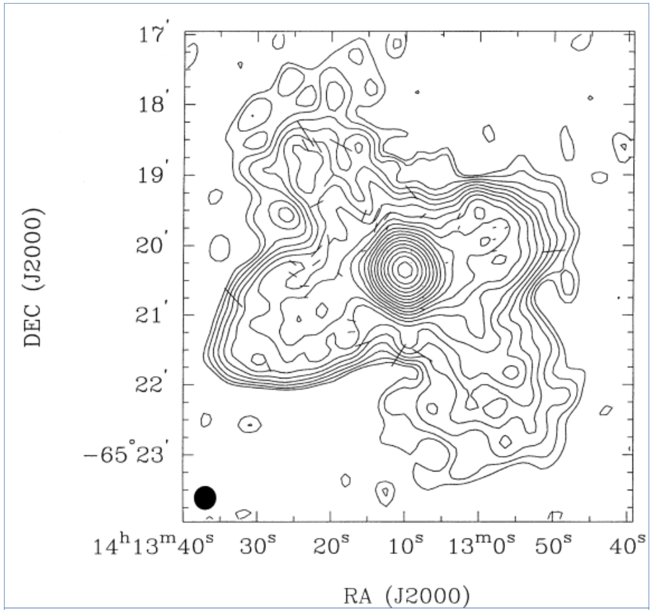


Figure A: 20cm ATCA Radio Contour Map with a 20×19arcsec^2 spatial resolution
Image: Taken from Elmouttie et al. (1998)

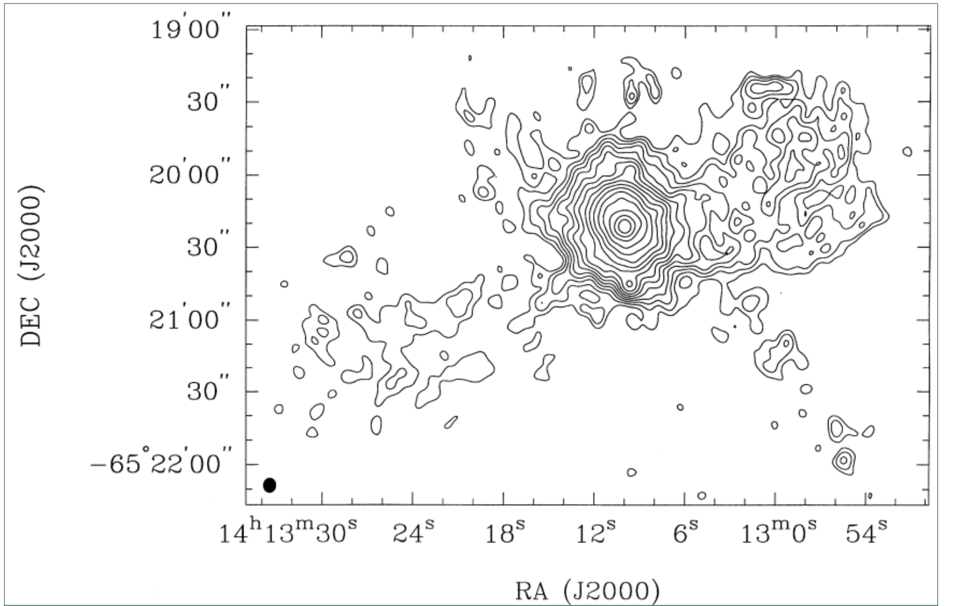
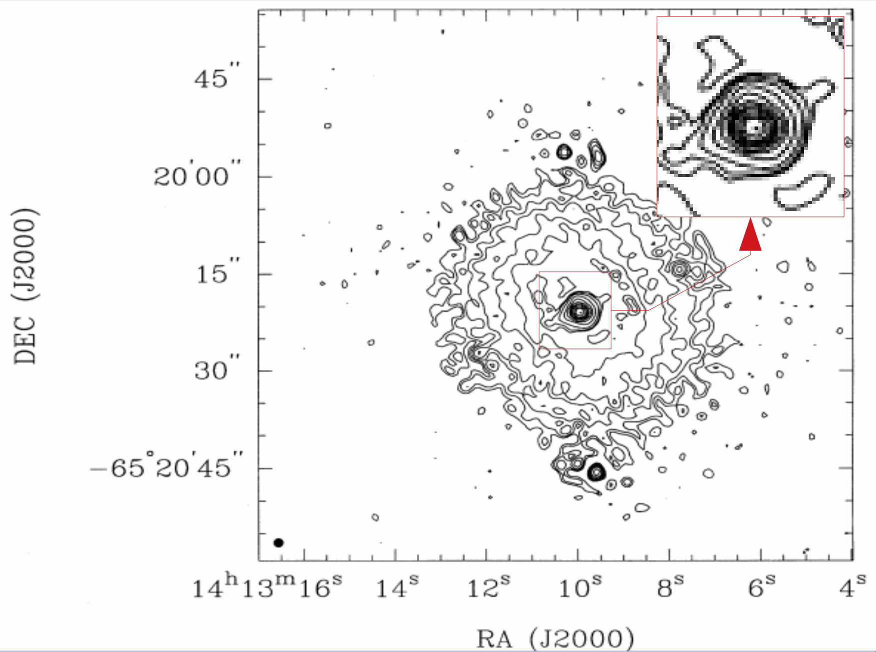


Figure B: 20cm ATCA Radio Contour Map with a 6.0×5.4arcsec^2 spatial resolution
Image: Taken from Elmouttie et al. (1998)

- Figure A: Large scale emission is observed but the image is not as sharp as MeerKAT
- Figure B: This image is sharper than Figure A but the larger scale emission is not visible and the sensitivity to fainter emission is reduced

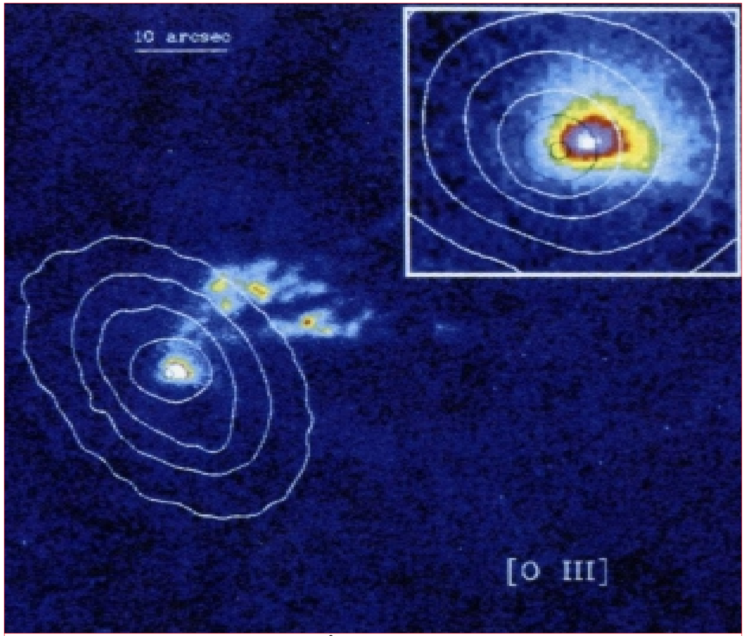
EXTRA SLIDE: Nuclear activity

- Previous Circinus studies show strong support for nuclear outflows
  - Bisymmetric spurs close to the core and parallel to the plumes (Elmouttie et al. (1998))
  - Ionization cone originating from the core and parallel to the lobes (Marconi et al. (1994))



6cm ATCA Radio Contour Map showing bisymmteric spurs near core

Image: Taken from Elmouttie et al. (1998)



SUSI image of Circinus' ionization cone as observed from [O III] line emission

Image: Taken from Marconi et al. (1994)

EXTRA SLIDE: Likelihood Analysis

- Likelihood analysis:
  - Select a region of interest centered on the source in which to consider events
  - Extract a model of the gamma-ray emission in this region from source models which includes the galactic diffuse background
  - Find the likelihood of obtaining the data given this source model and vary the parameters of the input source model (the sources' position, flux and spectral parameters) until the likelihood is a maximum
  - Output: counts map, model map, likelihood value, expected and observed counts, spectral model, average photon flux and test statistic value for the maximum likelihood fit
- Source model: 4th LAT catalog (4FGL) based on the first eight years of Fermi observations
  - 4FGL features the most data, better calibrations for reconstructing events, updated galactic diffuse emission models and a better source detection method
  - Previous studies of Circinus by the Fermi team including Hayashida et al. (2013) made use of the older catalog and so by using the updated one with more data, the likelihood of succesfully proving or disproving variability is higher