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

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The Circinus galaxy is a composite starburst/Seyfert galaxy which exhibits radio lobes inflated by kpc scale outflows along its minor axis. Its proximity (4 Mpc) makes it a unique target to study the physical nature of these outflows. We investigate if they originate from nuclear star formation activity or if they are jets from an active galactic core. The MeerKAT array performs 5 arcsecond resolution radio observations, which is in the observed range of the arcminute lobes of the Circinus galaxy. In this work, a multi-wavelength analysis of the radio lobe structures will be conducted using the available MeerKAT observations and Fermi-LAT data, which will aid in the understanding of the origin of these structures. The results can then be compared to the star-formation driven Fermi bubbles in the Milky Way, which have also been observed in both the gamma-ray and the radio bands to determine possible physical similarities between these structures.

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1. Introduction

The Circinus galaxy is a spiral galaxy at a distance of 4 Mpc [1] which possesses characteristics of both Seyfert and starburst galaxies.

In the AGN (Active Galactic Nucleus) classification scheme Seyfert galaxies feature relatively low luminosity nuclei, and like other AGNs, are powered by supermassive black holes. The core of Circinus is classified as a Seyfert 2 core for several reasons including the presence of characteristic narrow emission lines [2].

Starburst galaxies show very high star formation rates compared to normal galaxies. These galaxies are ideal laboratories to study star formation and its feedback into the interstellar and intergalactic medium. As a consequence of its star formation activity, Circinus hosts one of the brightest type II supernova in the radio and X-ray, SN1996cr [3]. The significant star-formation rate, starburst characteristic emission lines (HII regions) and the observed nuclear starburst ring in Circinus are indicators of its starburst nature [2].

2. Why Circinus?

2.1 Studying the origin of radio lobes

A prominent feature of Circinus is the kpc radio lobe outflows along its minor axis. There are two models commonly used to explain the origins of these lobes: (i) *Starburst-driven galactic winds*: The outflows result from supernova explosions in the core whose combined stellar winds form a super-bubble which is observed as a radio lobe. (ii) *AGN-driven jets*: In this model the lobes arise from the flow of jet fluid through a strong shock that spreads in a cocoon. With sufficient energy and momentum this flow can drive a bow shock, i.e. the shell, through the ambient gas [4]. Both the cocoon and the shell emit in the radio, X-ray, and gamma-ray bands [e.g.,[5]].

Studying the lobes of Circinus in greater detail could provide a better understanding of these emission models.

2.2 Studying Fermi bubbles

There is a similar type of kpc emission in our Milky Way known as the Fermi bubbles. They were first discovered as gamma-ray emitting lobes which extend from the Galactic centre about 8 kpc above and below the Galactic plane [6].

Similar to the origin of radio lobes in Circinus, the origin of Fermi bubbles is still debated: AGN-driven or starburst-driven outflows. A cosmic ray model has been advocated [7] to explain radio emission from the Fermi bubbles where these particles are transported from the galactic plane outwards and radiate via the synchrotron mechanism to produce the lobes. These bubbles are also observed to have a narrow waist which is consistent with a central star-forming ring of gas and this supports a star-formation driven outflow model [7].

The discovery of Fermi bubbles and the study of its origins demands the observation of other galaxies that feature a similar emission structure. Such galaxies include NGC 1068 which has AGN ejecta driven radio lobes [e.g., [8]], NGC 3079 which like Circinus has lobes and presents both AGN and starburst characteristics [9] and Centaurus A which is the nearest AGN and has jets, radio lobes and diffuse emission [e.g.,[10]].

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2.3 Studying radio lobed spiral galaxies

Radio lobes are usually observed in elliptical galaxies. Unlike elliptical galaxies, spiral galaxies feature a very dense interstellar medium (ISM) making it difficult for the jets to travel far out. These smaller jets mean less energy is being fed into the ISM to produce lobes.

The Milky Way is unusual in that it is a spiral galaxy with large outflows along with NGC 1068, NGC 3079 and Circinus. These galaxies are ideal candidates to investigate the interaction of AGN with their environment in spiral galaxies. In addition, we choose to study Circinus since it is much closer, enabling the study of the substructure of its lobes in better detail.

2.4 Research objective

We observe the radio lobes of Circinus and investigate its observational properties to study lobe formation through a multi-wavelength analysis of these structures using MeerKAT and Fermi-LAT data. These results will also be compared to the Fermi bubbles to determine any physical similarities between these structures.

3. Results

3.1 Spatial structure of radio lobes

MeerKAT provides deeper and more sensitive images compared to the earlier studies of Circinus with ATCA. This means that the regions of different brightness in Circinus can be identified more clearly, allowing us the opportunity to analyse new information which may have eluded previous efforts. There are 3.6 hours of 1.4 GHz MeerKAT data available for Circinus (Thorat et al., in preparation). Figure 1 shows the resultant image of the galaxy extracted from this data.

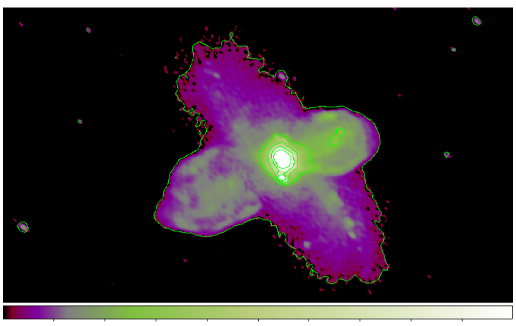

Figure 1: MeerKAT radio map of Circinus (Thorat et al., in preparation) with a 7.6×4.4 arcsec^2 beam, a central frequency of 1.375 GHz and in units of Jy/beam (1.3 arcsec/px).

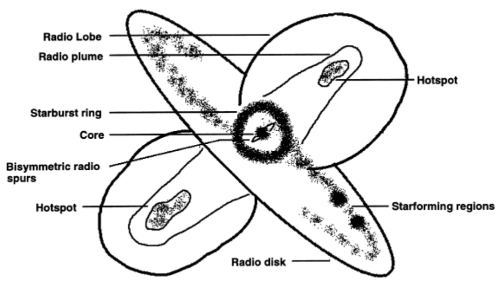

Figure 2: Proposed structure of Circinus from ATCA observations [2].

ATCA observations of Circinus [2] propose the structure shown in Figure 2, presenting an unresolved core surrounded by a diffuse radio starburst ring and radio lobes which are approximately 1.5 kpc in length consisting of a central plume (or a cocoon) and an edge brightened region. A similar ATCA radio map is shown in Figure 3 [11].

We found a similar morphology when comparing the MeerKAT image to their ATCA image: a bright core region, a visible radio galactic disk, and radio outflows oriented in the north-westerly and south-easterly directions. There were also star-forming regions at similar locations such as those observed in the southern part of the disk.

3.2 Comparisons between Circinus' lobes and Fermi bubbles

3.2.1 Edge-brightening

From the MeerKAT image, we identified the bright, thin regions along the edges of the lobes, to demonstrate the edge brightening effect shown in Figure 4. The localisation of these regions is more precise compared to previous ATCA observations of Circinus (Figure 3) since MeerKAT observations offer a higher sensitivity at a finer angular resolution.

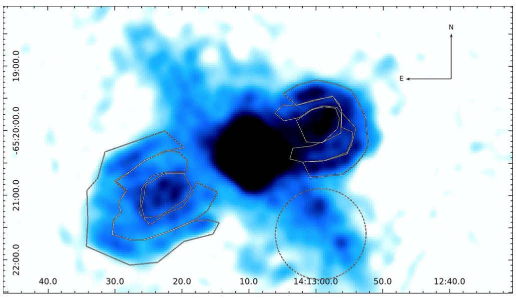

Figure 3: 13cm ATCA radio map of Circinus [11].

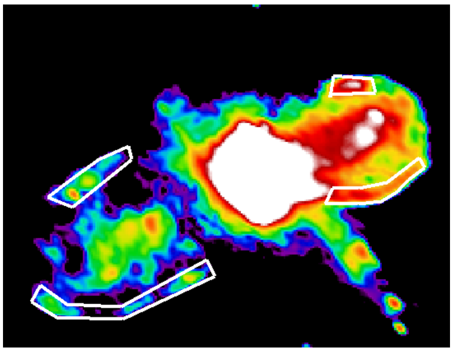

Figure 4: 1.4 GHz MeerKAT radio image of Circinus with edge-brightened regions outlined (Thorat et al., in preparation).

This effect has also been observed in X-ray observations of Fermi bubbles in which the edges of the bubbles line up with features in the ROSAT X-ray maps [6]. This is usually interpreted as shock waves.

3.2.2 Plumes

Another previously identified feature of the lobes of Circinus is its plumes. We identified these regions from the MeerKAT image as the brightest regions inside each lobe, as shown in Figure 5.

This can be compared to similar regions of enhanced gamma-ray emission found in Fermi bubbles, identified as 'cocoons' [12]. They investigated the possibility of a jet origin for the cocoons but did not find sufficient supporting evidence.

3.3 Broadband emission of the lobes

The bubbles in Circinus are also targets for gamma-ray telescopes. We modeled the broadband emission of the lobes of Circinus (Figure 6) to investigate the potential of their detection in the VHE range. For this, we assumed a leptonic framework based on the approach taken by Hayashida et al. (2013) [13] and Kataoka et al. (2018) [14] in their studies of the bubbles in Circinus and Fermi Bubbles, respectively.

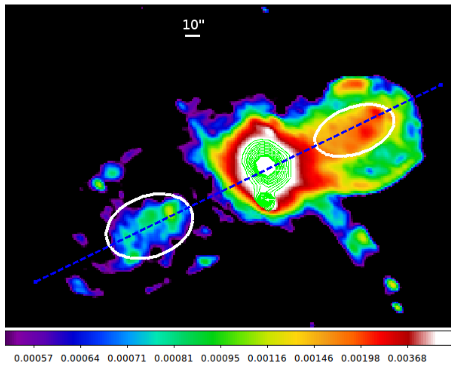

Figure 5: 1.4 GHz MeerKAT radio image of Circinus with plumes outlined (Thorat et al., in preparation).

We modeled the spectral energy distribution (SED) assuming a broken power-law electron distribution with energy equipartition between the electrons and the magnetic field and used the input parameters shown in Table 1. Our model (shown in green) assumes $N = 1.5 \times 10^{-10}\text{cm}^{-3}$ (the number of electrons per unit volume) and $\gamma_{break} = 5.0 \times 10^6$. The X-ray upper limit from Mingo et al. (2012) [11] and their corresponding radio data point were also used to constrain this model.

According to our model, the lobes cannot be detected by Fermi-LAT but, there is potential for a detection by the southern Cherenkov Telescope Array (CTA-South). CTA observations of other lobed galaxies are expected to better resolve the nuclear outflow associated gamma-ray emission (e.g. [15];[16]). Thus CTA observations of Circinus could also be fruitful in studying the physical nature of its lobes.

Parameter	Our Model	Hayashida et al. (2013)	Kataoka et al. (2018)
B (μG)	3.5	5.0-10.0	12.0
γ_{min}	2000	1.0	2000.0
γ_{max}	1.0×10^8	1.0×10^6	1.0×10^8

Table 1: Input parameters for SED modeling

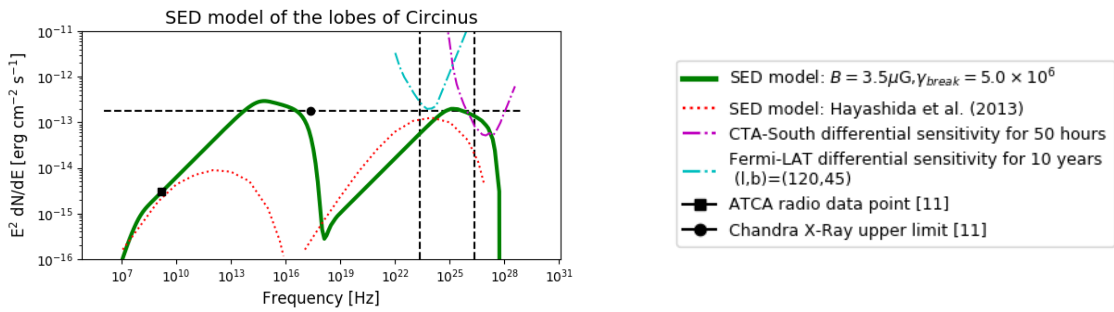

Figure 6: SED model of Circinus' lobes.

4. Future work

4.1 Radio

The existing MeerKAT observations will allow us to perform a spectral analysis which could provide new information on the ageing of electrons along the flow [2] and also help us better understand the structure and origin of the emission in each region. We also intend on performing further, in-depth, comparisons between the lobes of Circinus and Fermi bubbles to search for similarities.

4.2 Gamma-ray

In modern gamma-ray telescopes, the finest angular resolution is about 5 arcmin which is insufficient to resolve the disk and lobes of Circinus. Instead of a spatial analysis, a search for variability of the Seyfert nucleus may be performed to partially decompose the observed gamma-ray emission in the nucleus and diffuse components.

Hayashida et al. (2013) studied the gamma-ray emission from Circinus using Fermi-LAT. Their observations found a 7.3 σ signal above the background emission. However, there was no signature of temporal variability in their study.

Guo et al. (2019) [17] re-analysed the GeV emission from Circinus based on 10 years of Fermi-LAT data using the 8-year source catalog (4FGL) as opposed to the 4 years of data and 2-year source catalog used by Hayashida et al. (2013). Their findings include a significantly lower flux which is consistent with the empirical relation for star-forming galaxies. However, they also found borderline evidence of temporal variability which means an AGN jet origin cannot be completely ruled out either.

We will conduct an independent temporal analysis of gamma-ray emission coming from the Circinus galaxy by applying time-domain algorithms, e.g., Bayesian Blocks. Given that 11 years of the Fermi-LAT data and an updated 10-year source catalog (4FGLDR-2) are now available, the chance of finding an AGN core during its low or high states is higher.

All these results could be used to provide support for either a jet, starburst or composite model in explaining the origin of these radio lobes.

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