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

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Abstract. The Circinus galaxy is a composite starburst/Seyfert galaxy which exhibits radio lobes inflated by kpc scale outflows along its minor axis. It is located 4 Mpc away, which makes it a unique target to study the physical nature of these outflows. Our task will be to investigate if they originate from nuclear star formation activity or if they are jets from an active galactic core. The MeerKAT array can perform 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 connections to these structures.

1. Introduction

The Circinus galaxy is a spiral galaxy at a distance of 4 Mpc [1]. It is hence one of the closest galaxies to the Milky Way. This galaxy 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 massive black holes. In the visible wavelengths, Seyfert galaxies usually appear as spiral galaxies, but at other wavelengths the cores are much more luminous. 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. Circinus is one of the closest starburst 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 further indicators of its starburst nature [2] .

2. Why Circinus?

There are three key reasons why we are interested in studying Circinus:

2.1. Studying the origin of radio lobes

A prominent feature of Circinus is the kpc radio lobe outflows along its minor axis.

Radio lobes are radio emission that is created by outflows from the centre of a galaxy and extends outwards on both sides. The lobes are often much larger in size than the host galaxy.

There are two proposed models commonly used to explain the origins of these radio 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*: AGNs have super-massive black holes in their centres. The accreting matter surrounding the black holes are often flung out at relativistic speeds in the form of jets . These astrophysical jets move at much higher speeds relative to the surrounding medium, which can result in the formation of shock waves depending on the structure of the surrounding medium. This jet structure terminates at the beam head which is often observed as a radio hotspot and this also depends on the properties of the this medium. The fluid from the jet then passes through a strong shock and spreads in the cocoon. With sufficient energy and momentum this flow can then 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]. After their discovery in gamma rays in 2010, various features associated with these ”gamma-ray” lobes have been observed across the electromagnetic spectrum. In the radio regime they are observed as larger bi-conical lobes with ridges winding along the conical structure [7].

Similar to the origin of radio lobes in Circinus, the origin of Fermi bubbles is still debated: AGN-driven or starburst-driven outflows. A study by Caretti et al. (2013) [7] advocated for a cosmic ray model 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 which feature a similar emission structure. NGC 1068 features lobes which originate from AGN ejecta material [e.g., [8]]. NGC 3079 features large radio lobes and, like Circinus, has both AGN and starburst characteristics [9]. The nearest AGN, Centaurus A, is located at a distance of 3.4 Mpc and features jets, radio lobes and diffuse emission [e.g.,[10]]. The southern inner lobe of Centaurus A also features a shock similar to one observed in Circinus.

Since these galaxies feature similar structures to Fermi bubbles, studying the origin of radio lobes in other galaxies like Circinus could facilitate a better understanding of Fermi bubbles.

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. Other such cases include NGC 1068, NGC 3079 and Circinus which are all spiral galaxies. This makes them excellent objects of study to investigate the interaction of AGN with their environment in spiral galaxies. In addition we choose to study Circinus since it is much closer than the other candidates facilitating the study of the substructure of its lobes in better detail.

3. Research objective
For this project, our task is firstly to observe the radio lobes of Circinus. Then we will investigate their observational properties in order to study the formation of these structures. This will be achieved through a multi-wavelength analysis of the radio lobes using MeerKAT and Fermi-LAT data. Finally, the results will also be compared to the Fermi bubbles to determine possible connections to these structures.

4. Results
For this study we have used MeerKAT observations of the Circinus galaxy 3.6 hours in duration. These data form part of the MeerKAT telescope commissioning observations of the Circinus galaxy, carried out by SARAO.

For the data reduction we used the CARACal pipeline [11] supplemented by our own data imaging and calibration code. We made a radio image of the source from a 150 MHz sub-band of the total bandwidth shown in Figure 1 and wrote python script to perform the spatial analysis.

The measurement of the flux densities for the image made from the complete band as well as the spectral index and detailed astrophysical analysis will be presented in Thorat et al. (2020 in prep) [12]. In this proceeding we report a qualitative analysis identifying structures from the MeerKAT image and comparing it with data at other wavebands.

4.1. 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.

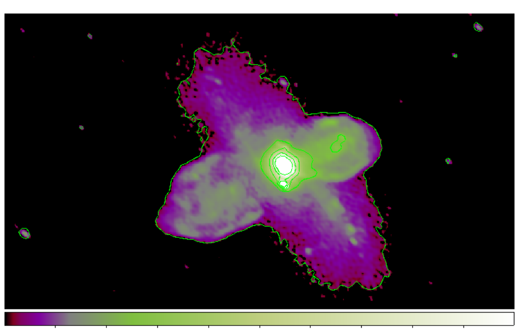

Figure 1. MeerKAT radio map of Circinus [12] with a 7.6x4.4 arcsec^2 beam, a central frequency of 1.375 GHz and in units of Jy/beam (1.3 arcsec/px).

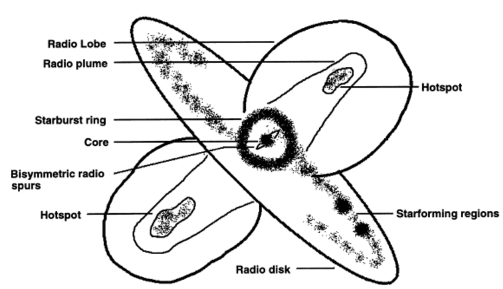

Figure 2. Proposed structure of Circinus from ATCA observations by Elmouttie et al. (1998) [2].

The ATCA study of Circinus by Elmouttie et al. (1998) [2] proposed the structure shown in Figure 2, presenting an unresolved core surrounded by a diffuse radio star-burst 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 was also produced by Mingo et al. (2012) shown in Figure 3 [13] .

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.

4.2. Comparisons between Circinus' lobes and Fermi bubbles

4.2.1. Edge-brightening MeerKAT observations offer a higher sensitivity at a finer angular resolution compared to previous observations of Circinus. This facilitates better observations of the edge-brightening of the lobes. From the MeerKAT image, we identified the bright, thin regions along the edges of the lobes, demonstrating the edge brightening effect shown in Figure 4. The localisation of these regions is more precise owing to the sharpness of the MeerKAT image than previous efforts from ATCA observations (Figure 3).

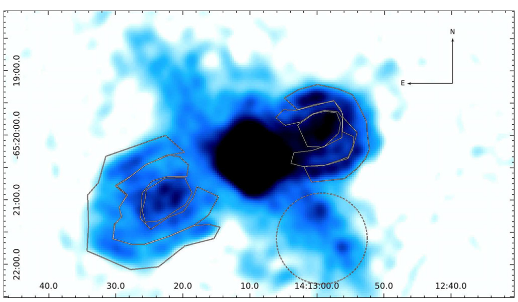

Figure 3. 13cm ATCA radio map of Circinus by Mingo et al (2012) [13].

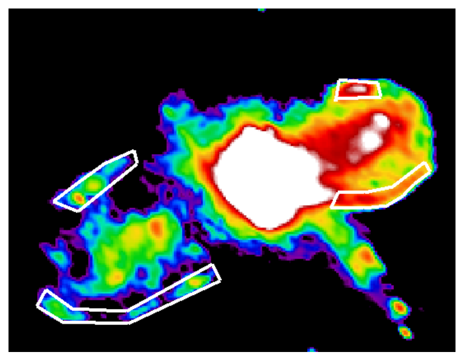

Figure 4. 1.4 GHz MeerKAT radio image of Circinus with edge-brightened regions outlined [12].

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.

4.2.2. Plumes Another previously identified feature of the lobes of Circinus are 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' by Ackermann et al. (2014) [14], which can be seen in Figure 6. They investigated the possibility of a jet origin for the cocoons but did not find sufficient supporting evidence [14].

5. Future work

5.1. Radio

The MeerKAT observations can also facilitate 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, including the possible presence of hotspots.

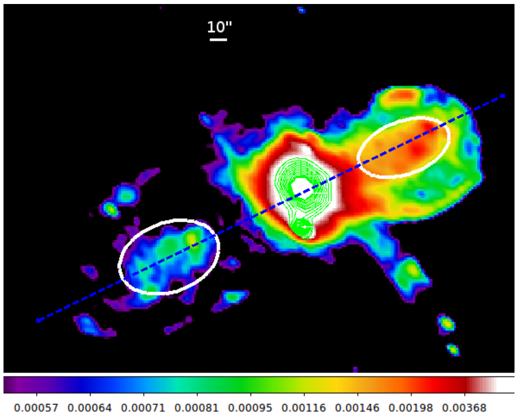

Figure 5. 1.4 GHz MeerKAT radio image of Circinus with plumes outlined [12].

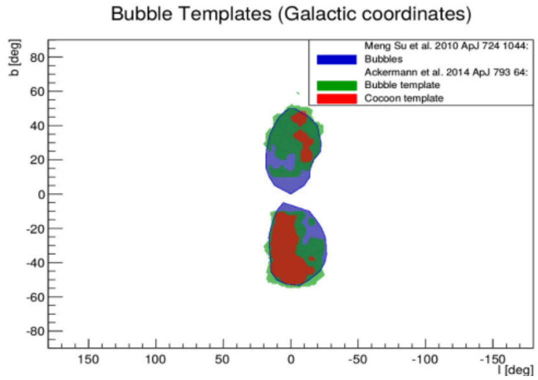

Figure 6. Templates of the Fermi bubbles by Su et al. (2010) [6] and of the Fermi bubbles and cocoons by Ackermann et al. (2014) [14] compiled by S. Hallmann.

We also intend on performing further, in depth, comparisons between the lobes of Circinus and Fermi bubbles to search for similarities.

The quantitative results of our analysis of the MeerKAT observations of the Circinus galaxy will be reported in Thorat et al. (in prep.) [12].

5.2. Gamma-ray

The Fermi-LAT telescope has been performing gamma-ray observations of the whole sky since 2008. 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 the spatial analysis, we will perform a search for variability of the Seyfert nucleus in order to partially decompose the observed gamma-ray emission in the nucleus and diffuse components.

Hayashida et al. (2013) [15] studied the gamma-ray emission from Circinus using Fermi-LAT. Their observations found a 7.3 σ signal above the background emission. There was no signature of temporal variability and no observations of significant spatial structure in their study [15]. The luminosity they found exceeds predictions for interactions of cosmic ray hadrons with the ISM and therefore an additional source of excess emission is needed [15].

Our gamma-ray analysis of Circinus will use a maximum likelihood technique. This involves finding the parameters (flux, position and spectral law of the emission) which best fit the data to a source model inclusive of the Galactic diffuse background. The source model that will be used comes from the 4th LAT catalog (4FGL) based on the first eight years of Fermi observations [16]. Compared to previous catalogs, the latest one features the most data. Previous studies of Circinus, including Hayashida et al. (2013) [15], made use of the older catalog. Given that 11 years of the Fermi-LAT data are now available and that Hayashida et al. (2013) [15] used only 4 years of the data, 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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