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^{12}CO $J = 1 \rightarrow 0$ Observations of the Circinus Galaxy using the Mopra 22 m Radio Telescope

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Abstract: The $J = 1$–0 rotational transition of carbon monoxide has been used to trace the molecular gas at five different positions in the Circinus galaxy using the Australia Telescope National Facility's 22 m radio telescope at Mopra. The intensity profile of the central CO emission has a full width at half maximum of 550 pc. The ^{12}CO (1–0) spectrum at the centre of the galaxy has an integrated temperature of 145 K km s^{-1}, with components peaking at 0·62 K and ranging in velocity from 200–600 km s^{-1}. The total mass of molecular gas in the Circinus galaxy, assuming that the CO intensity profile of the galaxy is similar to the radio continuum, is at least $7 \cdot 5 \pm 4 \cdot 1 \times 10^8$ M$_\odot$. This estimate, combined with previously published far infrared data, yields a value for the star-forming efficiency, SFE = 16±9 L$_\odot$ M$_\odot$$^{-1}$.

Keywords: galaxies: Circinus, active nuclei, spiral, Seyfert

1 Introduction

The Circinus galaxy is a member of a select group of nearby southern galaxies displaying strong core activity. It has a morphological classification of Sb-Sd and is located approximately 4 Mpc away (Freeman et al. 1977). Other characteristics are listed in Table 1. The nucleus can be described as 'active' based on its strong H_2O maser (Gardner & Whiteoak 1982), intense radio (Elmouttie at al. 1995; Harnett et al. 1990) and infrared emission (Moorwood & Glass 1984). Minor axis features, possibly indicative of outflows, have been seen in the form of anomalous radio emission (Elmouttie et al. 1995) and an ionisation cone (Marconi et al. 1994). A single carbon monoxide spectrum of the centre of the galaxy observed with the Swedish ESO Submillimeter Telescope (SEST) in 1988 has been presented as well as other spectra of various molecules (Israel 1992). Kinematical evidence for a rapidly rotating OH ring around the core is also available (Harnett et al. 1990).

Table 1. Properties of the Circinus galaxy
All figures taken from Freeman et al. (1977)

Centre position	$\alpha(2000) = 14$ h 13 m 10 s $\delta(2000) = -65° \; 20' \; 21''$
Systemic velocity	$V_{\rm hel} = 439$ km s^{-1}
Distance	$D = 4$ Mpc
Inclination angle	$i = 65°$
Position angle	PA = 210°
Holmberg diameter	$R_{\rm H} = 17' \cdot 2$

The proximity and activity of the Circinus galaxy offer an ideal opportunity to study the molecular gas in the nuclear regions of an active core galaxy. There has been relatively little attention given to this important southern hemisphere object, and this has prompted us to further the research on this galaxy at a number of wavebands, such as the radio (Elmouttie et al. 1995), the λ 21 cm neutral hydrogen line (K. L. Jones et al., in preparation) and the ionised hydrogen Hα line (M. Elmouttie et al., in preparation). Here we present results from our observations of the molecular hydrogen gas of the Circinus galaxy using the CO(1–0) line as the tracer.

2 Observations

2.1 The Mopra 22 m Telescope

The data presented here were obtained using the Mopra 22 m radio telescope in New South Wales, Australia. It is located at a southern latitude (31°S) and 850 m above sea level. The Mopra telescope consists of a 22 m Cassegrain dish, identical to that used in the Australia Telescope Compact Array (ATCA) (see Frater & Brooks 1992). The dish sits on a fixed-base altitude azimuth mount, unlike the moveable mounts of the ATCA. Only the central 15 m is surfaced for 115 GHz observing, providing a resolution of 45″ (900 pc at 4 Mpc). The front end was connected to a receiver of the SiS type covering the 86–115 GHz range with a 600 MHz bandwidth. The receiver and system temperatures were 150 K

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and 280 K respectively. The correlator was used in a 1-bit mode, providing 512 channels over a bandwidth of 256 MHz. At the observing frequency of 115 GHz, this provides a velocity spread of 660 km s^{-1} with a resolution of 1·6 km s^{-1}. Table 2 summarises the system setup used for the observations.

Table 2. System specifications

Illuminated diameter	15 m
FWHM beamwidth	45″
Receiver temp.	150 K
System temp.	280 K
Bandwidth	256 MHz
Frequency resolution	0·6 MHz

2.2 Observing Program

The weather conditions during the week allocated for observing were quite poor (only 2 of the 7 days allocated were suitable for 115 GHz observing). The observing program for these 2 days is summarised in Table 3. We used a position-switching mode for observing as opposed to beam switching (unavailable at the time) and frequency switching (unsuitable for broadband sources). The pointing accuracy of the telescope was checked by observing the SiO maser source W Hydra. We estimate a pointing accuracy of about 15″ in both the altitude and azimuth axes for our observations. Figure 1 shows the five pointing positions superimposed on a λ20 cm radio continuum map of the Circinus galaxy.

To estimate the atmospheric opacity at the observing site, we measured total power at several different zenith angles and calculated the opacity by fitting an exponential to the data (opacities ranged from 0·25 to 0·27). For the purpose of amplitude calibration, the source M17SW was observed once each day.

2.3 Data Reduction

The data were reduced using the Spectral Line Reduction Package (SPC). Baseline polynomials of order 1 were subtracted from individual quotient spectra (source spectrum divided by reference spectrum). The spectra were then binned so that a frequency resolution of 5 MHz (or 13 km s^{-1}) was achieved.

The amplitude data were calibrated to correct for the variation of atmospheric gain with elevation. Absolute amplitude calibration to the Rayleigh–Jeans main brightness temperature scale, T_{MB}, was achieved by scaling the elevation-adjusted fluxes to those of the CO calibrator M17SW ($T_{MB} = 40 \cdot 4$ K).

The velocity data were transformed to the local standard of rest (LSR) frame. Thus the spectra presented here show ^{12}CO (1–0) emission over a velocity range of 50–750 km s^{-1} with a resolution of 13 km s^{-1}, with RMS noise levels ranging from 0·05–0·07 K.

3 Results

Figure 2 displays the spectra of the observed ^{12}CO (1–0) emission and Tables 4 and 5 summarise the results of our observations. The spectrum observed at the centre of the Circinus galaxy shows that ^{12}CO (1–0) has been detected with a signal to noise ratio (S/N) of about 10. The spectrum shows CO emission over a 400 km s^{-1} range, beyond which the emission ceases sharply. The maximum intensity of CO from the central position is $T_{\rm MB} = 0 \cdot 62$ K, the average intensity being $T_{\rm MB} = 0 \cdot 47$ K. This spectrum compares well with that observed in 1988 using the SEST (see Figure 5 in Israel 1992).

The full width at half maximum (FWHM) of the central CO spectrum is 320±15 km s^{-1} and is centred on a systemic LSR velocity of $V_{\rm lsr} = 430 \pm 15$ km s^{-1} (or a heliocentric velocity of $V_{\rm hel} = 435 \pm 15$ km s^{-1}). We note that this agrees well with the value determined from a HI study performed by Freeman et al. (1977). The full width at zero level of the central spectrum is 445±15 km s^{-1}.

The emission observed at points 2 and 3 peak at $T_{\rm MB} = 0 \cdot 39$ K and $T_{\rm MB} = 0 \cdot 44$ K respectively. However, the velocities of the emission peaks vary markedly from 535 km s^{-1} for point 2 to 290 km s^{-1} for point 3. The points are located on the major axis of the galaxy and so this velocity differential is probably the result of solid-body rotation of the central bulge.

Points 4 and 5 were chosen as observing centres based on the published radio data of Elmouttie et al. (1995). These points are located near the minor axis of the galaxy, along the directions of

Table 3. Observing programme

The reference position used was 14 h 13 m 10 s, −65° 25′ 20″

	Date (dd-mm-yy)	Position α(2000), δ(2000)	Int. time (on-source) (mins)
1	27–10–95	14h 13m 10s, −65° 20′ 20″	70
2	27–10–95	14h 13m 08s, −65° 20′ 48″	45
3	27–10–95	14h 13m 12s, −65° 19′ 48″	45
4	29–10–95	14h 13m 04s, −65° 20′ 00″	45
5	29–10–95	14h 13m 16s, −65° 20′ 36″	30

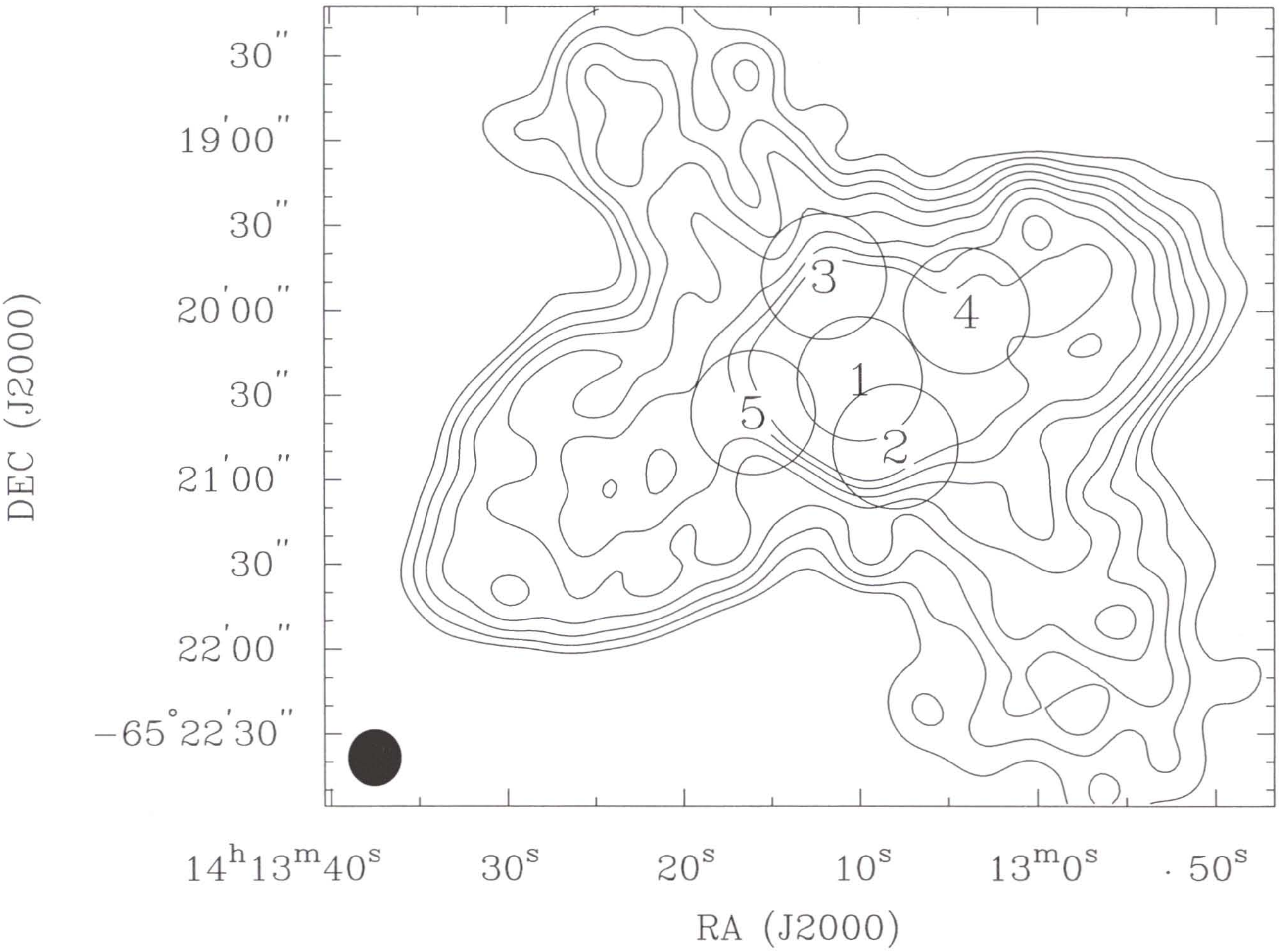

Figure 1—A total power radio continuum map of the Circinus galaxy at $\lambda = 20$ cm obtained using the ATCA. The major axis of the galaxy runs from top left to bottom right. Contours are 1·41, 2, 2·82, 4, 5·7, 8, 11·3, 16×1 mJy/beam. The five pointing centres are marked as open circles (representing the Mopra radio-telescope beam size). The filled circle in the bottom left corner shows the ATCA beam.

Table 4. Spectra statistics

Explanation of columns: Observing centre, peak antenna temperature and velocity at which it occurs, antenna temperature integrated over velocity and RMS spectrum noise

Position α(2000), δ(2000)	$T_{\rm MB}$ @ V (K @ km s^{-1})	$\int T_{\rm MB}\,{\rm d}V$ (K km s^{-1})	$\sigma(T_{\rm MB})$ (K)
14 13 10, −65 20 20	0·62 @ 315	145	0·06
14 13 08, −65 20 48	0·39 @ 585	44	0·06
14 13 12, −65 19 48	0·44 @ 290	62	0·07
14 13 04, −65 20 00	0·20 @ 565	4	0·05
14 13 16, −65 20 36	0·25 @ 500	37	0·06

the previously detected anomalous radio lobes. The emission at point 5 shows weak broadband emission of similar velocity distribution to the central point (200–600 km s^{-1}). This probably indicates that this point is near outer edge of the galactic disk. No broadband emission is seen at point 4, which is slightly further away from the nucleus than point 5 and probably away from the disk emission. However, the emission at point 4 shows a weak peak at around 565 km s^{-1}; the possible significance of this emission feature will be discussed later.

Fitting a gaussian to the data suggests that the intensity profile of the nuclear CO emission has a full width at half maximum (FWHM) of 53 arcsec, the peak emission being within 20″ of the optical centre (see Table 1). Deconvolving the 45″ primary beam from this profile yields a source FWHM of about 28″ or 550 pc at a distance of 4 Mpc. This can be compared with the dimensions of the radio nuclear bulge which measures about 15″ or 290 pc (Elmouttie et al. 1995). We clearly lack the resolution required to determine whether a

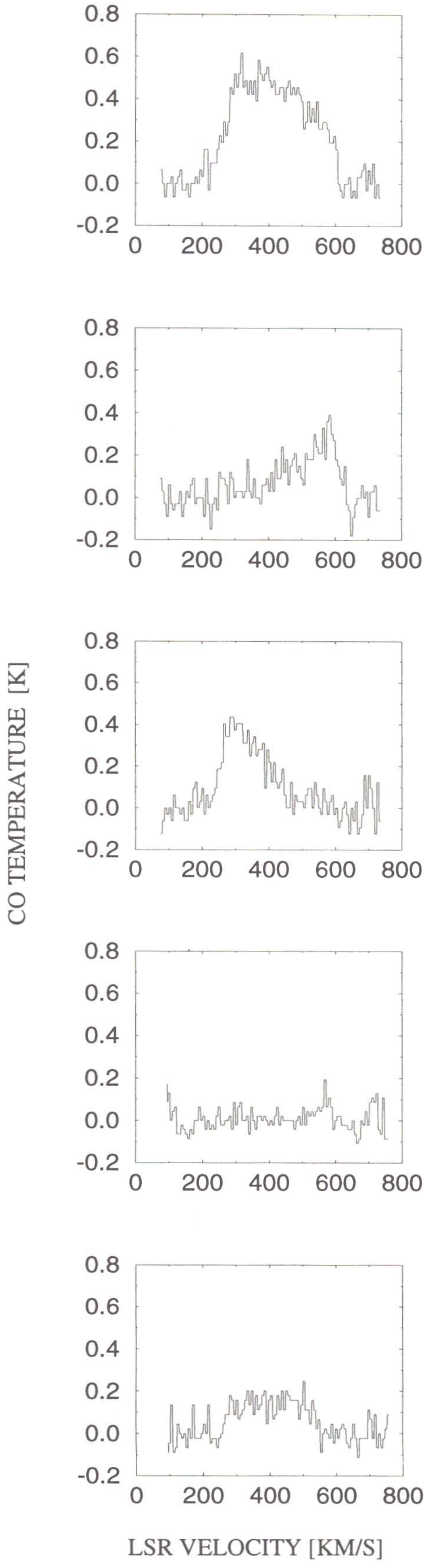

Figure 2—The Circinus galaxy CO spectra observed at the five pointing centres. Pointings 1 to 5 from top to bottom.

molecular counterpart which more closely resembles the radio source exists at the centre of the Circinus galaxy, as seen in other galaxies (Dahlem et al. 1993; Adler, Lo & Allen 1991).

Table 5. Summary of results

Explanation of rows: Systemic LSR velocity, systemic heliocentric velocity, full width at half maximum of central spectrum, integrated CO emission, average CO emission, mass of molecular gas, star formation rate and star-forming efficiency

$(V_{\mathrm{sys}})_{\mathrm{lsr}}$	430±15 km s^{-1}
$(V_{\mathrm{sys}})_{\mathrm{hel}}$	435±15 km s^{-1}
V_{FWHM}	320±15 km s^{-1}
I_{CO}	210±50 K km s^{-1}
$\langle I_{\mathrm{CO}} \rangle$	14±5 K km s^{-1} per beam
M_{mol}	$7{\cdot}5{\pm}4{\cdot}1{\times}10^8$ M$_\odot$
SFE	16±9 L$_\odot$ M$_\odot$$^{-1}$

4 Discussion

4.1 Molecular Mass and Densities in the Circinus Galaxy

We have only sparsely sampled the CO distribution of the Circinus galaxy. However, we can predict some global characteristics of the molecular gas if we make assumptions about the gas distribution in the galaxy. Based on CO observations of other edge-on spirals (Dahlem et al. 1993; Adler et al. 1991), we have assumed that the shape of the intensity distribution of integrated ^{12}CO (1–0) approximates that of the radio continuum emission. That is, the ^{12}CO (1–0) profile is probably also dominated by a strong gaussian-like nucleus sitting on a weak extended disk. The integrated CO emission at the centre of the Circinus galaxy is 145 K km s^{-1}. Assuming that the emission covers a solid angle ($9 \pm 2 \times 10^{-7}$ sr) similar to that observed in the radio continuum, as seen in other galaxies (Adler et al. 1991), and using a beam-convolved FWHM value of 53″ (see Section 3), we estimate the total integrated CO emission from the Circinus galaxy to be $I_{\mathrm{CO}} = 210{\pm}50$ K km s^{-1} and the mean integrated emission per beam area to be 14±5 K km s^{-1}. We can use this latter value to estimate the H$_2$ column density in the galaxy if we assume that the standard CO line intensity to H$_2$ column density conversion applies (Strong et al. 1988),

$$N(\mathrm{H}_2)/I_{\mathrm{CO}} = 2{\cdot}3 \times 10^{20}\ \mathrm{cm}^{-2}(\mathrm{K\ km\ s}^{-1})^{-1}\,. \quad (1)$$

We calculate a mean H$_2$ column density of $3{\cdot}2{\pm}0{\cdot}8{\times}10^{21}$ cm^{-2}. Assuming a distance of 4 Mpc, this yields a molecular gas mass of $M(\mathrm{H}_2) = 7{\cdot}5{\pm}4{\cdot}1{\times}10^8$ M$_\odot$. Note that this is a tentative value as we are making a global estimate based solely on 5 data points in the nuclear bulge, and have no information about the extended disk component. For comparison, the H I gas mass of the Circinus galaxy is $8\pm3\times10^{9}$ $M_\odot$ (Freeman et al. 1977) and so the ratio of molecular to atomic gas is around 0·1. This is a value typical for late-type spiral galaxies (Young & Scoville 1991).

4.2 Star Formation

The total far-infrared luminosity of a galaxy, $L_{\rm IR}$ is believed to represent the recent star formation rate (Helou 1986). The value of $L_{\rm IR}$ for the Circinus galaxy is $1\cdot2\times10^{10}$ $L_\odot$ (Moorwood & Glass 1984). We note the relation derived by Thronson & Telesco (1986) which states that the star-forming rate (SFR) and the $L_{\rm IR}$ are related by

$$\mathrm{SFR} = F \times 2\cdot1 \times 10^{-10}\ L_{\rm IR} \quad (L_\odot)\,. \tag{2}$$

The factor F takes account of the diffuse cloud component which is not responsible for star-forming (Helou 1986). Using $F = 1$, we derive a value of $\mathrm{SFR} = 2\cdot52\ M_\odot\ \mathrm{yr}^{-1}$. This assumes that the total observed FIR luminosity is a result of recent star formation; however, the coefficient is probably around 0·7 (e.g. Dahlem et al. 1993). Nonetheless, this SFR is above average for normal spiral galaxies (Devereux & Young 1991).

The star formation efficiency (SFE) is defined as the star formation rate per unit gas mass. Young & Scoville (1991) provided a measure of this by taking the ratio of the infrared luminosity to the H_2 mass. For the Circinus galaxy, this ratio is $16\pm9\ L_\odot\ M_\odot^{-1}$. This value is higher than for normal spiral galaxies (Devereux & Young 1991; Sanders 1990) or similarly active starburst galaxies like NGC 4945 (Dahlem 1993). However, note that estimates of SFE based on using global values of far infrared luminosity and molecular mass should be interpreted with caution, especially when investigating galaxies undergoing starbursts.

4.3 Kinematics of the Nuclear CO

The velocity dispersion at position 1 is similar to that seen in recently obtained H I data (K. L. Jones et al., in preparation) and is indicative of rapid rotation of the central molecular gas. The simplest interpretation of the spectrum is that a solid-body nuclear bulge, travelling with a systemic velocity of about $430\ \mathrm{km\ s^{-1}}$, is rotating with a velocity of about $200\times\mathrm{cosec}(i)\ \mathrm{km\ s^{-1}}$, where i is the inclination of the inner molecular disk. It is currently believed that the inner disk is inclined somewhat differently to the extended disk ($i = 65°$) and is probably closer to edge-on (Jones et al., in preparation). Previous studies (Harnett et al. 1990) have indicated that a rotating gas ring exists at the centre of the Circinus galaxy. Our results have insufficient resolution to determine whether a corresponding CO ring exists at the centre of the bulge.

Recently, Elmouttie et al. (1995) discovered the existence of a polarised radio morphology in the lobe regions. We believe that these lobes may represent outflow features emanating from a central source, and recent studies (Oliva et al. 1994; Marconi et al. 1994; M. Elmouttie et al., in preparation) indicate that this source is probably a compact Seyfert nucleus. However, the high values derived for the SFR and SFE may imply that the unusual radio morphology is also a product of a nuclear starburst. Such a starburst-driven wind has been seen in other galaxies, the most notable being NGC 3079 (Duric & Seaquist 1988).

The extent of the outflow features as determined from the radio study is approximately 2·5 kpc. There is a possibility that the anomalous CO emission detected at point 4 is related to this outflow mechanism, implying outflow (deprojected) velocities around $320\ \mathrm{km\ s^{-1}}$. This is consistent with those seen in other spiral galaxies with outflow features (Irwin & Sofue 1992). We emphasise, however, that more data are required to confirm the result.

5 Conclusion

Using the facilities at Mopra, we have successfully detected ^{12}CO (1–0) at five different positions in the Circinus galaxy. Our conclusions based on these initial results are as follows:

(a) The nuclear CO distribution has a profile with a FWHM of 550 pc. The peak emission occurs within 20″ of the radio continuum nucleus.

(b) The velocity components at the centre of the galaxy are distributed in a $445\ \mathrm{km\ s^{-1}}$ range, indicating rapid rotation of the molecular gas at the centre of the galaxy.

(c) The molecular mass of the Circinus galaxy is at least $7\cdot5\pm4\cdot1\times10^{8}$ $M_\odot$.

(d) The star-forming efficiency of the galaxy is $16\pm9\ L_\odot\ M_\odot^{-1}$.

These results are consistent with a galaxy undergoing an aggressive stage of nuclear star formation. More data with better resolution and sensitivity are needed to map the molecular gas in the outer regions of the Circinus galaxy and to obtain an understanding of how the gas and the spiral structure are related in this active galaxy. Also, high-resolution, high-sensitivity FIR data are needed to correctly determine which regions in the galaxy are responsible for star formation. This question is particularly interesting for the Circinus galaxy given its unusual radio continuum morphology and strong radio/infrared nucleus.

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