ARTILLERY SHELLS OVER CIRCINUS
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ABSTRACT

The recently identified Circinus galaxy is the nearest (\(\sim 4\) Mpc) Seyfert 2 galaxy known, and we now demonstrate it to be one of the best laboratories for studying the effects of nuclear activity on the surrounding environment. Here we present new imaging Fabry-Perot observations of Circinus that confirm the existence of an ionization cone in this object but also show for the first time a complex of ionized filaments extending radially from the nucleus out to distances of 1 kpc. Arcs suggestive of bow shocks are observed at the terminus of some of these filamentary structures. Most spectacular of all, one of the structures appears to be a scaled-up version of a Herbig-Haro jet. The velocity field of the filaments confirms that they represent material expelled from the nucleus (possibly in the form of “bullets”) or entrained in a wide-angle wind roughly aligned with the polar axis of the galaxy. The motions observed across the ionization cone are highly supersonic, so high-velocity shocks are likely to contribute to the ionization of the line-emitting gas. However, it is not clear at present whether shock ionization dominates over photoionization by the Seyfert 2 nucleus. Extrapolation of the filaments to smaller radii comes to within \(1^\prime\) (\(\sim 20\) pc) of the infrared nucleus, therefore suggesting an active galactic nucleus or nuclear starburst origin for these features. The complex of radial filaments detected in the Circinus galaxy is unique among active galaxies. The frequency of such events is unknown, since only a handful of galaxies have been observed at the sensitivity level of our present observations. The event in the Circinus galaxy may represent a relatively common evolutionary phase in the lives of gas-rich active galaxies during which the dusty cocoon surrounding the nucleus is expelled by the action of jet or wind phenomena.

Subject headings: galaxies: active — galaxies: individual (Circinus) — galaxies: jets — galaxies: kinematics and dynamics — galaxies: Seyfert — galaxies: starburst

1. INTRODUCTION

The Circinus galaxy is a large, isolated, gas-rich spiral seen through a relatively unobscured (\(A_V \approx 1.5\) mag) optical window near the Galactic plane (\(b = -3.8\); Lynga & Hansson 1972; Mebold et al. 1976; Freeman et al. 1977). The early detection of strong radio emission from the nucleus (Freeman et al. 1977) provided the first evidence of nuclear activity\textsuperscript{3} in this galaxy. Recent maps (Harnett et al. 1990; Elmouttie et al. 1995) have resolved spectral radio lobes centered on the nucleus and extending more than 90'' (\(\sim 2\) kpc) on either side of the galactic disk (P.A. \(\approx -60^\circ\)). Additional evidence of unusual nuclear activity is suggested by the discovery of an intense 22 GHz H\(_2\)O megamaser (Gardner & Whiteoak 1982; Whiteoak & Gardner 1986). Detailed spectroscopic studies at optical and infrared wavelengths have since revealed the presence of a Seyfert 2 nucleus (Marconi et al. 1995) surrounded by an extended (200 pc radius) circumnuclear starburst (Oliva et al. 1994, 1995; Ghosh 1992; Marconi et al. 1995). A one-sided ionization cone and extremely rapid variations of water maser emission have recently been discovered in the Circinus galaxy (Marconi et al. 1995; Greenhill et al. 1997), making it the closest galaxy where the engine responsible for the nuclear activity can convincingly be attributed to a supermassive black hole surrounded by a thick obscuring screen (see also Matt et al. 1996). In this Letter, we describe new TAURUS-2 and long-slit spectroscopic observations that reveal a complex of radial filaments emanating from the nucleus of this galaxy. We propose two possible scenarios to explain these features and briefly discuss the implications of our new results.

2. OBSERVATIONS

The Circinus galaxy was observed for 165 minutes on the night of 1995 February 21 using the TAURUS-2 imaging Fabry-Perot interferometer at the 3.9 m Anglo-Australian Telescope (AAT). This instrument was used in the angstrom imaging mode to maximize sensitivity to faint line emission (Bland-Hawthorn et al. 1997). A 40 \(\mu\)m gap etalon was used out of band to produce deep, low-resolution (\(\sim 350\) km s\(^{-1}\)) \([\text{O III}]\) \(\lambda 5007\) spectra at each point across this galaxy. Each square pixel subtended 0'315 on the sky; the atmospheric seeing at FWHM averaged approximately 4 times this value. These data comprise kinematic and photometric information for the \([\text{O III}]\) line at \(\sim 10,000\) positions over the central \(2'\) of the Circinus galaxy. At a later stage, Circinus was observed at several other etalon spacings to derive the distribution of H\(_\alpha\) emission and construct line profiles of [S ii] \(\lambda\lambda 6716, 6731\) and \([\text{O III}]\) \(\lambda 5007\) at 1 \(\AA\) resolution. Narrowband filters were also used at different tilt angles to isolate the lines of He ii \(\lambda 4686\), [S ii] \(\lambda\lambda 6717, 6731\), and H\(_\alpha\) and in order to subtract neighboring continuum emission. The H\(_\alpha\) flux map is discussed below, but the rest of these data are to be presented in a more detailed study (in progress).

In addition, S. L. Lumsden kindly obtained long-slit observations for us at two positions in Circinus. The Royal Greenwich Observatory spectrograph on the AAT was used at the Cassegrain f/8 focus with the 25 cm camera and the 270R grating. At a plate scale of 0'77 pixel\(^{-1}\), this setup yielded a
resolution of 3.4 Å FWHM at Hα and a wavelength coverage of 4770–8260 Å. The 2′ slit was somewhat oversized compared with the 1′1 FWHM seeing. Both slits were aligned at a position angle of 270°, one passing through the nucleus, the other offset 60′ north of the nucleus. The exposure time for both positions and an offset sky position was 600 s.

3. RESULTS

Figures 1 and 2 (Plates L3 and L4) show the [O III] and Hα line flux images obtained by integrating the line profiles in the Fabry-Perot data. Only the blueshifted (between −150 and 0 km s$^{-1}$) Hα emission is presented in these figures, to minimize contamination from the (redshifted) circumnuclear emission southwest of the nucleus. These data confirm the existence of a bright ionization cone in Circinus (Marconi et al. 1995), an effect also apparent in our He II and [S II] narrowband images. But the [O III] data also reveal a number of fainter filaments beyond this cone that cannot be explained by simple illumination effects of a homogeneous environment by an anisotropic (biconical) source of radiation in the nucleus.

The most striking [O III] feature extends along a position angle of roughly −50°, spanning a distance of ∼25°–45° (500–900 pc) from the nucleus. The lateral extent of this filament is near the limit of our resolution (∼1′5 after smoothing). This narrow feature is also visible at Hα but with a lower contrast. The gas at this location is highly ionized, with an [O III] λ5007/Hα flux ratio typically greater than unity. Extrapolation of this filament to smaller radii comes to within 1′ (20 pc) of the infrared nucleus (Marconi et al. 1995), suggesting a nuclear (AGN or compact starburst) origin for this feature. A second [O III] filament is also detected, emerging from the nucleus along P.A. ≈ −120° out to a maximum radius of ∼35° (700 pc). These radial filaments resemble the optical counterparts of radio jets in more powerful active galaxies (see, e.g., Sparks, Biretta, & Macchetto 1994).

The most spectacular feature in the Hα data is the hook-shaped filament that extends to 40′′ (800 pc) west of the nucleus (Fig. 2). Such features are commonly observed in Herbig-Haro (HH) objects (e.g., HH 47; Hartigan et al. 1993), although they have never been seen on galactic scales. The western “hook” is far more elongated than the windblown bubbles in M82 (Bland & Tully 1988) and NGC 3079 (Veilleux et al. 1994). Additional morphological evidence for outflow exists in the northern portion of our data (Fig. 1). The [O III] emission along P.A. ≈ −20° forms a broad filamentary “finger” or jet that points back to the nucleus. A knot is present at the tip of this “finger,” 25′′ from the nucleus. Bright Hα emission is also visible near this position, the southern portion of which forms a wide (∼8′′) arc resembling a bow shock. The arc is pointing in the downstream direction, consistent with its being produced by a collimated jet.

The kinematics derived from the [O III] Fabry-Perot data (Fig. 3 [Pl. L5]) and long-slit spectra (Fig. 4 [Pl. L6], Fig. 5) brings credence to this nuclear outflow scenario. Nongravitational motions are observed throughout the [O III] cone, superposed on a large-scale velocity gradient caused by galactic rotation along the major axis of the galaxy (P.A.$\approx$ 30°; Freeman et al. 1977). An unusually large velocity gradient of 4 km s$^{-1}$ pc$^{-1}$ is seen near the position of the bright knot ∼12′′ from the nucleus along P.A. $\approx$ −30° (Fig. 3). The side of the knot facing the nucleus presents velocities that are nearly 250 km s$^{-1}$ lower than gas only 3′ north of that position. The emission profiles near that knot are broad (∼250 km s$^{-1}$) and perhaps complex.

The material in the brighter portions of the northwest and southwest filaments does not seem to take part in the galactic rotation (Fig. 3). The velocities in the northwest [O III] filament appear systematically blueshifted by ∼0–100 km s$^{-1}$ with respect to the systemic velocity (439 km s$^{-1}$; Freeman et al. 1977), while the velocities of the gas in the southwest filament are roughly systemic within the errors of the measurements. Nongravitational motions are also detected along the western “hook” feature (Fig. 4). A velocity gradient of 80 km s$^{-1}$ over 8′ (0.5 km s$^{-1}$ pc$^{-1}$) is visible near the location of knot 2 (Fig. 4c). Perhaps the strongest evidence for shocks in our data is seen in knot 4. There the strong Hα line is blueshifted by 180 km s$^{-1}$ with respect to the [N II] doublet (Figs. 4b, 5). Velocity shifts between different emission lines are frequently observed in HH objects and reflect spatially distinct line-emitting regions (e.g., leading edge versus cooling tail; Morse et al. 1994 and references therein). A more detailed analysis of the nuclear long-slit spectra also suggests the presence of broad (FWZI $\approx$ 800 km s$^{-1}$), blueshifted wings in the emission-line profiles produced by knots 2 and 3, but this result needs to be confirmed with spectra of higher signal-to-noise ratio and velocity resolution.

The current radio data also support the existence of a wide-angle outflow in the Circinus galaxy. The northwest feature appears to have a radio counterpart at both 13 and 20 cm (the northwest “plume” in Figs. 2–4 of Elmouttie et al. 1995). This appears as a continuum ridge that runs southeast-northwest through the radio map out to 90″ in radius within the bisymmetric lobes. Radio jets in active galaxies are commonly observed to have associated optical emission, but it is normally confined to an outer surface at the terminus of the shock (Cecil, Bland, & Tully 1990). The radio data do not have sufficient resolution to argue whether the optical emission fills the northwest “plume” or is confined to the shock front. The

![Fig. 5.—Binned spectra at four positions along the slit through the nucleus corresponding to knots 1–4. Each spectrum has been offset by 400 counts. Knots 1 and 2 are bin vertices along the slit over 6′; knots 3 and 4 are bin offset over 4′. Note the greatly enhanced [N II]/Hα ratio along the jet, except on the bow shock at knot 4. Furthermore, the Hα line at knot 4 is blueshifted by 180 km s$^{-1}$ with respect to the [N II] lines. A faint blue wing can be seen on many of the emission lines.](image-url)
TABLE 1
Emission-Line Ratios Derived from Long-Slit Spectra

| Feature  | Region | [O III]/Hβ | [O II]/Hα | [N II]/Hα | [S II]/Hα | [S II] λ6717/λ6731 |
|----------|--------|------------|-----------|-----------|-----------|---------------------|
| Disk     |        | 8.94       | 0.23      | 0.84      | 0.60      | 1.38                |
| Knot 1   |        | 10.8–13.9  | 10.0      | 0.32      | 0.99      | 0.73                |
| Knot 2   |        | 14.6–16.2  | 13.9      | 0.23      | 0.89      | 0.58                |
| Knot 3   |        | 16.9–20.0  | 16.9      | 0.13      | 0.75      | 0.45                |
| Knot 4   |        | 20.8–22.3  | 17.2      | 0.13      | 0.97      | 0.59                |

| Knot 2   |        | 16.9–20.0  | 16.9      | 0.13      | 0.75      | 0.45                |
| Knot 4   |        | 37.7–42.4  | 17.2      | 0.13      | 0.97      | 0.59                |

Notes.—Col. (1): name of the emission-line feature, following the nomenclature of Fig. 2. Col. (2): region from the long-slit spectrum that was used to calculate the line ratios. The numbers listed in this column represent distances in arcseconds measured west of the nucleus. Col. (3): flux ratio \(F([\text{O III}]/\lambda6583)/F(H\beta)\). Col. (4): flux ratio \(F([\text{O III}]/\lambda6580)/F(H\alpha)\). Col. (5): flux ratio \(F([\text{N II}]/\lambda6583)/F(H\alpha)\). Col. (6): flux ratio \(F([\text{S II}]/\lambda6717,6731)/F([\text{S II}]/\lambda6731)\).

1 Uncertainties on the line ratios range from 10%:15% for the stronger lines to 20% for ratios involving [S II] and are sometimes as high as 40%, for [O II]/H\alpha.

2 H\beta undetected except perhaps for faint broad emission from knots 3 and 4.

3 [O I] \(\lambda6300\) undetected.

Nuclear Spectrum: Through Nucleus, P.A. = 270°

| Feature  | Region | [O III]/Hβ | [O II]/Hα | [N II]/Hα | [S II]/Hα | [S II] λ6717/λ6731 |
|----------|--------|------------|-----------|-----------|-----------|---------------------|
| Nucleus  |        | 13.9       | 0.12      | 1.12      | 0.28      | 1.20                |
| Knot 1   |        | 11.6–17.7  | 0.13      | 1.41      | 0.93:     | 2.0:                |
| Knot 2   |        | 18.5–23.9  | 0.8:      | 2.00      | 1.42      | 1.85                |
| Knot 3   |        | 30.8–33.9  | 0.13      | 1.10      | 0.67      | 1.80                |
| Knot 4   |        | 37.7–42.4  | 0.13      | 0.28      | 0.35:     | 2.0:                |

4 ORIGIN OF THE COMPLEX OF RADIAL FILAMENTS

Jets in active galactic nuclei are attributed to gas centrifugally accelerated along magnetic field lines tied at one end to the accretion disks (Lynden-Bell 1996). The existence of several jets in a single galaxy is difficult to explain in these models unless the active galaxy is host to two or more black holes, each possessing its own accretion disk and radio jet. A more plausible explanation for the optical filaments and the linear structures observed in the radio map is that they arise from individual mass structures ejected in a wide opening angle, possibly from an explosive nuclear event. The apparent extent and velocities of the outflowing gas in the Circinus galaxy suggest that the purported explosive event took place a few million years ago. It is not clear what triggered this event, since the Circinus galaxy shows no sign of recent galactic interaction (Freeman et al. 1977). The ejecta from this event have been funneled into a fan with opening angle of \(~100°\) and symmetry axis along P.A. \(\approx -65°\), i.e., along the direction of the northwest radio lobe (Elmouttie et al. 1995). The lack of any optical counterpart to the southeast radio lobe argues that the outflow on that side is hidden from view by the inclined \(\sim 15°\) dark matter halo. The symmetry axis of the conical outflow is roughly aligned with the minor axis of the galaxy and therefore suggests that our line of sight lies only \(~15°\) outside the cone defined by the outflow.

Hydrodynamic instabilities in the dense shell swept up by an expanding plasmon (Pedlar, Dyson, & Unger 1985; Taylor et al. 1989) or a time-variable wind (Garcia-Segura, Mac Low, & Langer 1996; Stone, Xu, & Mundy 1995) offer an alternative...
A clue to the origin of the outflow in the Circinus galaxy is provided by the energetics of this event. The mass taking part in this outflow can be estimated from the [O \textsc{iii}] \lambda5007 flux. We parameterize the mass in terms of the density, which is poorly constrained, and use an electron temperature of 10^4 K. The integrated observed [O \textsc{iii}] intensity of \(5 \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\) implies a mass of a few times \(10^4 M_\odot\). The exact mass is uncertain (cf. the last paragraph of § 3), the kinetic energy involved in the northwest outflow is a few times \(10^4 N_\odot^2\). A value closer to \(10^6 N_\odot^2\) is probably more representative of the total energy involved in the outflow event, since the radio data (Harnett et al. 1990; Elmouttie et al. 1995) suggest that a similar mass outflow is also taking place on the southeast side of the nucleus. The energetics of the optical outflow in the Circinus galaxy therefore appear to be relatively modest (equivalent to \(\sim 10^4\) supernova explosions if \(N_\odot \approx 100 \text{ cm}^{-3}\)) and appear to lie at the low-energy end of the distribution for wide-angle events observed in nearby galaxies (Cecil et al. 1990; Bland & Tully 1988; Heckman, Armus, & Miley 1990; Veilleux et al. 1994). This outflow can easily be powered by the AGN or by a compact nuclear starburst. The nuclear starburst detected in Circinus (Oliva et al. 1995) appears somewhat older than the present outflow event, however.

5. SUMMARY AND IMPLICATIONS

Deep imaging Fabry-Perot data reveal a complex of radial line-emitting filaments in the Circinus galaxy, the closest Seyfert 2 galaxy known. The kinematics of the gas producing these features suggests the ejection of material over a wide opening angle or inhomogeneities in a wide-angle outflow. The proximity of the Circinus galaxy makes it a unique laboratory to study with unprecedented resolution the impact of nuclear winds, supersonic ejecta, and jets on the interstellar medium of galaxies. The apparent rarity of radial filaments and bow shocks in active galaxies may reflect the ephemeral nature of this phenomenon or the difficulty in accelerating dense gas clouds coherently. However, few galaxies have been observed with the sensitivity of our present observations. The discovery of these features in the Circinus galaxy, a spiral galaxy with an abnormal richness of gas (Freeman et al. 1977), brings up the possibility that we may be witnessing a common evolutionary phase in the lives of gas-rich active galaxies. Observations of other active galaxies at similar sensitivity will help to establish the frequency and duration of this phenomenon.

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FIG. 1.—Line flux images of the Circinus galaxy: (a) [O III] λ5007 and (b) blueshifted (between −150 and 0 km s$^{-1}$) Hα. North is at the top, and west to the right. The position of the infrared nucleus (Marconi et al. 1995) is indicated in each image by a cross. The spatial scale, indicated by a horizontal bar at the bottom of the [O III] image, is the same for each image and corresponds to $\approx 25''$, or 500 pc for the adopted distance of the Circinus galaxy of 4 Mpc. The minor axis of the galaxy runs along P.A. $\approx 60^\circ$ (measured from north to east). The faintest features in the [O III] (Hα) image have a surface brightness of $\approx 4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. To suppress the wide dynamic range, the intensity gray scale wraps around and becomes logarithmic at high intensity levels. The radial features along the north (labeled “N”), northwest, west (labeled “W”), and southwest axes suggest the ejection of material (possibly in the form of “bullets”) over a wide opening angle or inhomogeneities in a wide-angle outflow. The inclined (\approx 65^\circ; Freeman et al. 1977) galactic disk hides the southeast portion of this outflow.

Veilleux & Bland-Hawthorn (see 479, L106)
FIG. 2.—Line flux images of the western hook-shaped filament: (a) [O III] λ5007 and (b) blueshifted (between −150 and 0 km s$^{-1}$) Hα. The position of the infrared nucleus (Marconi et al. 1995) is indicated in each image by a cross. The orientation is the same as in Fig. 1, but the horizontal bar at the bottom of the [O III] image now corresponds to ~250 pc. The faintest features in the [O III] (Hα) image have a surface brightness of $\sim$1 $(4 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$). Once again, the intensity gray scale wraps around and becomes logarithmic at high intensity levels. The hook-shaped filament shares a strong resemblance with HH objects produced by young stars, suggesting a bow shock origin for this feature. The bow shock terminus (labeled “4” in the figure) is only detected in Hα, but a rough correspondence is observed between the [O III] and Hα knots (labeled “1”–“3”) that delineate the northern edge of this structure.

Veilleux & Bland-Hawthorn (see 479, L106)
Fig. 3.—Velocity field derived from the [O III] data cube. The velocities range from 170 km s$^{-1}$ (white) to 650 km s$^{-1}$ (black). The uncertainties range from $\sim 50$ km s$^{-1}$ in the bright line-emitting regions to 100 km s$^{-1}$ or more in the fainter areas. The position of the infrared nucleus (Marconi et al. 1995) is indicated by a cross. The orientation is the same as in Fig. 1, but the horizontal bar at the bottom of the image now corresponds to $\sim 250$ pc. The large-scale velocity gradient along P.A. $\approx 30^\circ$ is due to galactic rotation. Superposed on this gradient are nongravitational motions observed at several locations, including the northwest, west, and southwest filaments visible in Fig. 1 and a compact region $\sim 12^\prime$ from the nucleus along P.A. $\approx -30^\circ$ coinciding with very strong [O III] emission.

Veilleux & Bland-Hawthorn (see 479, L106)
FIG. 4.—Sky-subtracted long-slit spectra: (a) 6′0 north of nucleus, P.A. = 270°, and (b) through nucleus, P.A. = 270°. The vertical bar at the right of each panel represents ~250 pc. The off-nuclear spectrum intersects knots 1 and 2 of Fig. 2, while the nuclear spectrum intersects knots 3 and 4 but only the southern portions of knots 1 and 2. Note the velocity gradient in knot 2 of (a) and the strong blueshifted Hα emission in knot 4.

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