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DISCOVERY OF A 500 PARSEC SHELL IN THE NUCLEUS OF CENTAURUS A

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ABSTRACT

Spitzer Space Telescope mid-infrared images of the radio galaxy Centaurus A reveal a shell-like, bipolar, structure 500 pc to the north and south of the nucleus. This shell is seen in 5.8, 8.0, and 24 μm broadband images. Such a remarkable shell has not been previously detected in a radio galaxy and, if confirmed, would be the first extragalactic nuclear shell detected at mid-infrared wavelengths. Assuming that it is a coherent expanding structure, we estimate that the shell is a few million years old and has a mass on the order of a million solar masses. A conservative estimate for the mechanical energy in the wind-driven bubble is 10^{53} ergs. The shell could have been created by a small, few-thousand solar mass, nuclear burst of star formation. Alternatively, the bolometric luminosity of the active nucleus is sufficiently large that it could power the shell. Constraints on the shell's velocity are lacking. However, if the shell is moving at 1000 km s^{-1}, then the required mechanical energy would be 100 times larger.

Subject headings: galaxies: individual (NGC 5128) — galaxies: ISM — galaxies: structure — ISM: bubbles — ISM: jets and outflows

Online material: color figure

1. INTRODUCTION

The nearest of all the giant radio galaxies, Centaurus A (NGC 5128) provides a unique opportunity to observe the dynamics and morphology of an active galaxy in detail across the electromagnetic spectrum. For a recent review on this remarkable object, see Israel (1998). In its central regions, NGC 5128 exhibits a well-recognized, optically dark band of absorption across its nucleus. *Spitzer* images of the galaxy reveal a parallelogram shape (Quillen et al. 2006) that has been modeled as a series of folds in a warped thin disk (e.g., Bland 1986; Bland et al. 1987; Nicholson et al. 1992; Sparke 1996; Quillen et al. 2006).

In this Letter, we report on the discovery of a 500 pc–sized bipolar shell in mid-infrared images in the center of the galaxy. Shells have been previously seen in active and star-forming galaxies (for a recent review on galactic winds, see Veilleux et al. 2005). For example, the Seyfert 2 galaxy NGC 2992 exhibits a figure-eight morphology in the radio continuum (Ulvestad & Wilson 1984). The starburst/LINER galaxies NGC 2782 (Jogee et al. 1998) and NGC 3079 (Ford et al. 1986; Veilleux et al. 1994) exhibit partially closed shell morphologies in optical emission lines and the radio continuum.

The above shells have been detected in the radio continuum, in optical emission lines, and in emission from atomic hydrogen. The only nuclear shell to have been previously detected at mid-infrared wavelengths is the 170 pc large bipolar bubble in the direction of the Galactic center (Bland-Hawthorn & Cohen 2003). As pointed out by Bland-Hawthorn & Cohen, infrared observations allow unique constraints on the mass of swept-up material. Theoretical models predict that in the early stages of a starburst-driven outflow, supernovae and stellar winds inject energy into the interstellar medium (ISM), forming a bubble of hot gas and thermalized ejecta (e.g., Castor et al. 1975; Chevalier & Clegg 1985; Tomisaka & Ikeuchi 1988; Heckman et al. 1990). Active galaxies can also drive winds (see, e.g., Veilleux et al. 2005; Begelman 2004). Based on the discussion by Israel (1998), we adopt a distance to Cen A of 3.4 Mpc. At this distance, 1′ on the sky corresponds to ~1 kpc.

2. OBSERVATIONS

Figures 1 and 2 show 8.0 and 24 μm broadband images from the Infrared Array Camera (IRAC) and Multiband Imaging Photometer for *Spitzer* (MIPS) on board the *Spitzer Space Telescope*. These images are described in Quillen et al. (2006) and Brookes et al. (2006). An oval or bipolar shell–like structure is evident in these images 30″ both above and below the nucleus. We refer to the shell-like features in the images as a shell; however, future work is required in order to confirm that these features correspond to a coherent structure and are not caused by a random distribution of dusty filaments on the sky. Along the minor axis of the shell, four bright spots lie in the parallelogram feature in the MIPS 24 μm image (see the dark contours in Fig. 2); these are also seen in the 8 μm image. The warped-disk models (Quillen et al. 2006) show that the parallelogram shape is caused by folds in the disk located at a radius of $\gtrsim$60″, and outside the expected location of the shell, at half this radius. Because of the difference in estimated radius, the four bright points are unlikely to be due to an interaction between the shell and the warped disk. They are probably due to a superposition of the shell (along its minor axis) and the warped disk.

We estimate that the shell has length 1′.1 and width 0′.7, corresponding to an axis ratio of ~0.63. At the distance of the galaxy, the angular scale of the shell places the rims at a distance of ~500 pc from the galaxy nucleus along the shell's major axis, north and south of the nucleus. The shell is oriented with major axis at a position angle P.A. ~ 10°. The radio jet is seen to the northeast of the nucleus at P.A. ~ 55° (Burns et al. 1983); this differs significantly from the shell's major axis. The

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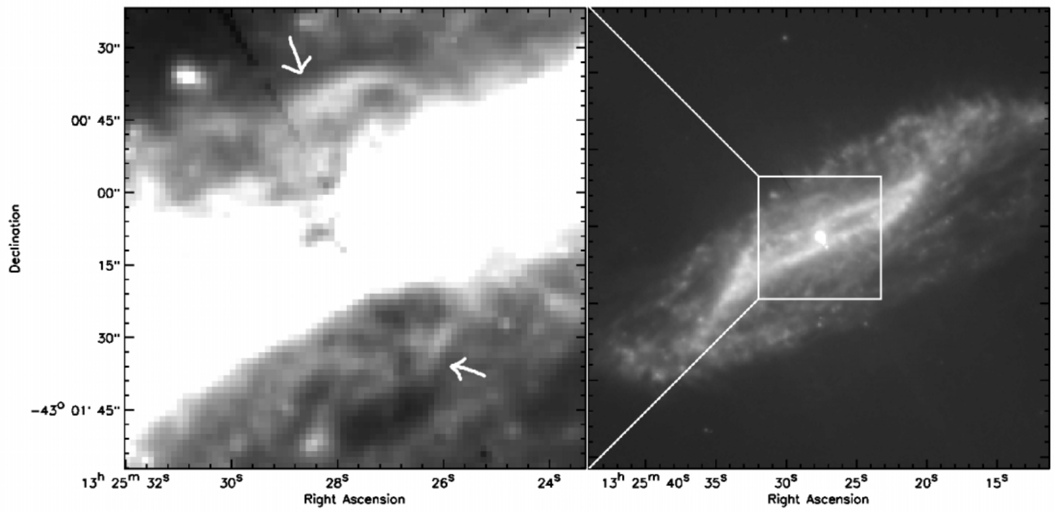

FIG. 1.—IRAC 8.0 μm image of the nuclear region of Cen A, showing the bipolar shell. A larger scale image is shown on the right. The emission is shown on a logarithmic scale on the right but on a linear scale in the left image. On the left, the 3.6 μm emission has been subtracted from that at 8.0 μm, removing some of the contribution from the background starlight. The rims of the shell are emphasized with white arrows. The shell rims are 30″, or 500 pc, from the galaxy nucleus. The linear streak extending from the nucleus to the northeast is an artifact of the array. [*See the electronic edition of the Journal for a color version of this figure showing the emission at* 3.6, 5.8, *and* 8.0 μm.]

galaxy isophotes at large radii, $r > 4'$, are elongated approximately along the same axis as that of the shell. However, inside a radius of $2'$ the underlying elliptical galaxy component is nearly spherical (see isophotes shown in Quillen et al. 2006). More relevant is that the gaseous and dusty disk is approximately perpendicular to the shell. The shell orientation would be consistent with a bipolar bubble expanding above and below the more massive and denser stellar and gaseous disk.

Because the shell is detected in more than one band (IRAC bands 3 and 4) and in more than one camera (both IRAC and MIPS), the feature is very likely to be real, and not an artifact of the *Spitzer Space Telescope* or due to scattered light from the nucleus. No artifact with similar structure has been reported by the instrument teams from observations of bright sources (e.g., Fazio et al. 2004; Rieke et al. 2004).

A cut along the shell's major axis at P.A. $= 10°$ is shown as a surface brightness profile in Figure 3. The shell can be seen as bumps at a distance $\pm 30''$ from the nucleus. By sub-

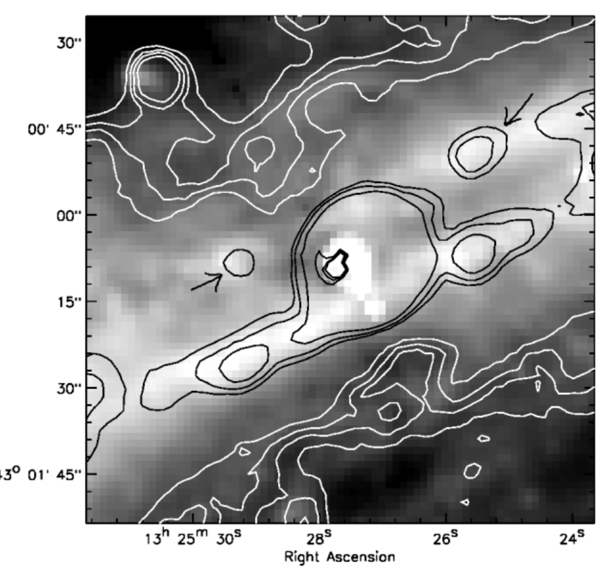

FIG. 2.—The 8.0 μm image (*gray scale*) overlaid with contours from the MIPS 24 μm image (again with the 3.6 μm image subtracted). Contours are shown at 2, 4, 6, 9, 56, 70, and 94 MJy sr^{-1} above the sky background. The shell is evident at 5.8, 8.0, and 24 μm. We point out with black arrows the upper two of the four bright points discussed in § 2.

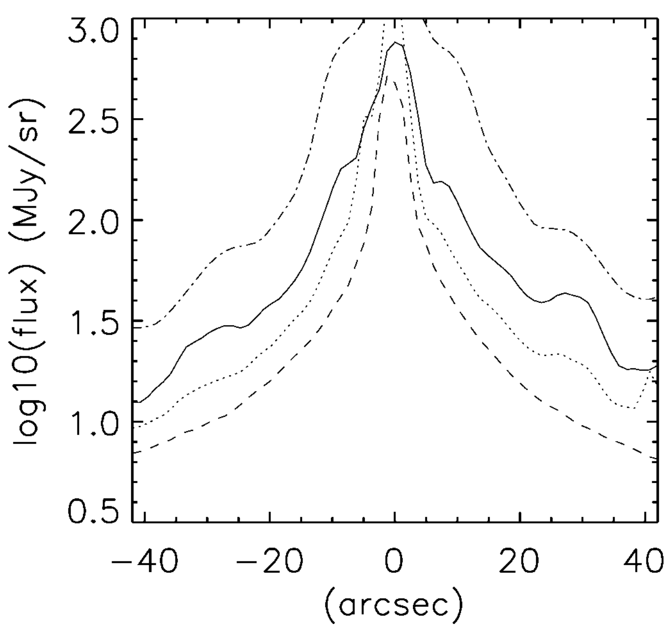

FIG. 3.—Surface brightness as a function of distance from the nucleus in a 3″ wide slice oriented along P.A. $= 10°$ containing and centered on the galaxy nucleus. The right side corresponds to positions north of the nucleus. From top to bottom, lines show the logarithm of the surface brightness at 24 μm, offset upward by $+0.5$, and that at 8.0, 5.8, and 4.5 μm, respectively, with no offsets. The shell is visible as bumps at $\pm 30''$ from the nucleus.

tracting a linear fit to the background emission on either side of the shell, we measure peak surface brightnesses in the shell of 2.5, 10, and 10 MJy sr^{-1} at 5.8, 8.0, and 24 μm, respectively. These measurements are approximate (uncertain by a factor of 50%) because of the uncertainty in the fit to the background. The flux ratios between the bands are not untypical of emission from dust in nearby galaxies, as compared with those listed by Dale et al. (2005).

No prominent feature coincident with the shell is clearly seen in the imaging done with the *Hubble Space Telescope* (e.g., Schreier et al. 1996; Marconi et al. 2000), though some of the filaments south of the nucleus are coincident with those in the shell in the 8.0 and 5.8 μm IRAC images. The shell features are not coincident with the radio and X-ray knots seen by Burns et al. (1983) and Kraft et al. (2000). Viewing the *Chandra* observations, we did not see a strong excess of diffuse X-ray emission within the shell; however, there may be a deficit of diffuse X-ray emission along the shell rim southwest of the nucleus (see Fig. 1 of Karovska et al. 2002). No shell-like feature is seen in existing radio continuum images of Cen A (e.g., Sarma et al. 2002; Clarke et al. 1992); however, faint continuum emission associated with the shell could be difficult to detect because of the proximity of the bright jet and radio lobes. As pointed out by Marconi et al. (2000), there may be a reduction in the extinction along the jet axis. In the 8.0 μm image there is a gap in the shell on the jet axis southwest of the nucleus. Northwest of the nucleus there is also a reduction in mid-infrared flux in the shell rim along the jet axis, suggesting that the jets have punctured holes in the shell.

Recent spectroscopic studies have focused on the ionized medium near the nucleus. A diffuse, broad, and blueshifted spectral component at the nucleus was reported by Marconi et al. (2006). It has a velocity ~300 km s^{-1} below the galaxy's systemic velocity and is fairly broad, with a width of 400 km s^{-1} (Marconi et al. 2006). This component could be associated with an expanding shell. Absorption lines in H I and CO have been seen against the radio nucleus (van der Hulst 1983; Sarma et al. 2002; Eckart et al. 1999; Israel et al. 1991; Wiklind & Combes 1997); however, none of these are blueshifted more than 20 km s^{-1} below the galaxy systemic velocity. We note that the H I and molecular band absorption spectra cited above do not extend below ~150 km s^{-1} of the galaxy's systemic velocity, so they would have missed a broad or significantly blueshifted absorption component.

2.1. *Estimating the Mass in the Shell from the Dust Emission*

Here we follow the procedure previously carried out by Bland-Hawthorn & Cohen (2003) for estimating the mass in the shell at the Galactic center. We estimate the column depth of the front of the shell from the surface brightness of the limb-brightened edge. The contrast between the peak surface brightness at the edge compared with that of the front of the shell is given by $C \approx 2(r/\delta)^{1/2}$ for a resolved shell, where r is the radius of the shell and δ is its thickness (Bland-Hawthorn & Cohen 2003). The shell structure is resolved with a thickness of a few arcseconds and radius $r \sim 30''$, giving us an estimated contrast of $C \sim 6$. From the background-subtracted surface brightness of 10 MJy sr^{-1} at 8 and 24 μm in the edge of the shell, we estimate that the front of the shell alone would have a surface brightness of ~2 MJy sr^{-1} at the same wavelengths.

Because of the difficulty in subtracting the background emission, we cannot measure the infrared colors in the shell well enough to estimate a dust temperature. We estimate the column depth in the shell from the flux at 8 and 24 μm using an estimated strength for the interstellar radiation field that sets the dust temperature in diffuse media (Li & Draine 2001). Cen A has a far-infrared luminosity of $\sim 10^{10}\ L_\odot$ (Eckart et al. 1990) in a region ~10 kpc^{-2}, corresponding to a star formation density in its disk of ~0.1 $M_\odot$ yr^{-1} kpc^{-2} (using conversion factors from Kennicutt 1998). This rate is a few hundred times larger than that of the solar neighborhood (estimated in the same way from the far-infrared luminosity; Bronfman et al. 2000). We estimate that the ratio χ of the UV radiation field to that of the Galactic UV interstellar radiation field in the solar neighborhood is a few hundred. This level is consistent with the approximate ratio of 1 for the 8 and 24 μm surface brightness in the shell. Using column depths estimated for the diffuse ISM as a function of the interstellar radiation field (Li & Draine 2001), the mid-infrared surface brightness for the front of the shell corresponds to a column depth of hydrogen of $N_H \sim 5 \times 10^{20}\chi_{100}^{-1}$ cm^{-2}. Converting this to a mass, we find a mass in the shell of $\sim 10^6\chi_{100}^{-1}\ M_\odot$. If the shell contains molecular material or if the radiation field is dominated by the active nucleus, then we may have underestimated the shell's mass. The estimated column depth implies that H I observations covering a wider velocity range than existing observations should be able to detect the shell in absorption against Cen A's nucleus.

The shell could be expanding. Using the shell mass estimated above, the shell would have kinetic energy $E_{kin} \sim 10^{53}\chi_{100}^{-1}v_{100}^2$ ergs, where the expansion velocity v_{100} is in units of 100 km s^{-1}. If the shell is moving faster than 100 km s^{-1}, then we will have underestimated its kinetic energy. The sound speed of the ambient X-ray–emitting material is ~300 km s^{-1}. The sound-crossing time at 500 pc is ~2 Myr. We use this timescale as a possible estimate for the age of the shell.

2.2. *Energy Estimates Based on Expansion of Wind-blown Bubbles*

Wind-blown bubble models predict the energy injection required to create a bubble expanding into a uniform medium (e.g., Chevalier & Clegg 1985; Tomisaka & Ikeuchi 1988). If the energy injection is continuous, then $dE/dt \sim 3 \times 10^{41} r_{kpc}^2 v_{100}^3 n_0$ ergs s^{-1} is required to produce a bubble of radius r_{kpc}, in units of kiloparsecs, velocity v_{100} in units of 100 km s^{-1}, expanding into a medium with ambient density n_0, in units of cm^{-3}. Here we have used scaling laws given by Castor et al. (1975) for an energy-conserving bubble. Assuming a β-model with density $n(r) = n_0[1 + (r/a)^2]^{3\beta/2}$, Kraft et al. (2003) estimate from the X-ray surface brightness distribution $n_0 \sim 0.04$ cm^{-3} and $a = 0.5$ kpc, though the central density may be an underestimate because absorption from the gaseous and dusty disk has not been taken into account. The central region has an estimated density of n_0. Inserting $n_0 = 0.04$ cm^{-3} into the above scaling relation, we find $dE/dt \sim 3 \times 10^{39} v_{100}^3 n_{0.04}$ ergs s^{-1}, where $n_{0.04} = 0.04$ cm^{-3} is the density used. Using the relation between mechanical luminosity and star formation rate based on the population synthesis models by Leitherer et al. (1999), this corresponds to a star formation rate of only 0.004 $M_\odot$ yr^{-1}. This power could easily be provided by the active nucleus, which has a bolometric luminosity of 10^{43} ergs s^{-1} (Whysong & Antonucci 2004).

If the injection was sudden, then the total energy required to create the hypothetical bubble can be estimated using a Sedov-type expansion model. In this case $E_{kin} \sim 5 \times 10^{54} r_{kpc}^3 v_{100}^2 n_0$ ergs. For our given radius and ambient density, we estimate a total energy of $E_{\rm kin} \sim 10^{52} v_{100}^2 n_{0.04}$ ergs. We note that this energy estimate is similar to that estimated above based on the dust mass. This mechanical energy only requires a dozen supernovae or a total mass of newly formed stars on the order of ∼1000 $M_{\odot}$ (based on Figs. 44 and 112 of Leitherer et al. 1999). A higher ambient density or expansion velocity would lead to increases in the required energy budget.

The size of the shell in Cen A is smaller than the shell or bubbles of NGC 2992, NGC 4388, M82, NGC 3079, and NGC 2782, which are 1 kpc to a few kiloparsecs in size (Ulvestad & Wilson 1984; Kenney & Yale 2002; Veilleux et al. 1994; Jogee et al. 1998). However, Cen A's shell is larger than the one at the Galactic center, which is only 170 pc (Bland-Hawthorn & Cohen 2003). Our energy estimates given above are highly uncertain because we lack constraints on the shell's velocity. If this shell is expanding at 1000 km s^{-1}, then it could have an energy as large as 10^{54} ergs, similar to that estimated for the Galactic center shell or that present in NGC 3079.

3. SUMMARY AND DISCUSSION

In this Letter we have presented *Spitzer Space Telescope* observations of the nuclear region of the galaxy Centaurus A that reveal a previously undetected 500 pc radius shell-like structure above and below the gaseous and dusty warped disk. The shell resembles a bipolar outflow or bubble and has an axis ratio of ∼0.6, a position angle of ∼10°, and a surface brightness of ∼10 MJy sr^{-1} at 8.0 μm. It is extended in the direction perpendicular to the gaseous and dusty disk and not in a direction obviously related to the radio jet. Observational studies are needed to confirm that the shell-like features seen in the infrared images correspond to a coherent shell structure, determine if this structure is expanding, and place better constraints on its mass, composition, and energetics. We conservatively estimate that the shell contains a million solar masses of hydrogen and that the energy required to create it, assuming that it is expanding, is $\sim 10^{53}$ ergs. Unfortunately, we lack constraints on the shell's velocity. If the shell is expanding at 1000 km s^{-1}, then the energy required could be 100 times larger. While a blueshifted, diffuse component was detected at the nucleus by Marconi et al. (2006), most spectroscopic observations fail to cover the shell or lack the bandwidth or sensitivity to have detected it.

If the kinetic energy in the shell is low (10^{53} ergs), then a modest starburst of a few thousand solar masses could have provided the mechanical energy. The orientation of the shell differs from that of the radio jets, so the shell might not have been caused by the active nucleus. However, the bolometric luminosity of the active nucleus exceeds that required to expand the bubble, so the active nucleus could have been important in its creation. This shell is too small to have evacuated the 0.1–0.8 kpc gap in the dust distribution in the disk reported in Quillen et al. (2006), suggesting that there could be or have been more than one expanding bubble in the heart of this galaxy.

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