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

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ABSTRACT

\textit{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\textmu m broad-band images. Such a remarkable shell has not been previously detected in a radio galaxy and is the first extragalactic nuclear shell detected at mid-infrared wavelengths. We estimate that the shell is a few million years old and has a mass of order million solar masses. A conservative estimate for the mechanical energy in the wind driven bubble is 10\textsuperscript{53} erg. 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\textsuperscript{-1} then the required mechanical energy would be 100 times larger.

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

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 shows a well recognized, optically-dark band of absorption across its nucleus. \textit{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; Sparks 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. 2003). For example, the Seyfert 2 galaxy NGC 2992 exhibits a figure-eight shaped 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 radio continuum.

The above shells have been detected in radio continuum, 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 sized bipolar shell in mid-infrared images in the center of the galaxy along the shell’s major axis, north and south of the nucleus. These images have been de-
ing elliptical galaxy component is nearly spherical (see isophotes shown by 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 features are 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 major axis of the shell at PA = 10° is shown as a surface brightness profile in Fig. 3. The shell can be seen as bumps at a distance ±30° from the nucleus. By subtracting a linear fit to the background emission to 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 24μm, respectively. These measurements are approximate (uncertain by a factor of 50%) due to 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 to 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 (HST) (e.g., Schreier et al. 1996; Marconi et al. 2000), though the filaments south of the nucleus are coincident with those in the shell in the 8.0 and 5.8μm IRAC images (see Fig. 4). Further than 10° south of the nucleus the galaxy center is not obscured by folds of the gaseous and dusty disk so a dusty structure could be better seen in absorption against the underlying galaxy (see Quillen et al. 2006 for further discussion on the morphology of the warped disk). North of the nucleus, a fold of the disk, evident as a dark band across the HST image, obscures the region where the shell is located. This may account for our failure to match absorption features in the visible HST images with the infrared shell on the northern side, but our ability to do so on the southern side. The dust extinction features in the visible broad-band Wide Field Planetary Camera-2 (WFPC2) HST images appear concentric as if there had been an explosion in the center (see Fig. 2). There could be remnants of an additional, more diffuse and outer shell at a radius of ~ 45° from the nucleus; also possibly seen in the 8.0μm image south of the nucleus (see outer contours in Fig. 2).

The shell features are not coincident with the radio and X-ray knots seen by Burns et al. (1983); Kraft et al. (1990). 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 south-west of the nucleus (see Fig. 1 by Karovska et al. 2002). No shell-like feature is seen in existing radio continuum images of Centaurus A (e.g., by 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 8.0μm image there is a gap in the shell on the jet axis south-west of the nucleus. North-west 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 emission near the nucleus. A diffuse, broad and blue-shifted spectral component at the nucleus was reported by Marconi et al. (2000). It has a velocity ~ 300 km s⁻¹ below the galaxy systemic velocity and is fairly broad, with a width of 400 km s⁻¹ (Marconi et al. 2000). This component could be associated with the expanding shell. Absorption lines in HI and CO have been seen against the radio nucleus (van der Hulst 1983; Sarma et al. 2002; Eckart et al. 1995; Israel et al. 1991; Wiklind & Combes 1997), however none of these are blue-shifted more than 20 km s⁻¹ below the galaxy systemic velocity. We note that the HI 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 blue-shifted 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 to that of the front of the shell is given by \( C \approx 2 \left( \frac{r}{d} \right)^{1/2} \), for a resolved shell, where \( r \) is the radius of the shell, and \( d \) is its thickness (Bland-Hawthorn & Cohen 2003). The shell 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 24μm in the edge of the shell, we estimate that the front of the shell, alone, would have a surface brightness of \( \sim 2 \) 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 24μm using an estimated strength for the interstellar radiation field which sets the dust temperature in diffuse media (Li & Draine 2001). Centaurus A has a far infrared luminosity \( \sim 10^{10} L_\odot \) (Eckart et al. 1990) in a region \( \sim 10 \) kpc⁻², corresponding to a star formation density in its disk of \( \sim 0.1 M_\odot \) yr⁻¹ kpc⁻² (using conversion factors by 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, \( \chi \), 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 24μm 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 \( N_H \sim 5 \times 10^{20} \) cm⁻² \( \chi^{-1} \) MeV⁻¹. Converting this
to a mass we find a mass in the shell of $\sim 10^6 M_\odot \chi_{100}^{-1}$. If the shell contains molecular material or if the radiation field is dominated by the AGN, then we may have underestimated the shell’s mass. The estimated column depth implies that HI observations covering a wider velocity range than existing observations should be able to detect the shell in absorption against Centaurus A’s nucleus.

The shell is likely to be expanding. Using the above estimated shell mass the shell would have kinetic energy $E_{\text{kin}} \sim 10^{53} A_{100}^2 v_{100}^2$ erg, 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 would have underestimated its kinetic energy. The sound speed of the ambient X-ray emitting material is $\sim 300$ km s$^{-1}$. The sound crossing time at 500 pc is $\sim 2$ 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 $dE/dt \sim 3 \times 10^{41} k_{\text{kpc}} v_{100}^2 n_0$ erg s$^{-1}$ is required to produce a bubble of radius $r_{\text{kpc}}$ in units of kpc, velocity $v_{100}$ in units of 100 km s$^{-1}$, expanding into a medium with the 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 $\beta$ model with density $n(r) = n_0 [1 + (r/a)^2]^{3/2}$, Kraft et al. (2003) estimate from the X-ray surface brightness distribution $n_0 = 0.04\text{cm}^{-3}$ 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 $n_0 = 0.04\text{cm}^{-3}$ into the above scaling relation, we find $dE/dt \sim 3 \times 10^{39} v_{100}^2 n_{0.04}$ erg 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 bubble can be estimated using a Sedov-type expansion model. In this case $E_{\text{kin}} \sim 5 \times 10^{54} k_{\text{kpc}} v_{100}^2 n_0$ erg. For our given radius and ambient density we estimate a total energy of $E_{\text{kin}} \sim 10^{53} v_{100} n_{0.04}$ erg. 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 of order $\sim 1000 M_\odot$ (based on Figures 44 and 112, by 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 Centaurus A is smaller than the shell or bubbles of NGC 2992, NGC 4388, M82, NGC 3079 and NGC 2782 that are 1 to a few kpc in size (Ulvestad & Wilson 1984; Kenney et al. 2002; Veilleux et al. 1994; Jogee et al. 1998). However Centaurus 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 moving at a 1000 km s$^{-1}$ then it could have an energy as large as $10^{54}$ erg and similar to that estimated for the Galactic center shell or that present in NGC 3079.

3. SUMMARY AND DISCUSSION

In this paper 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 above and below the gaseous and dusty warped disk. The shell resembles a bipolar outflow or bubble, has an axis ratio of $\sim 0.6$, a position angle of $\sim 10^\circ$ and a surface brightness of $\sim 10$ MJy sr$^{-1}$ at 8.0$\mu$m. It is extended in the direction perpendicular to the gaseous and dusty disk and not in a direction obviously related to the radio jet. We conservatively estimate that the shell contains a million solar mass of hydrogen and that the energy required to create it 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 blue shifted diffuse component was detected at the nucleus by Marconi et al. (2003), no spectroscopic observations fail to cover the shell or lack the bandwidth or sensitivity to have detected it. Observational spectroscopic studies are needed to confirm the presence of this transient shell and place better constraints on its mass, composition and energetics.

If the 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 may 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 by Quillen et al. (2004), suggesting that there could be or have been more than one expanding bubble in the heart of this galaxy.

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Fig. 1.—a) Nuclear region showing the bipolar shell at 8.0µm. The emission is shown on a log scale. The 8.0µm emission has been subtracted by that at 3.6µm, 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. b) The 8.0µm image (grayscale) overlayed with contours from the MIPS 24µm image (again with the 3.6µm 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 24µm. We point out with black arrows the upper two of the four bright points discussed in the text in section 2.
Fig. 2.— a) A somewhat larger view of the same region of the nucleus viewed in grayscale at 0.55µm taken with the WFPC2 camera on board HST (see Marconi et al. 2000) overlayed with contours from the IRAC 8.0µm image. Contours are shown at 13, 18, 23, 30, 56 and 90 MJy sr$^{-1}$. Extinction features at 0.55µm are coincident with the infrared shell rim 30′′ south of the nucleus. There may be a larger shell 45′′ south of the nucleus evident in the lower contour at 8.0µm.
Fig. 3.— Surface brightness as a function of distance from the nucleus in a 3′′ wide slice oriented along $PA = 10^\circ$ containing and centered at the galaxy nucleus. The right hand side corresponds to positions north of the nucleus. From top to bottom lines show the log$_{10}$ of the surface brightness at 24μm, offset upward by +0.5, that at 8.0, 5.8 and 4.5μm, respectively, and with no offsets. The shell is visible as bumps at ±30′′ from the nucleus.