FULL TITLE
*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***
NAMES OF EDITORS

Spitzer Observations of Centaurus A

Brookes, M.H.[1], Keene, J.[1], Quillen, A.C.[2], Charmandaris, V.[3], Lawrence, C.R.[1], Stern, D.[1], Werner, M.[1]

(1) JPL, 4800 Oak Grove Drive, CA 91109, (2) University of Rochester, Rochester, NY 14627, (3) University of Crete, GR-71003, Heraklion, Greece

Abstract. We describe infrared observations of the radio galaxy Centaurus A made using the *Spitzer Space Telescope*. Data from IRAC, MIPS have been used to model the structure of the warped dusty disk and to detect infrared synchrotron emission from the radio jet at the position of the Northern Inner Radio Lobe. We also discuss future work with IRS low resolution spectral mapping data which will be used to probe the physical characteristics of the warped disk.

1. Introduction

The radio source Centaurus A and its host galaxy, NGC 5128, provide a rare opportunity to observe the detailed behaviour of a recently merged system supporting a powerful active nucleus with jets and extended radio emission. At a distance of 3.4 Mpc (Israel 1998), Centaurus A is the nearest powerful radio galaxy, and its activity, merger remnants, and star-formation may be resolved and studied in detail . The host galaxy is believed to be a giant elliptical galaxy that recently merged (∼200 Myrs ago) with a small spiral galaxy, producing the prominent dust lanes seen in optical images (Baade & Minkowski 1954; Quillen et al. 1993), shell-like and tidal features (Peng et al. 2002) and a possible shell structure in the inner 500pc (Quillen et al. 2006b). Giant radio lobes extend over $\sim 6^\circ$ on the sky, with inner radio lobes extending about $6'$ to the north-east and south-west. For a comprehensive review of Centaurus A see, for example, Israel (1998).

Here we present observations of Centaurus A from the *Spitzer Space Telescope* using Infrared Array Camera (IRAC; Fazio et al. 2004) imaging in all four bands, Multiband Imaging Photometer (MIPS; Rieke et al. 2004) imaging at 24 μm and low resolution Infrared Spectrograph (IRS; Houck et al. 2004) spectral mapping data. The goals of this project are: to model the structure of the dusty warped disk; to investigate the infrared flux associated with the inner radio lobes and to probe the physics of the inner regions of the galaxy via low resolution IRS spectroscopy.

2. Modelling of the warped dusty disk

Spitzer IRAC imaging of Centaurus A reveals a parallelogram shaped structure (see Figure 1). When an optically thin warped disk is seen in emission, the edges of folds in the disk correspond to regions of higher surface brightness. Likewise since the morphology is symmetric across the origin we infer that the dusty disk must be nearly optical thin in the mid-infrared.

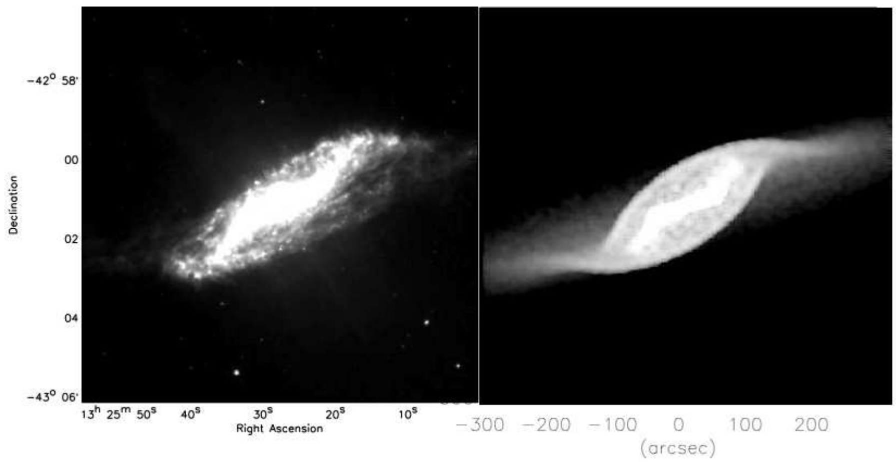

Figure 1. *Left:* The IRAC 8 μm image. *Right:* Modelling presented in Quillen et al. (2006a) which matches the disk structure.

A model of emission from a warped disk is produced by considering the disk to compose of a series of tilted rings of different radii. Model images were produced by integrating the emission along the line of sight, through the model disk, beginning with the precession and inclination angles of Quillen et al. (1993) and varying these angles in order to fit the IRAC image by eye. The best matching model to the IRAC morphology was produced by allowing the disk to twist to a greater extent than previously thought. This model predicts that the disk alternates between having the southern and northern side nearest to the observer. Further details appear in Quillen et al. (2006a; see Figure 1).

3. Infrared synchrotron emission from the radio jet

The IRAC and 24 μm MIPS imaging detect emission from the region associated with the Northern Inner Radio Lobe in Centaurus A, which, henceforth, we refer to as the jet. This is shown in Figure 2 (left) in which the 24 μm image is shown as a greyscale and the 1.4 GHz radio map is overlaid in contours.

In order to measure the spectral energy distribution (SED) of the jet, multiwavelength data from the literature were used, in addition to the *Spitzer* data. Radio data at 843 MHz, 1.4 GHz and 4.9 GHz were taken from (Bock et al. 1999), Condon et al. (1996) and Hardcastle (priv. comm.) respectively. Ultraviolet data was obtained with *GALEX* (Neff et al. 2003) at near and far UV bands. Measuring the surface brightness was done by rotating an aperture about the center of the galaxy, providing a measurement of the surface brightness for which the background emission from the host galaxy could be subtracted (Brookes et al. 2006).

Figure 2 (right) shows the surface brightness of the jet of Centaurus A as a function of frequency. The solid line is a power law, $S \propto \nu^{\alpha}$, fit to the IR points for which α = -0.68. This line comes remarkably close to the radio data points, and we conclude that the IR emission is also synchrotron in origin.

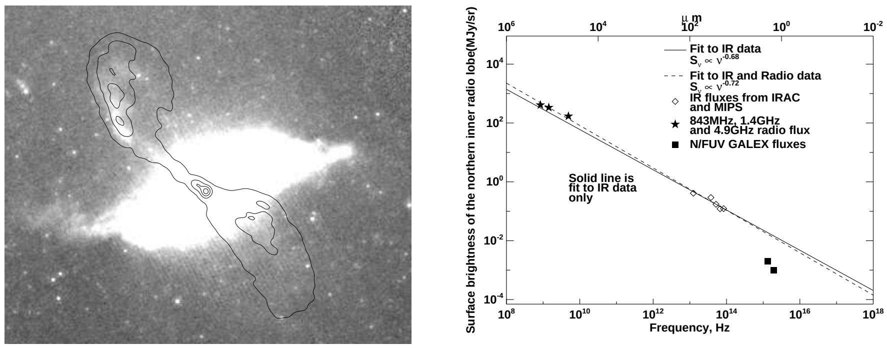

Figure 2. *Left:* The MIPS 24 μm image in greyscale with the 1.4 GHz radio contours overlaid. *Right:* The spectral energy distribution of the jet. The solid line shows a single power-law fit to the infrared data alone and the dashed line shows a similar fit to both the radio and infrared data.

However when compared to the ultraviolet data this single power-law does not fit well. This may be because there is a break in the spectrum, due to synchrotron aging. This is also suggested by the X-ray data, as presented in Hardcastle et al. (2006). However a broken power-law, as in Hardcastle et al. (2006) does not fit the ultraviolet data well either. Any interpretation of these data is complicated by extinction at ultraviolet wavelengths and will not be resolved without additional low frequency data which can independently constrain the SED (for a full discussion see Brookes et al. 2006).

4. Spectral Mapping of the warped disk

Low resolution spectra were taken, using both the short and long modules, with IRS in a grid pattern, covering the inner parallelogram structure. With this data set we may follow the strengths of spectral features as a function of position. The left panel of Figure 3 shows the 6.2 μm poly-cyclic aromatic hyrdocarbon feature, associated with star-formation. In stark contrast the [NeIII] 15.5 μm emission line (Figure 3; right) requires a much higher energy density irradiating field for its production and therefore its physical association with the nucleus is expected. Work with the spectral maps is ongoing and we intend to use the data to investigate the physical characteristics of the warped disk and nucleus.

5. Summary

Using new Spitzer data including IRAC and MIPS imaging, and IRS high resolution spectroscopy and low resolution spectral mapping, we investigate the

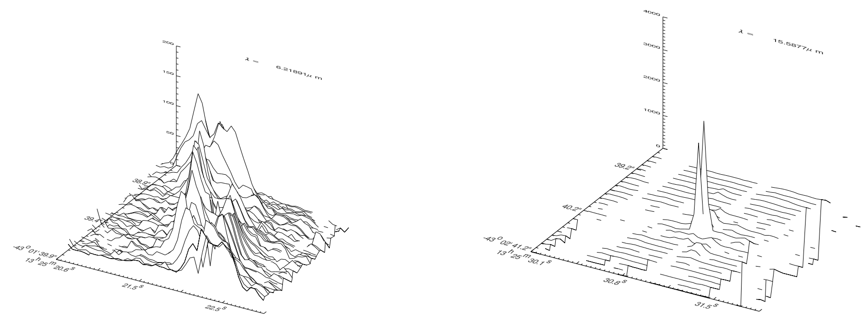

Figure 3. *Left:* The strength of the 6.2 μm PAH feature as a function of spatial position. *Right:* The strength of the 15.5 μm [NeIII] emission as a function of spatial position.

properties of the nearby radio galaxy Centaurus A. This has allowed detailed modelling of the structure of the warped dusty disk and has revealed infrared synchrotron emission associated with the northern inner radio lobe. On-going work will use IRS low resolution spectral mapping to further study the warped disk in terms of the characteristics of the nuclear activity and star-formation.

Acknowledgments. This work is based on observations with the NASA *Spitzer Space Telescope* under NASA contract 1407. We wish to thank Susan Neff from the *GALEX* team for providing the UV data. ACQ was supported by by National Science Foundation grant AST-0406823, and the NASA Grant No. NNG04GM12G issued through the Origins of Solar Systems Program.

References

Baade, W., Minkowski, R. 1954, ApJ, 119, 215

Bock, D.C., Large, M.I., Sadler, E.M., 1999, AJ, 117, 1578

Brookes, M.H, Lawrence, C.R., Stern, D., Keene, J., Gorijan, V., Werner,M., 2006, submitted to ApJL, astro-ph/0601413

Condon, J.J., Helou, G., Sanders, B.D., Soifer, B.T., 1996, ApJS, 103, 81

Fazio, G.G. et al., 2004, ApJS, 154, 10

Houck J.R. et al., 2004, ApJS, 154, 18

Hardcastle, M.J., Kraft, R.P., Worrall, D.M., 2006, MNRAS, submitted

Israel, F.P. 1998, A&A Rev., 8, 237

Neff, S.G., Schiminovich, D., Martin, C.D., *GALEX* Science Team, 2003, American Astronomical Society Meeting Abstracts, 203, 9607

Rieke G.H.et al., 2004, ApJS, 154, 25

Quillen, A.C., Graham, J.R., Frogel, J.A., 1993, ApJ, 391, 121

Quillen, A.C., de Zeeuw, P.T., Phinney, E.S., Phillips, T.G., 1992, ApJ, 412, 550

Quillen, A.C., Brookes, M.H., Keene, J., Werner, M.W., Lawrence, C.R., Eisenhardt, P.R., Stapelfeldt, K.R., Stern, D., Gorjian, V., 2006, submitted to ApJ, astro-ph/0601135

Quillen, A.C., Bland-Hawthorn, J., Brookes, M.H., Werner, M.W., Smith, J.D., Stern, D., Keene, J., Lawrence, C.R., 2006b, submitted to ApJL, astro-ph/0601147