SPIZTER OBSERVATIONS OF CENTAURUS A: INFRARED SYNCHROTRON EMISSION FROM THE NORTHERN LOBE

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ABSTRACT

We present measurements obtained with the Spitzer Space Telescope in five bands from 3.6 to 24 μm of the northern inner radio lobe of Centaurus A, the nearest powerful radio galaxy. We show that this emission is synchrotron in origin. Comparison with ultraviolet observations from GALEX shows that diffuse ultraviolet emission exists in a smaller region than the infrared but also coincides with the radio jet. We discuss the possibility that synchrotron emission is responsible for the ultraviolet emission, and we conclude that further data are required to confirm this.

Subject headings: galaxies: active — galaxies: individual (Centaurus A) — radiation mechanisms: nonthermal — radio continuum: galaxies

1. INTRODUCTION

The radio source Centaurus A and its host galaxy, NGC 5128, provide us with a rare opportunity to observe the detailed behavior 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), such that 1' ≈ 16.5 pc, 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 Myr ago) with a small spiral galaxy, producing the prominent dust lanes seen in optical images (Baade & Minkowski 1954; Quillen et al. 1993). The active nucleus gives rise to a jet and counterjet in the inner arcminute (1' ≈ 1 kpc) about the nucleus (Feigelson et al. 1981; Hardcastle et al. 2003). On larger scales, giant radio lobes extend over ~6° on the sky, with inner radio lobes extending about 6' to the northeast and southwest. The focus of this Letter is the northern radio “jet,” ~3–4 kpc from the nucleus (see Fig. 1). For a comprehensive review of Centaurus A, see, for example, Israel (1998), Morganti et al. (1999), and Junkes et al. (1993).

While jet-lobe emission is broadly understood in terms of synchrotron emission from electrons accelerated in the nuclear jet or in associated shocks, there remain uncertainties when interpreting the details of observed emission. Observing the synchrotron spectrum, particularly at sufficiently high frequencies that the cutoff due to spectral aging is measured, allows us to study the energy distribution of the underlying electron population.

Since the radio emission is produced by long-lived electrons, it alone does not provide detailed information about the underlying physical structure of the emitting plasma. At sites of acceleration, highly energetic electrons may emit at frequencies as high as X-rays (Smith et al. 1983; Feigelson et al. 1981), so a multifrequency approach is required to study these regions. Infrared (IR) observations provide important constraints at intermediate frequencies in modeling targets.

The Spitzer Space Telescope (Werner et al. 2004) offers us a powerful new capability to study IR emission from jets in active galactic nuclei. The Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) provide imaging at 3.6–160 μm, with sensitivity orders of magnitude better than any other telescope. While near-IR detections of FR II sources have been made recently (e.g., Floyd et al. 2006), no jet to date has been observed extensively in the IR.

The Spitzer Space Telescope’s advantage, in addition to offering several IR bands, is its sensitivity. In this Letter we present IRAC and MIPS photometry of the northern radio lobe, based on effective integrations of 72 and 160 s, respectively, and use them to describe and interpret the jet spectral energy distribution of Centaurus A. The IRAC observations and general processing are described in Quillen et al. (2006). The MIPS data are presented here for the first time. We use radio data at 843 MHz, 1.4 GHz, and 4.9 GHz from the literature: the 843 MHz data are taken from the Sydney University Molonglo Sky Survey (SUMSS; Bock et al. 1999); the 1.4 GHz and 4.9 GHz data are from Condon et al. (1996) and Burns et al. (1983), respectively. We show that the diffuse IR emission is also synchrotron in origin, and we compare it to ultraviolet (UV) emission detected by the Galaxy Evolution Explorer (GALEX; Martin et al. 2005). In § 2 we present the MIPS imaging and describe the IRAC, UV, and radio data sets. In § 3 we describe the method for measuring the surface brightness of the jet and present the derived photometry. In § 4 we interpret the results in terms of an underlying synchrotron spectrum and discuss the physical implications.

2. OBSERVATIONS

The multiwavelength emission we describe (Fig. 1) coincides with the part of the jet/lobe system usually referred to as the northern inner radio lobe (NIRL). The NIRL lies between the inner jet and the “large-scale jetlike feature” that connects the NIRL to the middle radio lobe (Morganti et al. 1999). Centaurus A is a Fanaroff-Riley class I (FR I; Fanaroff & Riley 1974) radio source, and has neither the hot spots nor the clear distinction between jet and lobe that characterize FR II sources. Referring to a part of the jet in Centaurus A as a “lobe” therefore can be confusing, particularly in the context of this Letter, which discusses its relation to the nucleus. We instead use the term “jet” to describe the source. Figure 1 shows the MIPS 24 μm image...
overlaid with 1.4 GHz radio contours and should clarify the source position with respect to the literature.

2.1. MIPS Imaging

Centaurus A was observed with MIPS on 2004 August 6 using the scan mapping mode with 14 scan legs at a medium scan rate, resulting in a total exposure of ~160 s at the center of the map. MIPS has three bands centered at 24, 70, and 160 μm with bandwidths of 4.7, 19, and 35 μm, respectively. Due to the presence of the bright, extended, dusty disk, measuring the surface brightness of the jet has only been possible at 24 μm, and we present only these data here. The 24 μm band “jail bar” artifacts were corrected by dividing each Basic Calibrated Data (BCD) frame by a normalized median frame (based on all BCDs excluding the source). These corrected BCDs were then mosaicked using the MOPEX software, which uses single, multiframe, and dual outlier rejection. The final mosaic used in the aperture measurements was created by manually selecting a rectangular region centered on the jet (i.e., the unresolved nucleus in the 4.5 μm image). The surface brightnesses measured when the aperture was adjacent to the jet are used to estimate the background due to the galaxy. The aperture is a polygon chosen by eye to match the shape of the lobe in the near-UV GALEX image. It covers 653 pixels in the BCD images, with six points starting at R.A. = 13°26′24″9, decl. = −43°18′16″4 (J2000), with vertices offset by 1°78, 2°47, 1°64, 0°13, and −1°92 east and 13°5, 30°7, 37°5, 33°7, and 19°5 north, respectively. Figure 1 (right panel) shows the position of the jet aperture overlaid on the 8 μm IRAC image. The aperture was rotated about the center of the galaxy in 100 steps covering π/2 radians on either side of the jet. At each position, the counts in the aperture were summed, excluding pixels on or near stars or other discrete sources. The mean count per aperture was then plotted as a function of angular separation from the radio lobe. By excluding the region corresponding to the radio lobe and fitting the mean count from apertures on either side of the lobe, an estimate of the background at the lobe was made and subtracted. Linear and quadratic fits to the galaxy background were made. Figure 2 (left panel) illustrates the 3.6 μm measurement. An estimate of the photometric error was taken to be the standard deviation of the difference between the fit to the background and the measured background across the range of the fit. This typically indicated a 10σ detection and shows that this measurement error dominates the 5% photometric error that is typical of IRAC mosaics. This method was repeated in all four IRAC images, the MIPS 24 μm, the GALEX images, and the radio images.

2.2. Data at Other Wavelengths

IRAC observations at 3.6, 4.5, 5.8, and 8 μm are taken from Quillen et al. (2006), and the 3.6 and 8 μm images are shown in Figure 1 (left and middle panels), stretched to emphasize detection of IR emission coincident with the radio lobe. These mosaicked observations had a typical exposure time of 72 s at the source and reached depths of 0.025, 0.024, 0.07, and 0.06 MJy sr⁻¹ in bands 1–4, respectively. Radio data at 1.4 GHz from Condon et al. (1996) show the jet with good signal-to-noise ratio (S/N), as do 843 MHz data taken from SUMSS (Bock et al. 1999). In addition, a re-reduced version of the 4.9 GHz data (Burns et al. 1983) was provided by M. Hardcastle (2005, private communication) and used to put limits on the radio emission at that frequency. Ultraviolet observations obtained with GALEX (Neff et al. 2003; S. G. Neff et al. 2006, in preparation) at near- and far-UV bands cover 1350–1800 and 1800–2800 Å, respectively. The effective wavelengths for the bands are 1528 and 2271 Å, respectively.

3. SURFACE BRIGHTNESS MEASUREMENTS OF THE NORTHERN INNER RADIO LOBE

Measuring the surface brightness of the jet requires careful subtraction of the underlying emission from the host galaxy. This was done by creating an irregularly shaped aperture matched to the jet and rotating it about the center of the galaxy (i.e., the unresolved nucleus in the 4.5 μm image). The surface brightnesses measured when the aperture was adjacent to the lobe are used to estimate the background due to the galaxy. The aperture is a polygon chosen by eye to match the shape of the lobe in the near-UV GALEX image. It covers 653 pixels in the BCD images (122 pixel⁻¹) and has six points starting at R.A. = 13°26′24″9, decl. = −43°18′16″4 (J2000), with vertices offset by 1°78, 2°47, 1°64, 0°13, and −1°92 east and 13°5, 30°7, 37°5, 33°7, and 19°5 north, respectively. Figure 1 (middle panel) shows the position of the jet aperture overlaid on the 8 μm IRAC image. The aperture was rotated about the center of the galaxy in 100 steps covering π/2 radians on either side of the jet. At each position, the counts in the aperture were summed, excluding pixels on or near stars or other discrete sources. The mean count per aperture was then plotted as a function of angular separation from the radio lobe. By excluding the region corresponding to the radio lobe and fitting the mean count from apertures on either side of the lobe, an estimate of the background at the lobe was made and subtracted. Linear and quadratic fits to the galaxy background were made. Figure 2 (right panel) illustrates the 3.6 μm measurement. An estimate of the photometric error was taken to be the standard deviation of the difference between the fit to the background and the measured background across the range of the fit. This typically indicated a 10σ detection and shows that this measurement error dominates the 5% photometric error that is typical of IRAC mosaics. This method was repeated in all four IRAC images, the MIPS 24 μm, the GALEX images, and the radio images.

4. RESULTS AND DISCUSSION

Figure 2 (right panel) shows the surface brightness of the designated region of the jet of Centaurus A as a function of frequency. The solid line is a power-law fit (S ∝ ν⁻α) to the IR points for which α = 0.68. This line comes remarkably

4 See http://ssc.spitzer.caltech.edu/postbcd/.
close to the radio points, suggesting that the IR emission is also synchrotron in origin, although the radio points are slightly flatter than the IR points. This suggests the possibility of a break in a synchrotron spectrum, rather than a simple, single-power-law spectrum. However, this is not a strong conclusion. We conclude that the IR emission is due to synchrotron emission, and when a single power law is fitted to both the radio and IR points, $\alpha = 0.72$ (the dashed line in Fig. 2).

Synchrotron-emitting electrons radiate at a rate proportional to their energy. The most energetic electrons lose their energy the fastest, leading to a slope that is a one-half power steeper in the high-frequency spectrum, at frequencies much above the break frequency, $\nu_\beta = eB/2\pi m_e c$ (e.g., Hughes 1991). Our observations indicate that this break must occur at frequencies higher than $10^{13}$ Hz. Although detailed modeling is required for an exact evaluation of the break frequency, an approximate limit may be gained. Following Miley (1980), we calculate the magnitude of the magnetic field on the assumption that the system is at its minimum-energy density. Using equation (3) of Miley (1980) at 1.4 GHz, we find $B \approx 3$ nT. Using the highest IR frequency observed (83 THz), an upper limit to the lifetime of the emitting electrons is found to be 30,000 years.

It is important to know how far the synchrotron spectrum extends without a break, since very high frequency emission is produced by short-lived, high-energy particles and may imply in situ particle acceleration. In both the near-UV and far-UV GALEX images, there are two kinds of emission: extended sources, likely associated with star formation sites, and diffuse emission, which coincides with the jet. Figure 3 shows the 1.4 GHz radio contours overlaid on the 8 $\mu$m IRAC image in gray scale (left panel) and the near-UV GALEX image (right panel; smoothed with a 7'6 circular Gaussian for clarity). The UV emission is seen only at
the inner portion of the jet, whereas the IR emission follows the jet to the north, consistent with the idea that the emission at all three wavelengths is synchrotron emission. The synchrotron lifetime of the UV-emitting electrons is shorter than that of the IR-emitting electrons, and so they do not live/emit long enough to trace the bulk motion downstream.

The surface brightness of the diffuse UV emission is compared to that of the radio and IR emission in Figure 2 (right panel). The UV points are significantly below the extrapolation of the synchrotron emission based on the radio and IR data. Several explanations must be considered. First, the diffuse UV emission might not be synchrotron at all. We consider thisunlikely because the jet emission extends to X-ray frequencies (Kraft et al. 2003), although it is possible that other mechanisms, such as diffuse star formation, also contribute to the UV. Second, we could be seeing the effects of extinction due to dust. Suppose that the best-fit power law to the radio and infrared measurements extends without break to ultraviolet frequencies, but that there is intervening dust. Assuming a Calzetti extinction law, only $E(B - V) = 0.56$ is required to produce the observed ultraviolet emission. Given the violent dynamic history of Centaurus A, there is clearly a large presence of gas, and therefore dust, associated with the merger, which can be found in distinct regions far outside the galactic disk. Hence, it is plausible that sufficient extinction, at the shortest wavelengths, exists along specific lines of sight. Note that if this were the case, the appropriate synchrotron lifetime for the UV-emitting particles (~6000 years) would be short enough to require in situ particle acceleration, given a projected distance of ~3 kpc from the nucleus and a bulk motion of ~0.5c in the kiloparsec-scale jet (Hardcastle et al. 2003).

However, inclusion of X-ray measurements argues for a third possibility: a spectral break between infrared and ultraviolet frequencies. Hardcastle et al. (2006) fit a broken power-law spectrum to all measurements from radio to X-ray frequencies, and they determine that a break occurs at ~0.3 THz. Figure 5 of Hardcastle et al. (2006) shows that this broken power-law accounts well for the radio, infrared, and X-ray measurements. However, it significantly underpredicts the ultraviolet measurements, even assuming no extinction from dust intrinsic to Centaurus A (Galactic extinction was included). If intrinsic extinction is important, this discrepancy becomes worse.

Neither dust alone nor a broken power law accounts for the data in an entirely satisfactory way. Submillimeter and 70 μm Spitzer measurements with a higher S/N would fill in the gap in the observed spectrum above and below 1 THz, providing significant new constraints on the overall spectrum, and would help us in resolving the issue.

5. SUMMARY

New IR observations of the jet, at the position of the NIRL associated with Centaurus A obtained with the Spitzer Space Telescope, show that synchrotron emission extends at least from radio to IR wavelengths. Diffuse UV emission is also present in the jet, and it is plausible that this emission is also synchrotron in origin, reddened by intervening dust. X-ray data imply a break in the spectrum, but further data are required to constrain this precisely.

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