THE ASTROPHYSICAL JOURNAL, 469:66–72, 1996 September 20

U-BAND POLARIMETRY OF THE RADIO-ALIGNED OPTICAL CONTINUUM IN THE ABELL 1795 CLUSTER CENTRAL GALAXY

BRIAN R. MCNAMARA[1]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

BUELL T. JANNUZI
National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726-6732, and Institute for Advanced Study

RICHARD ELSTON[1]
Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

CRAIG L. SARAZIN
Astronomy Department, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903

AND

MICHAEL WISE[1]
Massachusetts Institute of Technology, Center for Space Research, MS 37-667, Cambridge, MA 02139-4307

Received 1995 November 27; accepted 1996 April 4

ABSTRACT

We have obtained *U*-band polarimetry of the lobes of blue optical continuum located along the $z = 0.063$ F-R I radio source in the Abell 1795 cluster central galaxy. We find an upper limit to the degree of polarization of the light emitted from the lobes of less than 7%. The accuracy of this measurement is limited by the presence of diluting background starlight. This limit is inconsistent with the lobes being scattered light that originated in an obscured, anisotropically radiating nucleus, unless the radiation is beamed and is viewed at an angle $\lesssim 22°$ to the line of sight, which is unlikely. The absence of a polarized signal and detailed correspondence between the radio lobes and optical lobes is inconsistent with synchrotron light. The blue optical lobes are probably regions of recent star formation. If a burst of star formation were triggered by the expanding radio lobes, the age of the burst population should be $\sim 10^7$ yr. Then, the star formation rate in both lobes, assuming the local IMF, is $\sim 20\ M_\odot\ \mathrm{yr}^{-1}$, and the stellar mass of the lobes is $\sim 10^8\ M_\odot$. The material fueling the star formation and the radio source may have originated from the cooling flow or accretion from one or more gaseous cluster galaxies.

Subject headings: cooling flows — galaxies: clusters: individual (A1795) — galaxies: structure — polarization

1. INTRODUCTION

Centrally dominant cluster galaxies (CDGs) are composed primarily of relatively old, red, metal-rich stellar populations. They are thought to evolve by cannibalizing their neighbors—usually elliptical galaxies—and possibly by star formation fueled by accreting intracluster gas (cooling flows). CDGs may be useful standard candles owing to their large sizes, large luminosities, and apparently small luminosity dispersion (e.g., Postman & Lauer 1995). Their central location in clusters suggests that they formed under unusual circumstances. The Abell 1795 CDG appears to be a normal, elliptical-like galaxy in the *I* band (McNamara & O'Connell 1993, hereafter MO93); its surface brightness profile at *I* follows roughly a de Vaucouleurs law to a radius of ≈ 100 kpc (Johnstone, Naylor, & Fabian 1991). In the *U* and *B* bands, the inner 20–30 kpc is several tenths of a magnitude bluer than normal (Romanishin 1987; McNamara & O'Connell 1992). The CDG has a strong, $P_{1.4} \sim 10^{25}$ W Hz^{-1}, double-lobed, F-R I radio source that extends $\simeq 10$ kpc on either side of the nucleus (Heckman et al. 1989; van Bruegel, Heckman, & Miley 1984; Ge & Owen 1993). Luminous, $L(\mathrm{H}\alpha) \simeq 10^{42}$ ergs s^{-1}, nebular line emission is present in the central 20 kpc of the galaxy and in a filament that extends 80 kpc to the south of the nucleus (Heckman et al. 1989; Cowie et al. 1983). The cluster is rich, luminous in X-rays ($L_X \sim 10^{45}$ ergs s^{-1}), and contains a $\sim 300\ M_\odot\ \mathrm{yr}^{-1}$ cooling flow (Edge, Stuart, & Fabian 1992; Fabian 1994).

Among the CDG's interesting properties are the bright blue lobes of optical continuum straddling the nucleus in a roughly north-south orientation that extend to radii of $\simeq 10$ kpc (MO93). The blue optical lobes are located along the radio lobes in a similar manner to the distant, strongly aligned F-R II radio galaxies (McCarthy et al. 1987; Chambers, Miley, & van Breugel 1987), although with a size, luminosity, and distance that are roughly an order of magnitude smaller than the high-redshift F-R II galaxies.

The alignment effect in distant ($z \gtrsim 0.6$) radio galaxies appears as an elongation in the rest-frame ultraviolet along the radio axes. The galaxies become rounder toward redder, rest-frame colors as the aligned blue light becomes diluted by the redder background stellar population (Rigler et al. 1992). The aligned light was thought to originate in young stars that formed along the radio jets by shock overpressurization of the ambient gas (De Young 1989; Rees 1989; Begelman & Cioffi 1989; Daly 1990). This model has fallen into disfavor with recent detections of highly polarized ($\sim$5%–20%) light from the aligned components of several distant radio galaxies (di Serego Alighieri et al. 1989; Scarrott, Rolph, & Tadhunter 1990; Jannuzi & Elston 1991; Tadhunter et al. 1992; di Serego Alighieri, Cimatti, &

[1] Visiting Astronomer, Kitt Peak National Observatory. KPNO is operated by AURA, Inc., under contract to the National Science Foundation.

Fosbury 1993; Jannuzi 1994; Jannuzi et al. 1995; Dey et al. 1996; Jannuzi & Elston 1996). The current model that best explains the polarized light postulates the presence of an obscured active nucleus that is anisotropically beaming light along the radio axis. (In this paper, "beaming" refers to any anisotropic distribution of radiation from the nucleus, whether due to relativistic motion, an absorbing torus, or any other mechanism.) The beamed light is being scattered into the line of sight by dust and/or electrons in a surrounding dense gas (di Serego Alighieri et al. 1989; Fabian 1989). It has yet to be demonstrated, however, that all of the light in the aligned components is scattered, or that all cases of optical alignments result from scattering. Young stars may be contributing to the aligned components at some level (McCarthy 1993).

The discovery of optical lobes in the A1795 galaxy is significant for several reasons. It may be the closest ($z = 0.063$) case of the "alignment effect." Its proximity affords the opportunity to study such an alignment, its host galaxy, and the interaction between an F-R I radio source and its surrounding gas in detail. By analogy with the radio-triggered star formation model for the high-redshift alignments, it has been suggested that the blue lobes may have originated in a burst of star formation formation that was induced by the radio source (MO93; De Young 1995). The cooling flow is capable of providing an ample supply of cold gas to fuel star formation. Furthermore, F-R I radio sources have been proposed to be the parent population of BL Lac objects (Padovani & Urry 1990; Urry & Padovani 1995). The electron density in the volume of A1795's radio source, and possibly its BL Lac nucleus, could provide a scattering medium for light that may be anisotropically radiated from its nucleus along the radio axis, producing the blue lobes (Sarazin & Wise 1993; Crawford & Fabian 1993; Murphy & Chernoff 1993; Sarazin et al. 1995). The light from such scattered lobes should be polarized with the polarization axis perpendicular to the radio axis, while the light from young stars should be unpolarized. Therefore, optical polarimetry should, in principle, discriminate between these models. Here we discuss a search for polarized *U*-band light from the CDG's blue lobes to attempt to discriminate between these models. All distance- and time-dependent quantities discussed in this paper assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

2. OBSERVATIONS

The images were obtained with the 4 m telescope of the Kitt Peak National Observatory during the nights of 1993 April 21 and 22, using the Texas Instruments 800 × 800 pixel (scale = 0".29 pixel^{-1}) CCD chip mounted at the prime focus. The *U*-band observations minimize the amount of dilution from background starlight and nebular line emission, while maximizing the sensitivity to blue scattered light. In order to measure the Q and U Stokes parameters, images were obtained through a combination of a *U*-band filter attached to a copper sulfate blocking filter, and one of four Polaroid transmission filters (HNP'B sheet Polaroid) with transmission axes at 0°, 45°, 90°, and 135°. The data were acquired in "shortscan" mode, which shifts the charge in each pixel while physically shifting the camera so that each point in the image is formed over many pixels. In addition, the pointing was shifted by ≈20" between frames. These procedures were taken to minimize the effect of high-frequency sensitivity variations on the CCD chip. Dome flat-field frames were obtained each night. Bias frames were obtained each night and combined into nightly master bias frames. The master bias frames were subtracted from the target frames; the bias level was adjusted on each frame to the overscan level; the target frames were divided by normalized dome flat-field frames; the sky background was measured and subtracted from each image, and the target frames obtained over two nights in each of four position angles were combined into master frames for each polarization angle. Eight frames were obtained (1200 s each) for each position angle. The data were taken during transparent but probably unphotometric conditions.

3. ANALYSIS

In Figure 1 we show the 3.84×10^4 s exposure *U*-band image, formed by summing the data from all position angles (the efficiency is reduced to ≃13% due to the poor transmission of the Polaroid filters), after a model for the background galaxy light has been subtracted (see § 3.1). The central region of the galaxy is displayed with a transfer function that has been adjusted to emphasize the optical lobes (*black*). In the right panel we show the $U-I$ color map (see MO93) using our new *U*-band image and a regridded version of the *I*-band image from MO93. (The *I*-band image was obtained with a telescope with a larger plate scale.) The lobes are shown with dark gray-scale levels in both color and intensity. A 3.6 cm radio continuum map obtained with the VLA (Ge & Owen 1993) is superposed on both maps (*contours*). The optical lobes are located along the radio lobes (see MO93 for a more complete discussion). The remainder of this paper is concerned with polarimetric observations of these lobes.

The Stokes flux images were formed by taking differences between frames, S, as $Q = S_{0°} - S_{90°}$, $U = S_{45°} - S_{135°}$. We computed the normalized Stokes flux frames as $q_n = Q/(S_{0°} + S_{90°})$ and $u_n = U/(S_{45°} + S_{135°})$, and the degree of polarization was computed as $P = (q_n^2 + u_n^2)^{1/2}$. Prior to forming the Stokes flux images, the flux levels were scaled until the presumably unpolarized signal from neighboring stars and galaxies was minimized. Upon inspection of the Stokes flux frames, we found that the lobes vanished indicating little or no polarized signal from the lobes. In order to place limits on the degree of polarization, we placed rectangular apertures over the nucleus of the CDG, the blue lobes, and several neighboring galaxies, and measured the polarized flux in the apertures as described above. The larger southern lobe was tiled with two rectangular apertures. (The aperture sizes and locations with respect to the nucleus are given in Table 1, described below.) We report an upper limit to the degree of polarization of the *total* light from the lobes (lobes + galaxy) of less than 2%. The statistical error in the each of the Stokes parameters, which included variations in the *U*-band sky background (≲1%) and photon statistics (≪1%), was found to be less than 1%. A nearly identical polarization of 2% was found for a number of presumably unpolarized galaxies in the field. This offset reflects the systematic error associated with registering and scaling the image plus, perhaps, some intrinsic polarization across the field of view imparted by aligned dust grains along the line of sight through our Galaxy.

3.1. *Stellar Background Models*

In order to determine the intrinsic polarization of the lobes, we attempted to model and remove the contribution

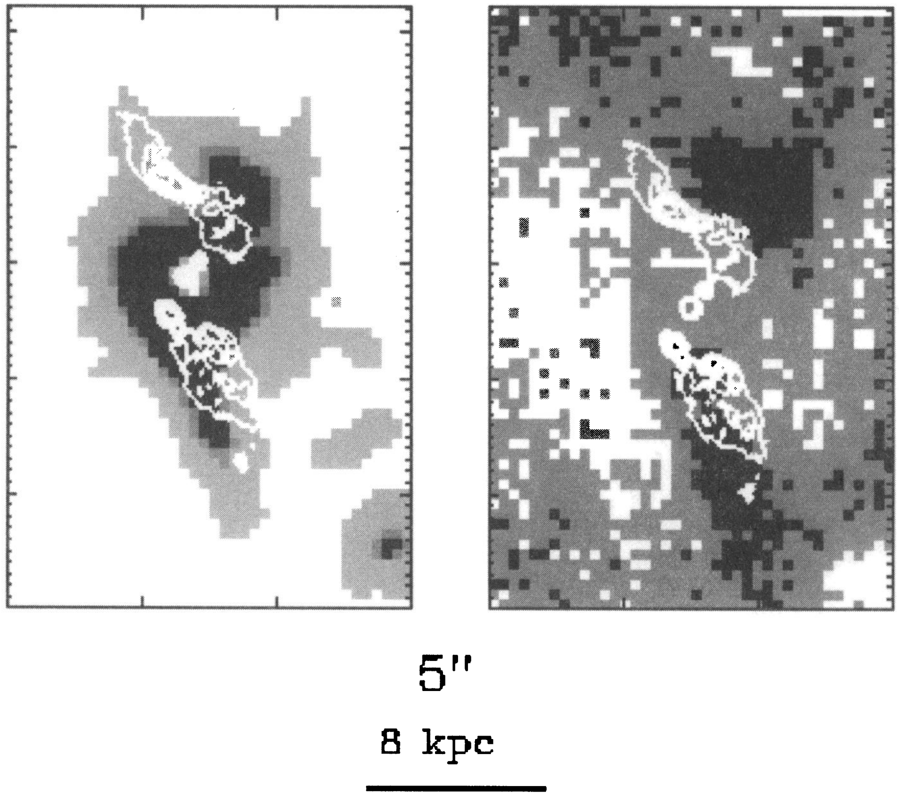

FIG. 1.—*Left*: *U*-band image of the nucleus, formed by adding all of the data and subtracting a model background galaxy, superposed on the 3.6 cm radio continuum map (*contours*). *Right*: $U-I$ color map constructed with the *U*-band image and a rescaled version of the *I*-band image discussed in MO93. The optical lobes are clearly aligned with the radio lobes. The gray regions are somewhat redder (although intrinsically blue; see MO93) than the blue lobes (*black*). Some of the reddening is due to dust. North is at top, east is to the left.

of presumably unpolarized star light from the CDG. In addition to the light contributed by the old background stellar population, the lobes are surrounded by diffuse blue light with an irregular spatial distribution (MO93). We therefore constructed several models of the old population alone and of the old population plus the diffuse blue light surrounding the lobes. The models were used to remove the contaminating light, in order to obtain a range of plausible limits to the degree of intrinsic lobe polarization. The sizes and locations of the apertures are given in Table 1. Columns (1)–(3) give the locations of the aperture centers with respect to the nucleus defined as the peak in the *U*-band flux. The offsets are in arcseconds; a positive offset in right ascension is increasing eastward and a positive offset in declination is north of the nucleus. Columns (4) and (5) list the rectangular aperture size in arcseconds. The apertures were placed with north-south, east-west orientations. Column (6) lists the observed upper limit to the degree of polarization, prior to the removal of the surrounding galaxy light. The remaining two columns list the upper limits to the degree of polarization after subtracting the background models discussed below.

The surface brightness profile of the background population was measured after excluding superposed stars and galaxies from the image using masks. We then measured the radial surface brightness profile using elliptical annulae with major-axis position angles and isophotal ellipticities matched to the *I* band (MO93). The model image shape was identical to the mean isophotal shape of the galaxy in the *I* band, but its radial surface brightness distribution was determined using fits to the *U*-band radial surface brightness profile. The fits were made in the plane of surface brightness, in magnitudes per square arcsecond, against radius to the 1/4 power. In this plane, a line represents an $R^{1/4}$ law profile.

The *U*-band surface brightness profile, plotted as circles, and the model profiles are shown in Figure 2. The surface brightness profile includes the lobe light. Model A represents the $R^{1/4}$ law profile fitted to the light beyond the unusually blue central region of the galaxy in an annular

TABLE 1

LOBE POLARIZATION LIMITS

Location (1)	R.A.$_0$ (2)	decl.$_0$ (3)	δR.A. (4)	δdecl. (5)	P (6)	P(A) (7)	$P(B)$ (8)
North lobe......	−1.5	+2.6	5.0	3.2	0.02	0.03	0.07
South lobe......	−1.5	+4.4	4.9	3.5	0.02	0.03	0.07
South lobe......	−0.6	−1.2	2.4	2.9	0.03	0.04	0.07

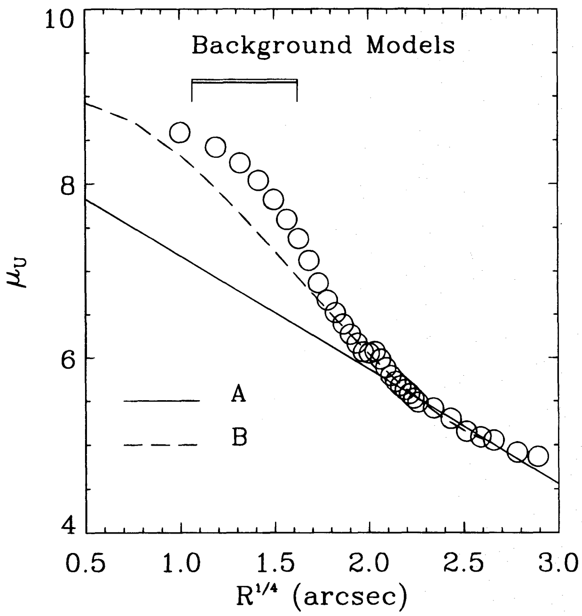

FIG. 2.—The *U*-band surface brightness profile (*circles*) in arbitrary magnitudes per square arcsecond, plotted against semimajor axis to the 1/4 power. The surface brightness profile includes the light from the lobes. The solid and dashed lines represent the model surface brightness profiles used to correct the polarization measures for dilution by surrounding starlight. Model A is an $R^{1/4}$ law profile for the old background stellar population. The model B profile includes starlight from the blue regions surrounding the lobes. The bracket above the profile indicates the radial interval occupied by the lobes.

region at radii between 16″ and 40″. This profile was extrapolated inward in order to construct a model of the presumably older background population at the location of the lobes. The contribution of background light to the apertures was found by measuring the flux in the model galaxy using the apertures listed in Table 1. The Stokes parameters of the net flux from the lobes were then estimated as $q_{\rm net} = Q/(S_{0°} + S_{90°} - f_{M(r)})$ and $u_{\rm net} = U/(S_{45°} + S_{135°} - f_{M(r)})$, where $f_{M(r)}$ is the contribution of model background light. The degree of polarization determined from the net lobe flux is $P_{\rm net} = (q^2_{\rm net} + u^2_{\rm net})^{1/2} \lesssim 3\%$.

This model does not, however, account for additional dilution by the diffuse blue light surrounding the lobes (MO93). In order to remove both the red and diffuse, blue backgrounds, we fitted a third-order polymomial to the surface brightness profile at radii adjacent to the lobes. This fit is shown as profile B in Figure 2. Profile B was used to construct a model galaxy similarly to the $R^{1/4}$ law model (model A), and the aperture dilution was similarly removed. The 3 σ upper limit to the degree of polarization based on this model is less than 7% (see Table 1). The significance of this limit was determined by noting an acceptable background model giving $P < 5\%$–6%. A 3 σ positive error on the zero-point fitting coefficient for this model provides a 7% upper limit. At this value, the net flux surrounding the lobes was negative, indicating oversubtracted background light. The 3 σ upper limits to the total polarized flux (lobe + galaxy) from the lobes at *U* using the calibrated photometry of MO93 and the upper limit of 2% to the degree of polarization of the total light at *U* presented here are less than 6×10^{-16} ergs cm^{-2} s^{-1} and less than 9×10^{-16} ergs cm^{-2} s^{-1} for the north and south lobes, respectively.

4. DISCUSSION

4.1. *Comparison to a Scattering Model*

We have calculated the expected linear polarization of the lobes for the model where the lobes are due to electron scattering of anisotropic nuclear emission by the cooling flow (Sarazin & Wise 1993). We discuss this model, rather than isotropic emission, because no strong nuclear point source is seen in A1795 (MO93; McNamara et al. 1996), implying anisotropic emission in the event the lobes are scattered light (Sarazin & Wise 1993; Crawford & Fabian 1993). Our upper limit would apply to all scattered radiation regardless of the geometry. The calculated polarization is for the scattered light only, without dilution by the background galaxy light. We assume that the scattered light is due to single-electron scattering, as the observed electron scattering optical depth of the cooling flow is small ($\sim 1\%$; see Sarazin et al. 1995). In this limit, the polarization is independent of the flux of the anisotropic nuclear source or the scale of the electron density of the cooling flow. We assume that the electron density, n_e, in the cooling flow varies with radius, r, as $n_e \propto r^{-1}$, which gives a reasonable fit to the observed X-ray surface brightness at small radii (Sarazin 1996). For this calculation, we assume that anisotropic radiation from the central nucleus is conical, initially unpolarized, and uniformly illuminated. The polarization is calculated including the effects of averaging along the line of sight through the beam and averaging the azimuthal polarization across the projected width of the beams. The polarization depends slightly on the observed width of the lobes. We estimate an angular half-width $\phi_{\rm max} \approx 33°$ for the northern lobe and $\phi_{\rm max} \approx 21°$ for the southern lobe. We will adopt $\phi_{\rm max} = 30°$; the resulting polarization is not strongly dependent on this assumption or any of the other assumptions described above (Sarazin & Wise 1993). The one parameter upon which the predicted polarization does depend strongly is the angle θ between our line of sight and the central direction of the beams. (See Fig. 1 in Sarazin & Wise 1993 for the definitions of the angles.) For each value of the angle θ, we determine the angular width of the beams, θ_b, which is consistent with the observed width $\phi_{\rm max}$ of the blue lobes in A1795. The existence of distinct lobes and the fact that the nucleus is not extremely bright both require that our line of sight be outside of the beams, so that $\theta_b < \theta$.

Figure 3 shows the predicted polarization (*solid line*) of the scattered lobe light, P, as a function of the angle of the beams to the line of sight, θ. For comparison, the predicted polarization for a very narrow beam $[P = \sin^2 \theta/(1 + \cos^2 \theta)]$ is shown as the dashed line. It is clear that the various assumptions about the properties of the beams or the width of the lobes do not appreciably affect the predicted polarizations, at least for small values of the observed polarization. The observed upper limit of $P < 7\%$ is shown as a dotted horizontal line. The observed upper limit is consistent only with the prediction of the simple electron scattering model if $\theta \lesssim 22°$. The chance that the beam would be randomly oriented this close to our line of sight is $\lesssim 7\%$. (Note that for small polarizations, the limit on the chance of alignment and the polarization are always nearly equal.) Thus the consistency of the observed upper limit on the polarization of the lobes with the simple electron-scattering model would require an unlikely alignment of the beams from the nucleus. While A1795 is a single object and a posteriori probability arguments are always dangerous, the strong

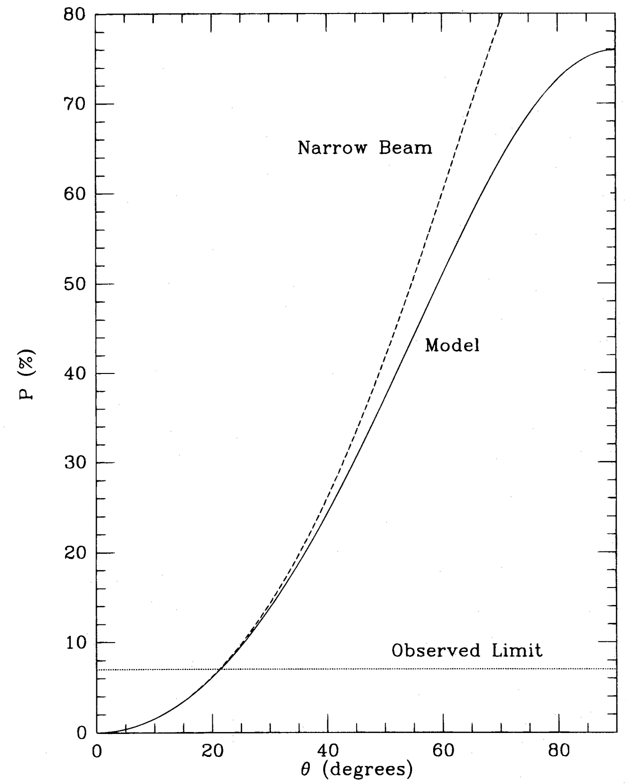

FIG. 3.—The predicted degree of polarization, P, for electron-scattering lobes is shown as a function of angle, θ, from the central direction of the cones to our line of sight (*solid line*). The predicted polarization is corrected for the effects of averaging along the line of sight through the lobe and across the width of the lobes. For comparison, the predicted polarization for very narrow cones [$P = \sin^2 \theta/(1 + \cos^2 \theta)$] is also shown (*dashed line*). The observed upper limit of $P < 7\%$ is plotted as a dotted horizontal line.

upper limit on the polarization of the lobes makes it unlikely that they are due to electron scattering.

This calculation of the polarization in Figure 3 assumed that the anisotropic emission from the nucleus of the active galaxy was unpolarized. If the nucleus contains a BL Lac object, then the nuclear emission might itself be highly polarized. Generally, this will increase the polarization of the scattered light (eq. [15] of Sarazin & Wise 1993 gives the resulting polarization). However, if the initial polarization of the radiation is in the plane of the scattering ($\psi = 0$ in Fig. 2 of Sarazin & Wise 1993) and the intrinsic polarization of the radiation, Π, and the scattering angle θ have carefully chosen values, the effect of the intrinsic polarization and scattering can cancel and produce no polarization. For example, this occurs for $\psi = 0$, $\theta = 45°$, and $\Pi = 1/3$. However, a small variation of these parameters away from the required values will result in a polarization greater than the observed limit; for the example given above, this would only require $\delta\psi \gtrsim 6°$, $\delta\theta \gtrsim 6°$, or $\delta\Pi \gtrsim 0.07$. Again, an unlikely coincidence would be required to reconcile the electron scattering model with the observed upper limit on the polarization.

The blue lobes in A1795 might also be due to scattering by dust grains. Dust is a much more effective scatterer than free electrons. If the radiation from the putative active nucleus in A1795 were as bright as a BL Lac object when viewed directly, the blue lobes could be produced by a column of dust which would correspond to a negligibly small extinction or reddening ($E_{B-V} \sim 10^{-2}$ mag; Sarazin et al. 1995). The polarization produced by scattering from dust depends on the distributions of sizes, shapes, and orientations of the grains, and on the complex index of refraction of the grain material (e.g., Bohren & Huffman 1983). Very small dielectric grains are Rayleigh scatterers with the same polarization as free electrons, so that Figure 3 would still apply. Larger grains are less effective at polarization, and this would tend to somewhat weaken the limits on θ in Figure 3. However, observations of reflection nebulae still show polarizations at U which are larger than the upper limit in A1795 (e.g., Zellner 1973). Also, dust grains tend to scatter mainly in the forward direction, so the relative symmetry of the two lobes would be difficult to understand if the lobes were due to scattering by dust and the angle θ were small. Thus, unless the composition of dust grains in A1795 is very different from that in the local interstellar medium, it is unlikely that the lobes could be due to dust scattered light given the observed upper limit on the polarization. The absence of polarized light and the absence of a detailed coincidence between the optical and radio lobes exclude synchrotron radiation. Inverse Compton scattering of microwave background photons (e.g., Daly 1992) is unlikely on energetic grounds, and the optical bremsstrahlung continuum is too weak for any reasonable range of gas densities. The lobes are probably composed of stars.

4.2. *Radio-triggered Star Formation*

The higher surface brightness and bluer colors of the lobes are indications of vigorous star formation. The star formation rate in the lobes is higher than that of the surrounding region (MO93). De Young (1995) presented a model to explain the lobes as a burst of star formation triggered by the rapid collapse of cold clouds compressed by shocks along the expanding radio source. The nebular gas velocities near the lobes are disordered (Heckman et al. 1989). Assuming the star formation is fueled by cold gas with a similar velocity structure, the stellar lobes are unlikely to be rotationally supported and will disperse in less than the free-fall time. For stellar lobes embedded in a homogeneous sphere of stars with a velocity dispersion of $\simeq 300$ km s^{-1}, the free-fall timescale is $t_{ff} \simeq 4 \times 10^7$ [B/(10 kpc)] yr, where R is the distance of the lobe from the nucleus. The strong alignment between the radio lobes and optical lobes suggests that the stars have not moved large distances from their birth sites along the radio lobes. In addition, the stars may have initial velocities of a few hundred kilometers per second imparted by their parent gas motions (MO93). Therefore, we expect the lobe population age to be much less than t_{ff}. De Young (1995) found dispersal timescales of $\simeq 10^7$ yr using hydrodynamic simulations, which is indeed considerably less than t_{ff}. The dispersal timescale is consistent with the probable radio age $t_{rad} \gtrsim (5–10) \times 10^6$ yr (van Breugel et al. 1984).

An accurate determination of the lobe population age and mass-to-light ratio is impossible using broadband photometry (see, e.g., MO93) because of degeneracy in the model isochrones as a function of the age and duration of the star-forming episode (see, e.g., McNamara 1995). Additional uncertainty is associated with the unknown metallicity of the background stars, the amount of extinction, and the form of the initial mass function. Population models for star formation with the local initial mass function and solar abundances are, however, compatible with the colors for a burst of star formation that occurred $\simeq 5$ Myr ago and continuous star formation that has been occurring for $\simeq 4$ Gyr (MO93). These ages imply star formation rates in the lobes of $\simeq 20\ M_\odot\ \mathrm{yr}^{-1}$ and $\simeq 5\ M_\odot\ \mathrm{yr}^{-1}$ respectively. The unlikelihood that the lobe structure can be maintained for more than the free-fall timescale is incompatible with the 4 Gyr model, whereas the burst model age is roughly compatible with the radio age, the dispersal timescale, and the $\lambda\lambda 3500$–5500 spectrum, which shows an O and B star continuum (McNamara & O'Connell 1989; Allen 1995).

Radio-triggered star formation models may describe the situation in A1795 (De Young 1995; Begelman & Cioffi 1989), but much is not understood. First, the optical lobes are associated with the radio lobes, rather than the radio jets: the jets are located in the inner few arcseconds along P.A. $\approx 135°$. The radio lobes, located at the ends of the jets, expand to the northeast and southwest at a $\approx 90°$ angle with respect to the jet orientation. De Young's model predicts star formation along radio jets, rather than the lobes. The Begelman & Cioffi (1988) model predicts star formation along the expanding cocoon surrounding radio lobes, which may better describe A1795. A direct comparison to this model is hampered by the physical conditions they chose to describe high-redshift radio galaxies, which differ from those in A1795.

The optical lobes in A1795 (and A2597) are embedded in nebular line emission associated with cold gas that may be fueling the star formation. (The stellar nature of the lobes in A2597 has not been firmly established.) The mass of gas at 10^4 K is only $\sim 3 \times 10^6\ M_\odot$ (Heckman et al. 1989), similar to the mass of 10^4 K gas in other cooling-flow clusters. In order to account for the observed rates of star formation, ~ 30 times the ionized gas mass in the form of atomic hydrogen or molecules must be associated with the emission nebula. The limit on the amount of 100 K H I in the inner 15 kpc, based on the sensitive H I absorption limits by O'Dea, Gallimore, & Baum (1995), is $\lesssim 10^8\ M_\odot$, which is consistent with the young stellar mass (MO93). Furthermore, molecular hydrogen emitting in the 2.1 μm emission line has been detected in the CDG's nucleus (Elston & Maloney 1995), supporting our conjecture that substantial amounts of molecular gas must be associated with the nebula. (It is difficult to estimate its total mass, because only the fraction of the molecular hydrogen that is either shock-excited or illuminated by X-rays is observed. One can measure only the excited surface area of the clouds.)

De Young's (1995) model assumes that star formation is fueled by cold gas that has cooled out of the 10^7 K gas (White & Sarazin 1987a, 1987b) in the solid angle subtended by the radio lobes. Ten percent of the cooling gas deposited in this region, if converted to stars, would match the star formation rate associated with the 5 Myr old population model of MO93. This assumption is reasonable from the aspect of cooling-flow models; however, the gas associated with the central nebula may not have originated from the cooling flow (Baum 1992), and the radio sources in large cooling flows with otherwise similar X-ray properties are not always embedded in nebular emission and blue light. An example is the Hydra A CDG, whose powerful radio jets emerge nearly perpendicular to the major axis of a blue, circumnuclear disk (McNamara 1995). The disk is confined to the dimensions of a similar disk of line-emitting gas (Baum et al. 1988; Hansen, Jørgensen, & Nørgaard-Nielsen 1995). There are no indications that its relatively powerful radio source has interacted significantly with the emission-line gas, and there are no blue features associated with the radio jets and lobes. Based on the similarly large hot gas densities and cooling rates in the Hydra A and A1795 clusters, De Young's model would presumably predict lobes of star formation along the radio jets, which is not observed.

Finally, the possibility remains that the expanding radio lobes were simply deflected by preexisting sites of star formation giving the correlation that is seen (McNamara et al. 1996; Pinkney et al. 1996).

4.3. *An Age Problem?*

The radio-triggered star formation model requires a lobe population age of $\sim 10^7$ yr, similar to the lower limit on the radio age (see § 4.2). Two studies of A1795's central spectral energy distribution covering the wavelength range $\lambda\lambda 3500$–5500 (McNamara & O'Connell 1989; Allen 1995) concluded that very young O and B stars were present, which would be consistent with the young ages predicted by radio-triggered star formation models. A third study based on large-aperture ($10'' \times 20''$) spectrophotometry extending into the population-sensitive ultraviolet using the *International Ultraviolet Explorer* (Crawford & Fabian 1993) concluded that the earliest stellar type present in the center of the galaxy corresponds to B5, which would imply a population of $\sim(4$–$10) \times 10^7$ yr. Such an advanced age would exceed the dispersal timescale by several times and would be inconsistent with radio-triggered star formation, unless the initial mass function is truncated above $\sim$B5, or the youngest stellar type has been misestimated as a result of extinction by dust (McNamara et al. 1996; Pinkney et al. 1996). Ultraviolet imaging and spectroscopy of the lobes using the *Hubble Space Telescope* will provide a definitive answer.

4.4. *The Alignment Effect*

The proximity of the A1795 CDG affords study of the alignment properties and host galaxy in detail, and its discovery bears directly on the question of the redshift dependence of the alignment effect. McCarthy & van Breugel (1989) compiled data showing that the alignment effect becomes significant in powerful radio galaxies with redshifts $z \gtrsim 0.6$. It is not clear, however, whether the alignment effect is indeed absent at lower redshifts (later epochs), or whether the effect in nearby galaxies has been overlooked to selection, such as the tendency to observe low-redshift galaxies in red rest-frame passbands (see, e.g., McCarthy 1993). The alignments in the A1795 and A2597 clusters ($z = 0.083$; MO93; Sarazin et al. 1995) were found in a U-band survey of ≈ 20 central cluster galaxies selected on the basis of their being in X-ray–luminous, cooling-flow clusters within a redshift of $z < 0.1$ (McNamara & O'Connell 1992; MO93). The lobes would have been missed had the survey been restricted to the R or I bands where the galaxies appear to be normal in ground-based images. These considerations would favor the conjecture that the alignment effect occurs over a wider range of epochs than had been thought, if the alignments in the lower power F-R I radio sources have a similar origin to those seen in F-R II radio galaxies at large redshifts.

The apparently stellar nature of the blue lobes in A1795 contrasts with the increasing evidence for a nonthermal (scattering) origin for the radio-optical alignments in the more radio-luminous F-R II galaxies at large redshifts (see references in § 1). However, the extent to which both stellar and nonstellar light contribute to the alignments, both within and among sources, is not clear. Let us assume for the moment that the alignment in A1795 and those in distant radio galaxies have a similar physical origin while differing in the ratio of scattered to stellar light. Then, a radio luminosity dependence on this ratio would be suggested (F-R I sources having a lower fraction of aligned scattered light). Larger samples and additional polarimetric and imaging studies of nearby F-R I radio galaxies, especially those where there are possible alignments (e.g., van Breugel et al. 1985; van Breugel & Dey 1993), will be necessary to address this possibility.

5. SUMMARY

We have found a 3 σ upper limit to the degree of polarization of the light emitted from A1795's blue optical lobes to be less than 7%. This limit renders improbable scattered light or a synchrotron origin for the optical lobes. The lobes are probably composed of blue stars associated with recent star formation. The vigorous star formation in the optical lobes may have been triggered by the expanding radio lobes.

The A1795 CDG at a redshift of $z = 0.063$ may be the nearest case of the alignment effect, although scaled down by roughly an order of magnitude in size and luminosity compared to high-redshift radio galaxies. The absence of polarized light associated with its F-R I radio source contrasts with the significantly polarized ($P > 5\%$) blue and rest-frame ultraviolet continuum found in several high-redshift and nearby ($z \lesssim 0.1$; Cimatti & di Serego Alighieri 1995) F-R II radio galaxies. Our limits do not support the conjecture that A1795's blue optical lobes are scattered light from an obscured, highly inclined BL Lac object or blazar nucleus. If the alignments in A1795 and in the high-redshift radio galaxies are of similar origin, our result would suggest that the ratio of polarized light to stellar light in the aligned component may be a function of radio power.

B. R. M. gratefully acknowledges conversations with Thijs van der Hulst, Mark Birkinshaw, Dave De Young, Bob O'Connell, Glen Mackie, and the referee, Stefi Baum. B. T. J. acknowledges support from Hubble Fellowship HF-1045.01-93A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-2655. C. L. S. was supported in part by NASA Astrophysical Theory Program grant NAGW-2376 and *ROSAT* grant NAG 5-1891. B. R. M. was supported by grant NAS 8-39073 to the Smithsonian Astrophysical Observatory.

REFERENCES

Allen, S. W. 1995, MNRAS, 276, 947
Baum, S. A. 1992, in Clusters and Superclusters of Galaxies, ed. A. C. Fabian (Dordrecht: Kluwer), 171
Baum, S. A., Heckman, T., Bridle, A., van Breugel, W., & Miley, G. 1988, ApJS, 68, 643
Begelman, M. C., & Cioffi, D. F. 1989, ApJ, 345, L21
Bohren, C. F., & Huffman, D. R. 1983, Absorption and Scatterimg of Light by Small Particles (New York: Wiley)
Chambers, K. C., Miley, G. K., & van Breugel, W. 1987, Nature, 329, 604
Cimatti, A., & di Serego Alighieri, S. 1995, MNRAS, 273, L7
Cowie, L. L., Hu, E. M., Jenkins, E. B., & York, D. G. 1983, ApJ, 272, 29
Crawford, C. S., & Fabian, A. C. 1993, MNRAS, 265, 431
Daly, R. A. 1990, ApJ, 355, 416
———. 1992, ApJ, 386, L9
Dey, A., Cimatti, A., van Breugel, W., Antonucci, R., & Spinrad, H. 1996, ApJ, 465, 157
De Young, D. S. 1989, ApJ, 342, L59
———. 1995, ApJ, 446, 521
di Serego Alighieri, S., Cimatti, A., & Fosbury, R. A. E. 1993, ApJ, 404, 584
di Serego Alighieri, S., Fosbury, R. A. E., Quinn, P. J., & Tadhunter, C. N. 1989, Nature, 341, 307
Edge, A. C., Stewart, G. C., & Fabian, A. C. 1992, MNRAS, 258, 177
Elston, R., & Maloney, P. 1995, preprint
Fabian, A. C. 1989, MNRAS, 238, 41P
———. 1994, ARA&A, 32, 277
Ge, J. P., & Owen, F. N. 1993, AJ, 105, 778
Hansen, L., Jørgensen, H. E., & Nørgaard-Nielsen, H. U. 1995, A&A, 297, 13 (erratum 301, 640)
Heckman, T. M., Baum, S. A., van Breugel, W. J. M., & McCarthy, P. J. 1989, ApJ, 338, 48
Jannuzi, B. T. 1994, in IAU Symp. 159, Multi-Wavelength Continuum Emission of AGN, ed. T. J.-L. Courvoisier & A. Blecha (Dordrecht: Kluwer), 470
Jannuzi, B. T., & Elston, R. 1991, ApJ, 366, L69
———. 1996, ApJ, submitted
Jannuzi, B. T., Elston, R., Schmidt, G. D., Smith, P. S., & Stockman, H. S. 1995, ApJ, 454, L111
Johnstone, R. M., Naylor, T., & Fabian, A. C. 1991, MNRAS, 248, 18P
McCarthy, P. J. 1993, ARA&A, 31, 639
McCarthy, P. J., & van Breugel, W. J. M. 1989, in Epoch of Galaxy Formation, ed. C. S. Frenk et al. (Dordrecht: Kluwer), 57
McCarthy, P. J., van Breugel, W. J. M., Spinrad, H., & Djorgovski, S. 1987, ApJ, 321, L29
McNamara, B. R. 1995, ApJ, 443, 77
McNamara, B. R., & O'Connell, R. W. 1989, AJ, 98, 2018
———. 1992, ApJ, 393, 579
———. 1993, AJ, 105, 417 (MO93)
McNamara, B. R., Wise, M., Sarazin, C. L., Jannuzi, B. T., & Elston, R. 1996, ApJ, 466, L9
Murphy, B. W., & Chernoff, D. F., 1993, ApJ, 418, 60
Nørgaard-Nielsen, H. U., Goudfrooij, P., Jørgensen, H. E., & Hansen, L. 1993, A&A, 279, 61
O'Dea, C. P., Gallimore, J. F., & Baum, S. A. 1995, AJ, 109, 26
Padovani, P., & Urry, C. M. 1990, ApJ, 356, 75
Pinkney, J., et al. 1996, ApJ, 468, L13
Postman, M., & Lauer, T. R. 1995, ApJ, 440, 28
Rees, M. J. 1989, MNRAS, 239, 1P
Rigler, M. A., Lilly, S. J., Stockton, A., Hammer, F., & Le Fèvre, O. 1992, ApJ, 385, 61
Romanishin, W. 1987, ApJ, 323, L113
Sarazin, C. L. 1996, in preparation
Sarazin, C. L., Burns, J. O., Roettiger, K., & McNamara, B. R. 1995, ApJ, 447, 559
Sarazin, C. L., & Wise, M. W. 1993, ApJ, 411, 55
Scarrott, S. M., Rolph, C. D., & Tadhunter, C. N. 1990, MNRAS, 243, 5P
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Tadhunter, C. N., Scarrott, S. M., Draper, P., & Rolph, C. 1989, MNRAS, 256, 53
van Breugel, W., & Dey, A. 1993, ApJ, 414, 563
van Breugel, W., Filippenko, A. V., Heckman, T., & Miley, G. 1985, ApJ, 293, 83
van Breugel, W., Heckman, T., & Miley, G. 1984, ApJ, 276, 79
White, R. E., & Sarazin, C. L. 1987a, ApJ, 318, 612
———. 1987b, ApJ, 318, 629
Zellner, B. 1973, in IAU Symp. 52, Interstellar Dust and Related Topics, ed. J. M. Greenberg & H. C. van de Hulst (Dordrecht: Reidel), 109