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1E 0116.3−0116: A PECULIAR, X-RAY–BRIGHT EARLY-TYPE GALAXY[1]

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ABSTRACT

1E 0116.3−0116 is an extended X-ray source with a luminosity (0.3–3.5 keV) of 1.1×10^{43} ergs s^{-1}. The identification of this MSS source with an E3 galaxy belonging to a sparse group of galaxies makes this object quite peculiar. The X-ray emitting gas has a radius of $\sim 4'$ ($\sim$300 kpc, $H_0 = 50$ km s^{-1} Mpc^{-1}) and a temperature greater than 2 keV. The optical spectrum of the galaxy shows no signs of nuclear activity, and its radio emission is consistent with its being an early-type galaxy. If the gas is isothermal, its surface brightness profile yields a total mass greater than 10^{13} $M_{\odot}$. In optical and X-ray luminosity and mass-to-light ratio, this galaxy most resembles M87. Although the cooling time of the gas is on average of the same order as the Hubble time, we cannot exclude a cooling flow in the inner regions of the galaxy.

Subject headings: galaxies: individual (1E 0116.3−0116) — galaxies: X-rays

I. INTRODUCTION

Dynamical studies of clusters of galaxies and of single galaxies have shown that dark matter is a gravitationally important constituent of the universe. While there is evidence that the mass-to-light ratio increases going from isolated galaxies to rich clusters, there is also evidence that this ratio does not change with the scale of the object when dark matter is included. The total mass of large clusters is on the order of 1×10^{15} $M_{\odot}$, $\sim$10 times more than their luminous (at all wavelengths) mass. This ratio seems to hold also for small groups of galaxies, as well as for single galaxies, for which the total mass estimates are on the order of 1×10^{12} $M_{\odot}$ (Blumenthal *et al.* 1984).

In the last few years, several authors have estimated the total mass of galaxies by interpreting the detected diffuse X-ray emission associated with many galaxies as due to hot gas (Fabricant, Lecar, and Gorenstein 1980; Bechtold *et al.* 1983; Forman, Jones, and Tucker 1985). Galaxies in Abell 1367 and in the outskirts of rich clusters have been found to possess hot coronae, implying total masses on the order of 1×10^{12} $M_{\odot}$, while in the case of M87, the total mass implied by the diffuse X-ray emission exceeds 1×10^{13} $M_{\odot}$. The large mass measured in the case of M87 is generally explained as due to the fact that this galaxy lies almost at rest at the center of the Virgo Cluster.

As a general point, the X-ray luminosity of early-type galaxies is correlated with their blue luminosity (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985), which suggests that the hot gas stored in the halos is produced by stellar evolution.

In this paper we present the case of an early-type galaxy with extended X-ray emission indicating a total mass comparable to that of M87. The X-ray luminosity, which is of the same order as that of the 3CR galaxies studied by Fabbiano *et al.* (1984), is far above the value predicted on the basis of the optical luminosity. The optical spectrum does not show signs of nuclear activity. The galaxy is a member of a poor group of galaxies.

Throughout this paper we adopt $H_0 = 50$ km s^{-1} Mpc^{-1}.

II. THE DATA

1E 0116.3−0116 is one of the 3 sources identified with a "normal" galaxy in the Medium Sensitivity Survey (Gioia *et al.* 1984; for a description of the survey, see also Maccacaro *et al.* 1982; Stocke *et al.* 1983). The galaxy is listed both in the *Uppsala General Catalogue of Galaxies* (Nilson 1973) and in the *Catalogue of Galaxies and of Clusters of Galaxies* (Zwicky, Karpowicz, and Kowal 1965). Its V-magnitude integrated over the central 10″ is $V = 15.59$. It appears to lie on the outskirts of Abell 194, but at $z = 0.045$ it is not associated with the cluster, which is at the much smaller redshift of 0.0186 (Chincarini and Rood 1977). The optical field of 1E 0116.3−0116 is shown in Figure 1 (Plate 1), a reproduction of the Palomar Observatory Sky Survey (POSS) E plate, and is only lightly populated with galaxies. A number of galaxies have been marked: object No. 1 is the brightest object in the field and lies within the X-ray error circle. It is a weak radio source, having been detected with the Very Large Array (VLA) telescope at a flux level of 1.1 mJy at 6 cm (Gioia *et al.* 1983). The radio source is unresolved, and its position coincides with the optical position of the galaxy. According to the radio luminosity function of normal elliptical galaxies obtained by Gavazzi and Jaffe (1986), a galaxy of the same Zwicky optical magnitude as 1E 0116.3−0116 has a probability between 10% and 20% of being as powerful in radio, and in this respect 1E 0116.3−0116 can be considered quite normal. On the other hand, a normal elliptical galaxy of that radio power is not expected to be so luminous in the X-rays. In fact, in a plot of log l_x versus log l_R

[1] Research reported here used the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

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PLATE 1

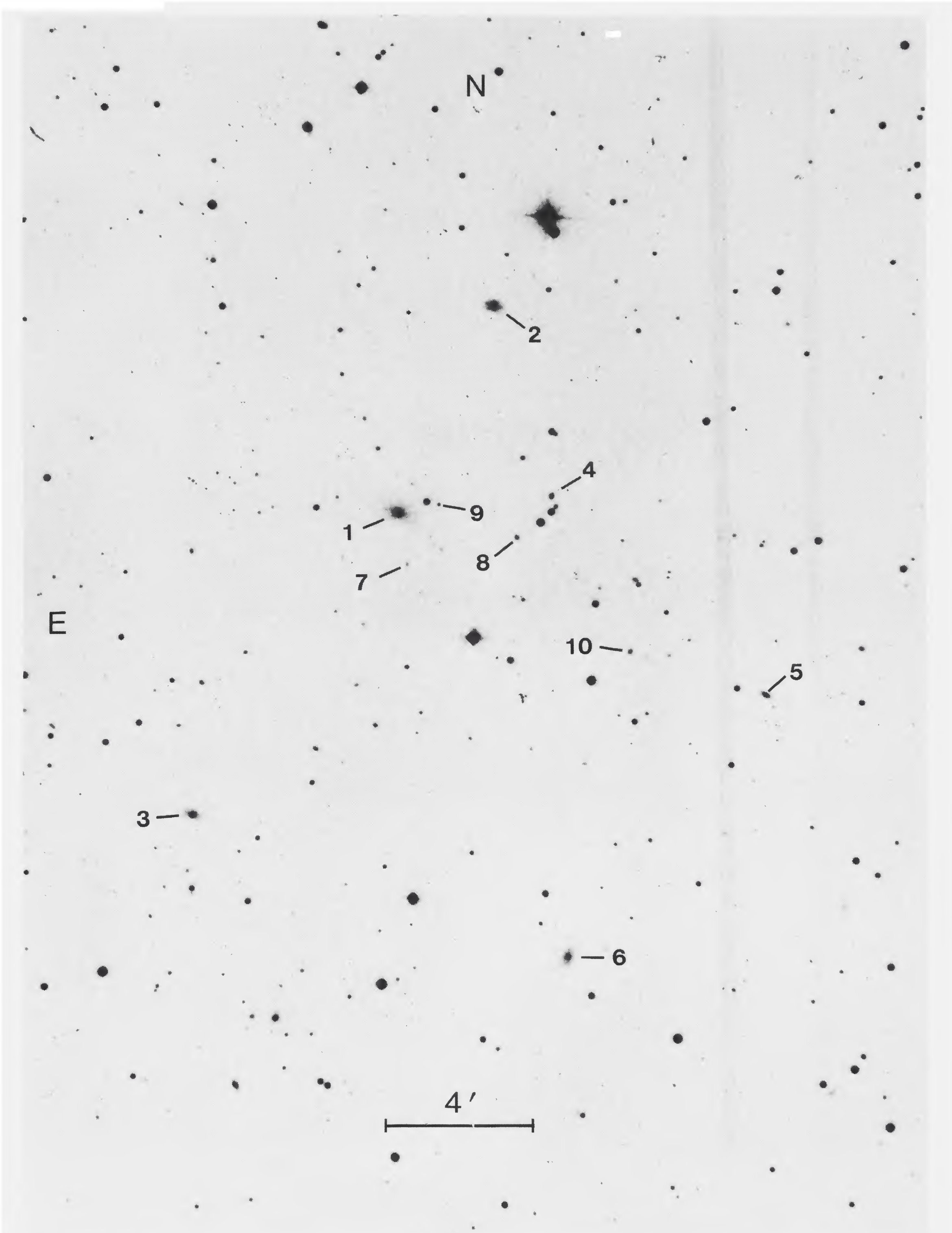

FIG. 1.—Enlargement of the red plate of the POSS showing the field of 1E 0116.3−0116 (marked No. 1). Numbers identify other galaxies in the field (see Table 1).

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TABLE 1

RADIAL VELOCITIES OF GALAXIES IN THE FIELD OF 1E 0116.3−0116

Galaxy No.	Velocity (km s^{-1})	Comment
1	13,556 ± 32	1E 0116.3−0116
2	...	Foreground
3	14,213 ± 46	
4	14,168 ± 60	
5	...	No spectrum obtained
6	14,042 ± 38	
7	...	No spectrum obtained
8	...	No spectrum obtained
9	13,500 ± 300	
10	...	No spectrum obtained
Mean	13,900 ± 340	

(see Fig. 3 of Fabbiano *et al.* 1987), 1E 0116.3−0116 falls outside the region of early-type galaxies, having an X-ray luminosity typical of radio galaxies ~100 times more luminous at radio wavelengths.

a) Optical Spectroscopy

We have obtained redshifts for six of the galaxies marked in Figure 1 and all but object No. 2 (which is a foreground galaxy) are at similar redshifts (see Table 1). Based on these observations, the group surrounding 1E 0116.3−0116 is quite sparse, with a total of only four other bright galaxies projected within 1 Mpc of the X-ray emitter. The modest radial velocity dispersion of ~340 km s^{-1} does not suggest the presence of an inordinate amount of dark matter, and it is quite comparable to other small groups of similar size (Faber and Gallagher 1979).

Figure 2 shows the optical spectrum of galaxy No. 1 obtained at the Multiple Mirror Telescope (MMT) using the Faint Object Grism Spectrograph (FOGS; see Geary, Huchra, and Latham 1986). This spectrum is shown in actual counts and has not been flux-calibrated. Mg *b* and Na D absorptions are clearly visible. These lines yield a velocity of 13,556 ± 32 km s^{-1}, corresponding to a redshift $z = 0.0452$. We also obtained a bluer spectrum extending to 4000 Å, showing Ca II H and K absorption at the expected wavelengths. Neither of these spectra shows any evidence for a source of light other than stars, nor for the presence of emission lines. Unfortunately, the blue spectrum does not extend to [O II] λ3727, so we are unable to say whether this emission line is present. We can, however, set a limit on the equivalent width of Hα of $W(\mathrm{H}\alpha) < 2$ Å (3 σ), despite its position on the edge of the atmospheric *B*-band.

b) CCD Imaging

CCD images were obtained as 10 minute exposures with *B*, *V*, and *R* filters. To study the brightness profile with maximum signal-to-noise ratio, the *V* and *R* frames were co-added after a small shift to register the images correctly. Elliptical isophotes of variable ellipticity and major axis angle were fitted to the optical image. No significant rotation of the major axis was found to a radius of 30″, and beyond this radius simple ellipses were fitted because of the low signal level.

The radial brightness profile so generated was fitted by least squares to a de Vaucouleurs law, as shown in Figure 3. The fitting was done with a software system written by Dr. S. Kent,

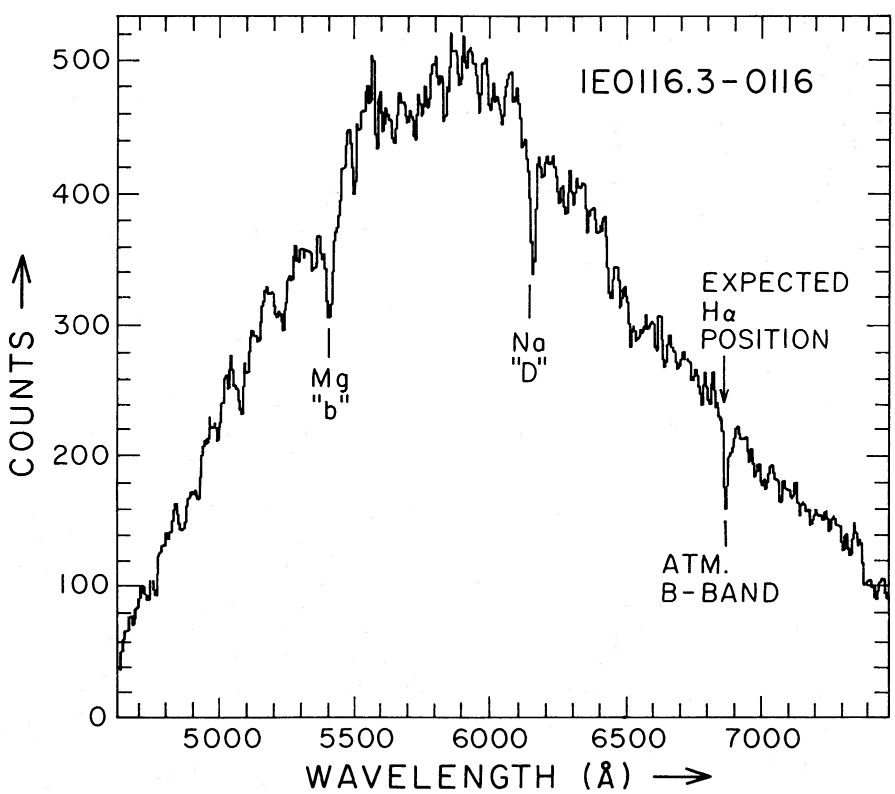

FIG. 2.—Optical spectrum of the galaxy identified with 1E 0116.3−0116, taken at the MMT with the FOGS

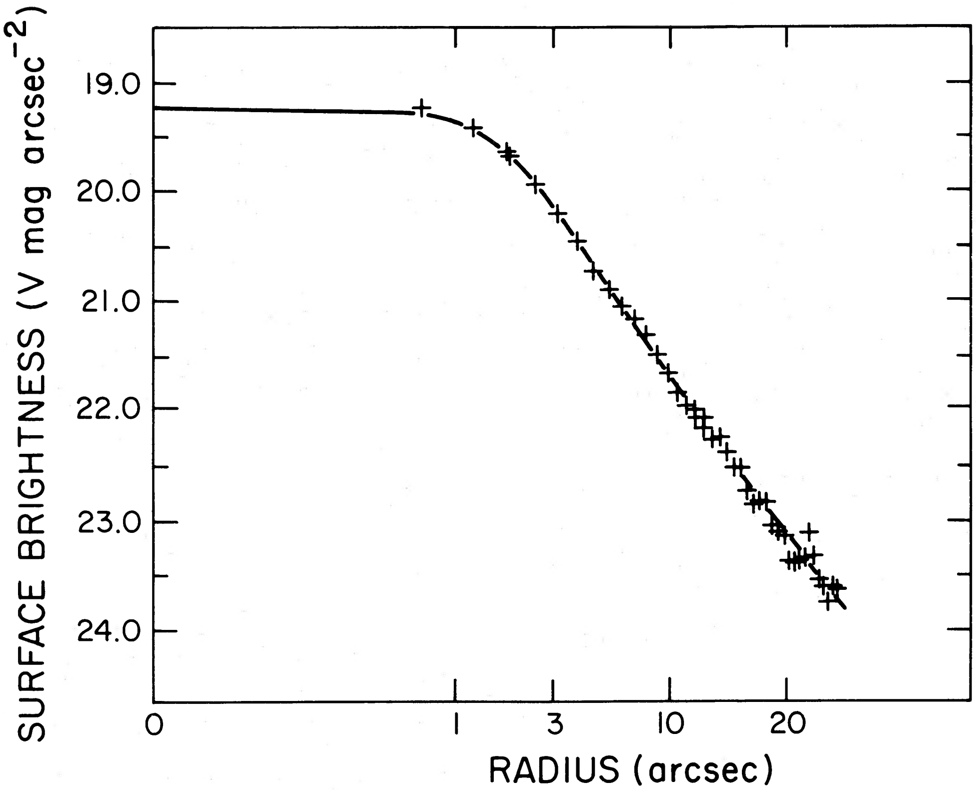

FIG. 3.—Optical surface brightness profile of the galaxy identified with 1E 0116.3−0116. Out to a radius of ~30″, the profile is well fitted by de Vaucouleurs' $r^{1/4}$ law.

and the excellent fit shows that the galaxy is an early-type system. There may be evidence of a slight brightening of the profile between 6″ and 10″ which could indicate the presence of a faint disk, but no significant change in eccentricity or major axis angle is found for this region, and we attribute the effect to noise. Corwin (Chincarini and Rood 1977) classified the galaxy SB0 from inspection of the POSS plates. Because the radial brightness profile is so well fitted by a de Vaucouleurs profile, we hereafter refer to 1E 0116.3−0116 as an elliptical galaxy, although the presence of a small disk is by no means excluded. Corresponding to the fitted eccentricity of 0.62, the galaxy morphological type is E3.

c) X-Ray

1E 0116.3−0116 has been detected as a faint serendipitous X-ray source. The small number of detected photons (~250) and the off-center position in the detector prevent an accurate spectral analysis. However, assuming a Raymond-Smith spectrum with low-energy cutoff due to an amount of hydrogen along the line of sight near the value of 4×10^{20} atoms cm^{-2} (Stark *et al.* 1986), constraints on the gas temperature can be set. The measured IPC pulse height distribution is incompatible with temperatures below 2 keV, while no meaningful upper limits can be obtained. In what follows, unless otherwise specified, we adopt a temperature of 4 keV. To analyze the spatial extent of the source, net counts have been obtained in circular annuli of increasing radius with a step of 0′.8 by subtracting the local background (i.e., the estimated background at the position of the source computed using the IPC background map model recently made available as part of Revision 1 processing of the data; see Harnden *et al.* 1984 for details). The surface brightness profile thus obtained has been compared with a simulated point source profile for the same position, instrumental gain, energy range, and spectral type. The integral distributions are shown in Figure 4. A Kolmogorov-Smirnov test on the measured and simulated distributions of counts in the annuli yields a χ^2 of 144 (2 degrees of freedom), and therefore we can reject the hypothesis that the point source radial distribution represents the data at a confidence level of greater than 99.9%. In the following, we consider 1E 0116.3−0116 as an extended X-ray source, with a radius of 4′ (beyond this radius, the statistical significance of each bin in the surface brightness profile drops below 2.5 σ; see Fig. 5).

The previously published X-ray flux of 1E 0116.3−0116 (Gioia *et al.* 1984) was computed under the assumption that the source was pointlike. The new instrument calibration and data reduction procedure (Rev. 1 processing) and the extended nature of the source prompted us to recompute its flux. Net counts within a 4′ radius circle were corrected for vignetting and mirror scattering effects and multiplied by a conversion factor obtained assuming a Raymond-Smith spectrum with a temperature of 4 keV. The ensuing luminosity between 0.3 and 3.5 keV is 1.1×10^{43} ergs s^{-1}.

Is the extended X-ray emission associated with galaxy No. 1 or with the intergalactic medium of the group of galaxies? As Forman and Jones (1982) have shown, the X-ray emitting gas in clusters presents distinct morphologies depending on whether the cluster is dominated by a single centrally located galaxy or not. If 1E 0116.3−0116 has an X-ray morphology similar to Abell 85 or Abell 2199, which have central dominant galaxies, we would detect only the central peaked emission. However, the optical morphology of the group of galaxies we

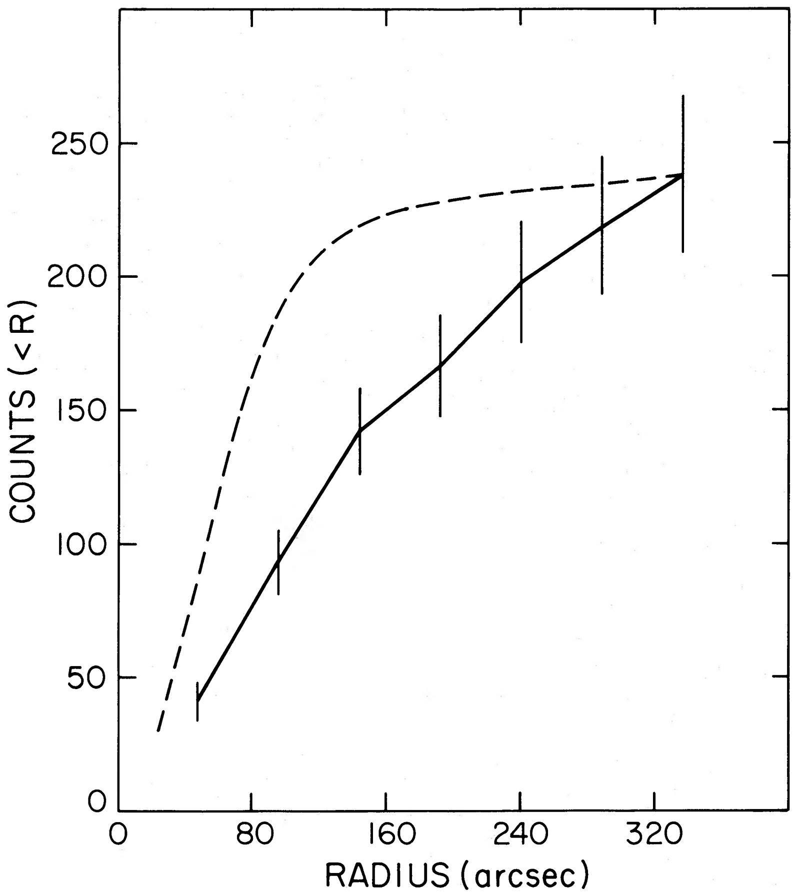

FIG. 4.—Comparison of the distribution of X-ray counts of 1E 0116.3−0116 inside radius R (*solid line*) and of a simulated point source (*dashed line*)

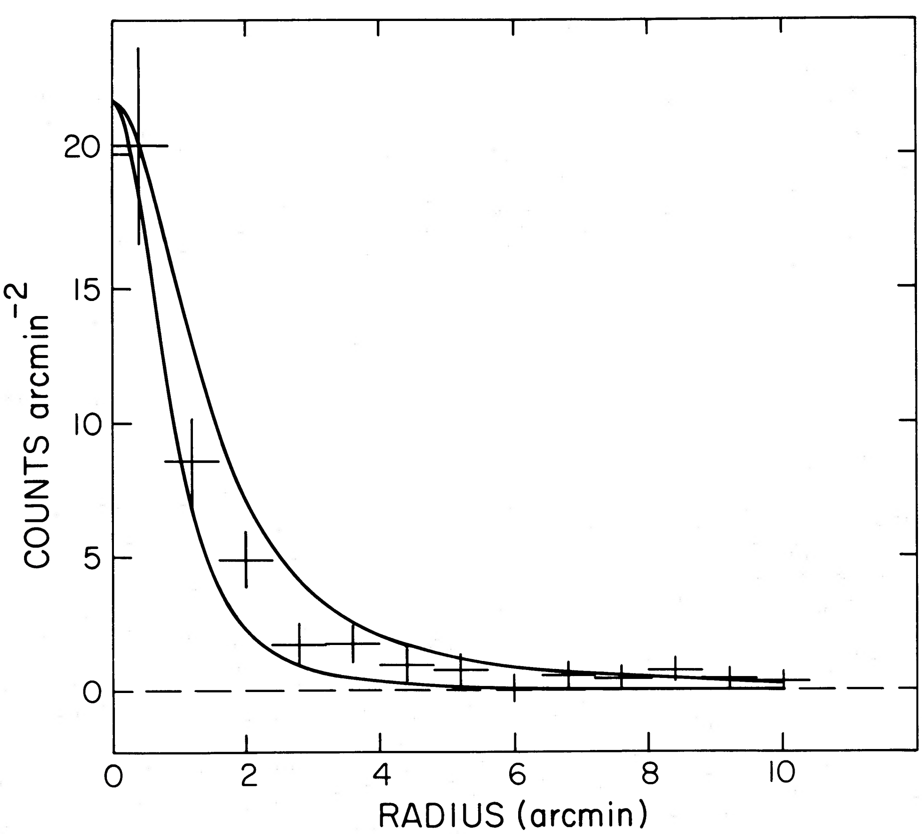

FIG. 5.—X-ray surface brightness profile of 1E 0116.3−0116. The solid lines represent the function $S(r) = S(0)[1 + (r/a)^2]^{-n}$ with $S(0) = 22$, core radius $a = 1'.6$, and $n = 1.2$ (*upper curve*) and core radius $a = 1'.2$ and $n = 1.7$ (*lower curve*).

are concerned with shows four rather bright galaxies (No. 1, which is the brightest; Nos. 3, 5, and 6, see Fig. 1), with galaxy No. 1 at the northern edge. As far as we know, from such a projected distribution of galaxies we would not expect the X-ray morphology and position of the X-ray source we have unless galaxy No. 1 were a cD or at least a D galaxy. It is true that the X-ray luminosity of 1E 0116.3−0116 is well within the range of poor clusters with central dominant galaxies (Kriss, Cioffi, and Canizares 1983), but galaxy No. 1 lacks many of the primary and secondary attributes of a cD or D galaxy (Dressler 1984). We cannot *a priori* exclude that it is surrounded by a stellar envelope, because the dynamic range of our optical imaging is not large enough (see, for instance, the study of cD galaxies performed by Schombert 1986), but its diameter on the POSS print is only a couple of times larger than the diameters of galaxies Nos. 3, 5, and 6, and its absolute V-magnitude is at the dim edge of the distribution of cD absolute magnitudes (Hoessel 1980). The overall properties of groups of galaxies can be described by the richness parameter and by the central galaxy density N_0 (Bahcall 1980). The galaxy counts in the field of 1E 0116.3−0116 yield a richness class of −1, and $N_0 = 3$ galaxies in a 0.5 Mpc radius around galaxy No. 1. That the central galaxy density should be so low is at once apparent if one compares our Figure 1 with the plates of some of the groups published by Albert, White, and Morgan (1977), most of which are X-ray sources (Kriss, Cioffi, and Canizares 1983), but where many bright galaxies are generally found within a few diameters of the dominant galaxy. As a consequence of the very low central galaxy density, the well-established correlation between the X-ray luminosity of clusters and groups of galaxies and N_0 (Bahcall 1980) predicts a luminosity of 5×10^{40} ergs s^{-1} between 0.3 and 3.5 keV for the group of 1E 0116.3−0116, more than two orders of magnitude below the measured luminosity. In order to detect the X-ray emission from this group of galaxies, the mass distribution has to be such that galaxy No. 1 is in a deep potential well. Because of the low central density and the way the bright galaxies are distributed in this group, the gravitational potential described by the X-rays must be due to galaxy No. 1 itself. This set of considerations has convinced us that the extended X-ray emission of 1E 0116.3−0116 is associated with galaxy No. 1 and not with the general intergalactic medium of the sparse group.

Table 2 summarizes the observed properties of 1E 0116.3−0116.

TABLE 2

RADIO, OPTICAL AND X-RAY PROPERTIES OF 1E 0116.3−0116

Parameter	Value
Radio	
Flux (6 cm)	1.1 mJy
Luminosity (6 cm)	9.5×10^{28} ergs s^{-1} Hz^{-1}
Optical	
z	0.0452
V	15.59
$B-V$	1.14
$V-R$	0.85
Absolute blue magnitude M	−20.47
Total V_{mag} from model fit	13.0
Central surface brightness	15.3 V_{mag} arcsec^{-2}
de Vaucouleurs R_{eff}	27″
Major axis angle	112° west of north
Eccentricity	0.62
X-Ray	
Flux (0.3–3.5 keV)	1.3×10^{-12} ergs cm^{-2} s^{-1}
Luminosity (0.3–3.5 keV)	1.1×10^{43} ergs s^{-1}
Luminosity (2 keV)	1.2×10^{25} ergs s^{-1} Hz^{-1}

III. DISCUSSION

The radial surface brightness profile of Figure 5 can be fitted with an expression of the type

$$S(r) = S(0)[1 + (r/a)^2]^{-n} ,$$

which, under the hypothesis that the X-ray gas is in hydrostatic equilibrium, allows us to derive the gravitating mass as a function of radius r (Fabricant, Lecar, and Gorenstein 1980). We have not attempted a formal parameter estimation because of our poor statistics, but the data are well represented for core radii a between 1′.2 and 1′.6 and indices n between 1.7 and 1.2 (corresponding to the parameter p of the gas density [Fabricant and Gorenstein 1983] between 1.1 and 0.85, if the gas is isothermal). Uncertainties of this order introduce an uncertainty of only 20% in the mass estimation. Assuming the lower limit for the temperature of the X-ray gas (2 keV), and that no temperature gradient is present, we can then calculate the total mass of the galaxy, i.e., the mass inside $r_{max} = 4' = 290$ kpc. We obtain $3.7 \times 10^{13}\ M_{\odot}$, very similar to the mass of M87 measured by Fabricant and Gorenstein (1983), and one order of magnitude higher than the total masses of the galaxies in the sample of Forman, Jones, and Tucker (1985). The total mass scales linearly with the gas temperature, and since our data are incompatible with temperatures below 2 keV, the measured mass cannot be significantly smaller. Furthermore, as Fabian *et al.* (1986) have shown, the mass computed assuming an average temperature with no gradient is lower than the total gravitational binding mass present, provided the gas is in hydrostatic equilibrium. A lower limit to the total mass can be obtained if the gas follows an adiabat, and this is $6.8 \times 10^{13}\ M_{\odot}$. The mass of the X-ray gas is $1.4 \times 10^{12}\ M_{\odot}$. The X-ray luminosity of this gas is so high that the primary heating process can only be gravitational (see Canizares, Fabbiano, and Trinchieri 1987). A cooling flow would then be expected, as discussed by Nulsen, Stewart, and Fabian (1984). Our data can give us only average properties, and assuming the lower limit for the gas temperature of 2 keV, the average radiative cooling time is 3.6×10^{10} yr, comparable to the Hubble time. However, this does not exclude the presence of a cooling flow in the inner parts of the galaxy.

IV. CONCLUSIONS

1E 0116.3−0116 has an X-ray luminosity of 1.1×10^{43} ergs s^{-1}, far in excess of what is expected on the basis of the optical and radio luminosity of the elliptical galaxy with which it has been identified. The X-ray emission is extended, and the total binding gravitational mass is greater than $10^{13}\ M_{\odot}$, which implies a mass-to-light ratio on the order of 140 in solar units. This galaxy must therefore possess a significant amount of dark matter. From the point of view of mass and mass-to-light ratio, the object which most closely resembles 1E 0116.3−0116 is M87. To push the comparison further deeper optical observations would be needed, but in any case the two objects are found in quite different environments, i.e., the center of the Virgo Cluster in the case of M87 and a poor, sparse group of galaxies in the case of 1E 0116.3−0116.

Objects like 1E 0116.3−0116 can be found only through X-ray surveys. In the 90 deg^2 of sky covered by the MSS, 1E 0116.3−0116 is the only "normal" galaxy in a galaxy-poor environment with such a high total mass. This prevents an assessment of the frequency of the phenomenon, which can be investigated further only once the identification process of the extension of the MSS (Gioia *et al.* 1986) is completed and when future X-ray all-sky surveys at similar or higher sensitivity limits are conducted.

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