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UGC 7636 AND NGC 4472: TIDAL INTERACTION BETWEEN A STRIPPED DWARF IRREGULAR AND A GIANT ELLIPTICAL GALAXY

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ABSTRACT

We present new B and I CCD and H I observations of the system in the Virgo Cluster composed of the dwarf irregular galaxy UGC 7636 and the giant elliptical galaxy NGC 4472. These observations strongly suggest that both ram-pressure and tidal stripping have occurred in this system. The H I gas between the two galaxies has been stripped from UGC 7636. Its $M(\text{H I})/L_B$ ratio is 0.26 $M_\odot/L_{B\odot}$, in the range observed for dwarf irregulars. Ram-pressure stripping of the H I gas from the dwarf is suggested by the large velocity width ($\Delta v_{50} \sim 110$ km s^{-1}) of the spatially extended H I envelope. The presence of a red optical tidal tail and countertail in the dwarf, with the same colors as the stars in the dwarf's outer regions, as well as a disturbed morphology in the dwarf's inner parts, are evidence for tidal interaction between the two galaxies.

Subject headings: galaxies: evolution — galaxies: individual (UGC 7636, NGC 4472) — galaxies: interactions — galaxies: interstellar matter — galaxies: photometry

1. INTRODUCTION

It is now generally accepted that galaxian properties are the combined results of both genetic processes occurring at birth and environmental processes which modify them subsequently (see the review papers in Thuan, Balkowski, & Van 1993). While the study of the role of nature versus nurture has been mainly focused on bright normal galaxies, environmental influences have also been discussed for dwarf galaxies. For example, it has been proposed that a dwarf irregular (dI) galaxy can evolve into a dwarf elliptical (dE) galaxy by being stripped of its gas (e.g., Faber & Lin 1983). To test this hypothesis, observational efforts have been devoted to the study of dwarf galaxies where the gas removal process has happened or is occurring. Vigroux et al. (1986) find that IC 3475, the prototype of the huge, very low surface brightness dI galaxies, has lost its gas due to ram-pressure stripping by the hot X-ray gas near the core of the Virgo Cluster. Sandage & Hoffman (1991) describe NGC 4286 as a dI which has evolved into a dS0 by losing most of its gas through a supergalactic wind generated by a superluminous star cluster.

In this *Letter* we focus our attention on a dI galaxy, UGC 7636, whose properties have been modified by interaction with its environment by two different physical processes: not only has it lost its gas through ram-pressure stripping, but it has also been tidally perturbed by a nearby massive galaxy. Sancisi, Thonnard, & Ekers (1987), using the Westerbork radio telescope, found H I gas between UGC 7636 and the giant elliptical galaxy NGC 4472, the brightest elliptical galaxy in the Virgo Cluster. The dwarf galaxy, however, was deficient in neutral hydrogen, and it was suggested that the H I gas has been removed from the dwarf either by tidal stripping or by ram-pressure stripping by the hot gaseous halo surrounding NGC 4472 (Forman, Jones, & Tucker 1985).

We examine these suggestions here in the light of new optical and radio 21 cm observations. CCD images with their large dynamic range are necessary to test the tidal stripping hypothesis: first to check the faint suggestion of an optical tail from the dwarf toward NGC 4472 seen on images obtained with photographic plates (Arp 1966), and second to look for the optical countertail expected in a tidal interaction. H I observations using a telescope with a beam large enough to include the whole interacting system and its surroundings were also necessary to measure the total amount of neutral hydrogen and to test the ram-pressure stripping hypothesis. The Westerbork interferometric observations are not sensitive to extended low surface brightness features and provide only a lower limit. All previous single-dish observations were made with the Arecibo telescope, which has a 3'.3 beam size, while the optical extent of the UGC 7636–NGC 4472 system is at least $\gtrsim 8'$. In § 2 we describe the optical and radio observations. In § 3 we discuss a possible scenario for the interaction between the dwarf and the elliptical galaxy in the light of these new observations. We shall adopt throughout a distance of 10 h^{-1} Mpc for the Virgo Cluster, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

2. OBSERVATIONS

2.1. *Optical Imaging*

The observations were obtained on the night of 1991 April 21 with a CCD camera consisting of an Tektronix chip (the "TEK2" chip) installed at the f/7.5 focus of the 2.1 m telescope at Kitt Peak National Observatory under photometric conditions. The chip was 512 × 512 pixels, with an overscan strip of 32 × 512 pixels. The scale was 0".34 pixel^{-1}, giving a field of view of ~2'.9 × 2'.9.

UGC 7636 was imaged through the B and I filters in the KPNO Mould filter system (B [λ_c = 4400 Å, FWHM = 1152 Å] and I [λ_c = 8205 Å, FWHM = 1851 Å]) for a total of 30 minutes in the B and 21 minutes in the I filter. Each observation was broken up into three separate exposures (10 minutes in B and 7 minutes in I) and displaced from each other by ~10". These separate exposures are useful in the subsequent processing for removing bad pixels and cosmic-ray hits. The

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resulting final image size was ~2'.5 × 2'.7. Repeated observations of a number of bright standards from Landolt (1983) were made in order to calibrate the photometry.

Figures 1*a* and 1*b* (Plates L6 and L7) show respectively the processed *B* and *I* frames with the contrast adjusted so as to show the faintest features of UGC 7636. The tidal tail between UGC 7636 and NGC 4472, extending in the southeast-northwest direction, is very evident on both frames. The CCD images also show clearly the presence of a countertail on the opposite side of the dwarf galaxy, extending in the northeast-southwest direction. Detailed comparison of the *B* and *I* frames also reveal an extremely blue patch (indicated by tick marks) lying near the tidal tail: it is clearly visible in the *B* frame, while it is not seen in the *I* frame.

Figures 1*c* and 1*d* (Plates L8 and L9) show the central regions of UGC 7636. These are very disturbed, showing a V-shaped morphology. One feature of particular interest is a thin, narrow arc oriented north-south at the eastern edge of the central parts.

The two-dimensional CCD images were reduced to one-dimensional profiles using the IRAF software package following standard procedures (see Thuan et al. 1992 for a detailed description). One major change in reduction procedure was that a quadratic surface was fitted to the sky background and subtracted (instead of the usual plane surface), in order to remove most of the contribution of the halo of NGC 4472. Ellipses with major and minor axes *a* and *b* were then fitted to the isophotes of the reduced images using the ISOPHOTE routines in the STSDAS software package. The ellipticity, position angle, and center of the ellipses were all allowed to vary for each isophote.

For both the *B* and *I* profiles, the data are best fitted by an exponential law of the form $I = I_0 e^{-\alpha r}$, characteristic of a disk structure, in the radius range $r \lesssim 30''$ (Fig. 2). This is also supported by the *H*-band data of James (1991), who found a good exponential fit out to 20". For $r \gtrsim 30''$ there is a systematic excess of light above the exponential fit, reflecting the presence of the tidal tail and its countertail. The extrapolated *B* central surface brightness is 22.65 mag arcsec^{-2}. Adopting a measured axial ratio $a_{25}/b_{25} = 1.43$, and applying the line-of-sight integration correction, the *B* central surface brightness becomes $\mu_B = 23.04$ mag arcsec^{-2}. Galactic extinction, derived from the H I maps of Burstein & Heiles (1982), was found to be negligible. No correction for internal extinction was applied. The exponential scale lengths were found to be $\alpha^{-1}(B) = 13''.5$ and $\alpha^{-1}(I) = 18''.3$, corresponding respectively to linear sizes of 0.65 and 0.88 h^{-1} kpc.

Integrating the *B* luminosity profile (including the contribution from the tidal tails), we obtain a total apparent magnitude $B_T = 14.87 \pm 0.13$, which corresponds to an absolute magnitude $M_T(B) = -15.13 + 5 \log h$ and a total blue luminosity of $L_T(B) = 1.76 \times 10^8 h^{-2} L_{B\odot}$, adopting $M_{B\odot} = 5.48$. The total blue magnitude is in good agreement with the Zwicky magnitude of $B_T = 14.71$ given in the RC3 (de Vaucouleurs et al. 1991).

The integrated color of the galaxy within the 25 mag arcsec^{-2} isophote is $B-I = 1.37 \pm 0.03$. The color of the tidal tail, integrated over its whole extent, is $B-I = 1.40 \pm 0.04$. The blue patch has a color $B-I = -0.1 \pm 0.2$. The galaxy becomes redder toward its outer parts; the central regions ($r \lesssim 10''$) have $B-I = 1.10 \pm 0.03$, while the color is as red as 1.5 in the outer parts. *UBV* photometry of UGC 7636 by Gallagher & Hunter (1986) gives $B-V = 0.50 \pm 0.04$ and $U-B = 0.08 \pm 0.05$ within an aperture of diameter 30".

2.2. H I *Observations*

The H I cloud between UGC 7636 and NGC 4472 was discovered during a search for neutral hydrogen gas in elliptical galaxies by Kumar & Thonnard (1983). No H I emission was detected at the location of NGC 4472, but a narrow emission feature was seen to the southeast, which was attributed to the dwarf irregular galaxy UGC 7636, 5'.6 from NGC 4472. Sancisi et al. (1987), using the Westerbork radio interferometer, found extended H I lying between UGC 7636 (an optical heliocentric velocity of 276 ± 78 km s^{-1} was measured by Huchra 1992) and NGC 4472 ($v_H = 983$ km s^{-1}; RC3), with a peak intensity of 12 ± 3 mJy. They also reported a detection with the Arecibo telescope (3'.3 beam) at the location of the peak

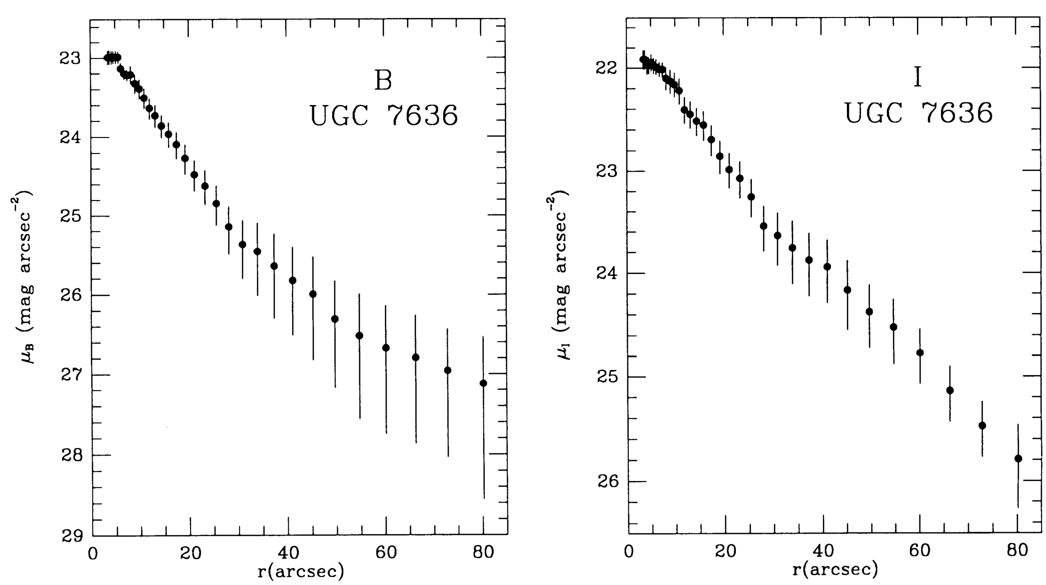

FIG. 2.—*B* (*left*) and *I* (*right*) surface brightness (in mag arcsec^{-2}) profiles along the major axis of UGC 7636 as a function of $r = (ab)^{1/2}$ in arcseconds. A perfect fit to an exponential law $I = I_0 e^{-\alpha r}$ would correspond to a straight line. The error bars have been calculated taking into account photon statistics.

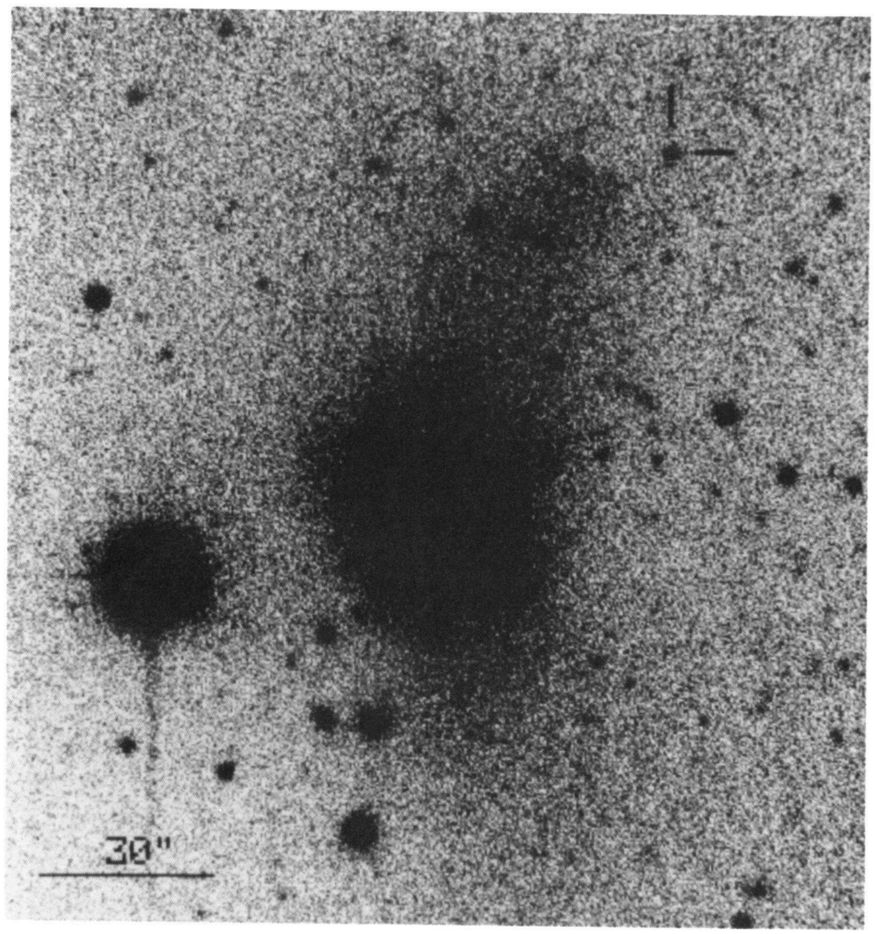

FIG. 1*a*

FIG. 1.—(*a*) A 30 minute *B* CCD frame of the dwarf irregular galaxy UGC 7636 obtained with the KPNO 2.1 m telescope, with the contrast adjusted to show the lowest surface brightness features and with the halo of NGC 4472 removed. The frame covers a region of 2'.5 × 2'.7. North is at the top, and east is to the left. With a distance of 10 h^{-1} Mpc to the Virgo Cluster, 1' corresponds to a linear size of 2.91 h^{-1} kpc. The tail in the southeast-northwest direction and the countertail in the northeast-southwest direction can be seen. Note the very blue patch (*marked*) which is clearly visible in the *B* frame but absent in the *I* frame. (*b*) A 21 minute *I* CCD frame of UGC 7636. (*c*) Same as (*a*), except that the contrast is set to show the V-shaped inner region of UGC 7636. Note the small arc at the left. (*d*) Same as (*c*), but for the *I* frame.

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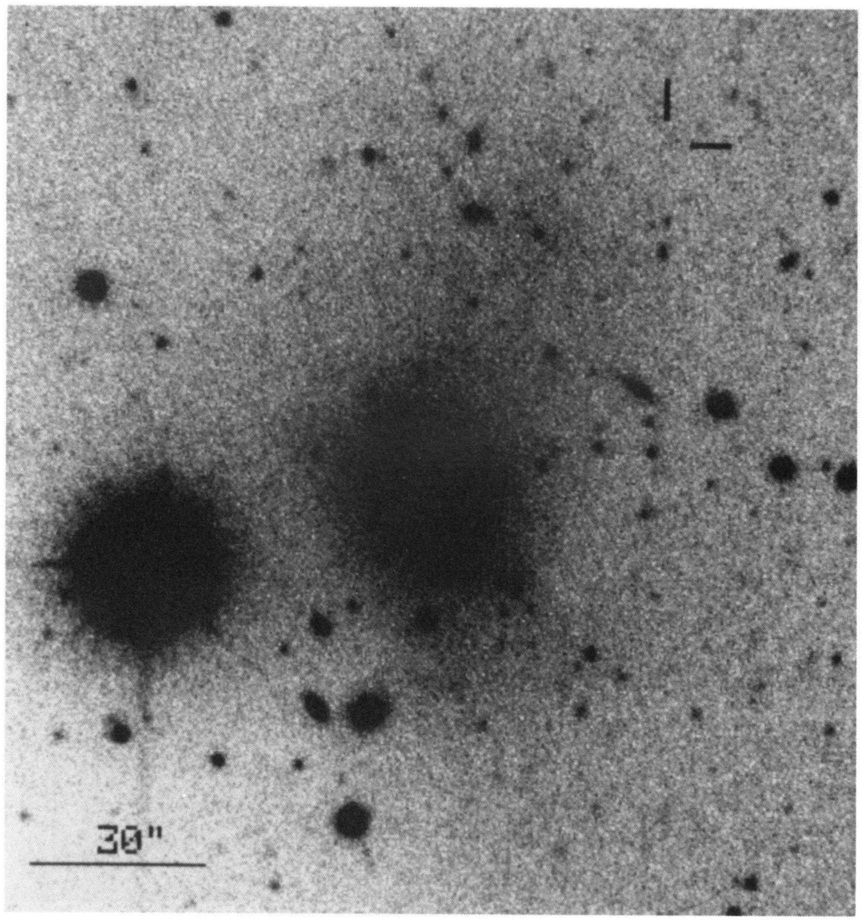

FIG. 1*b*

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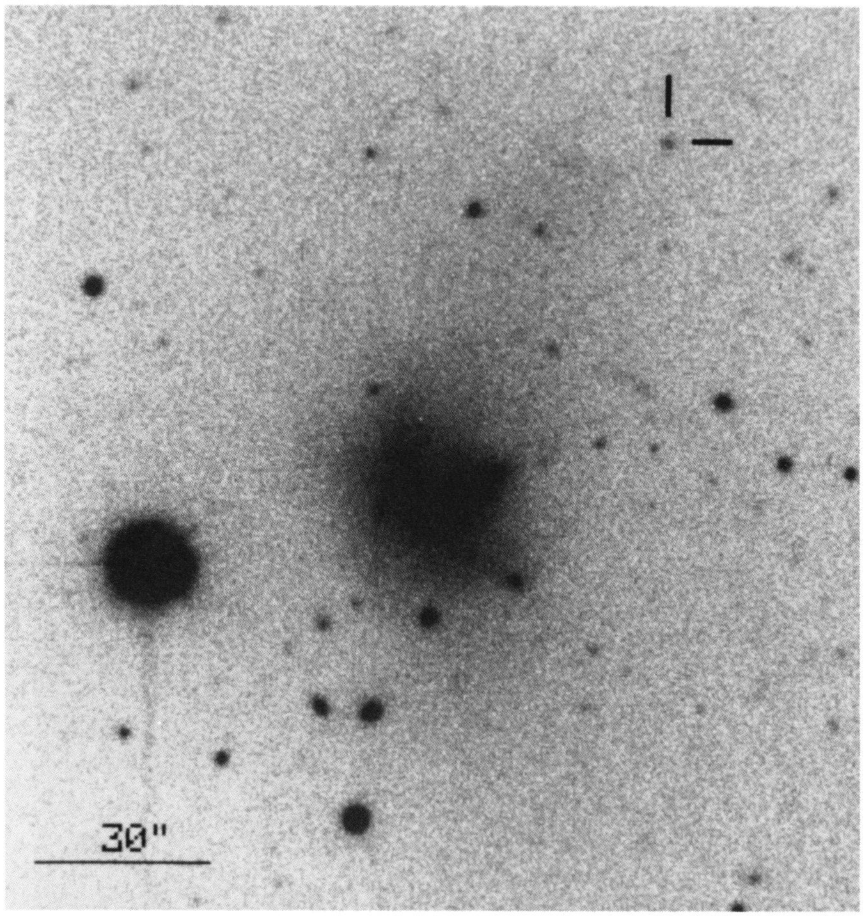

FIG. 1*c*

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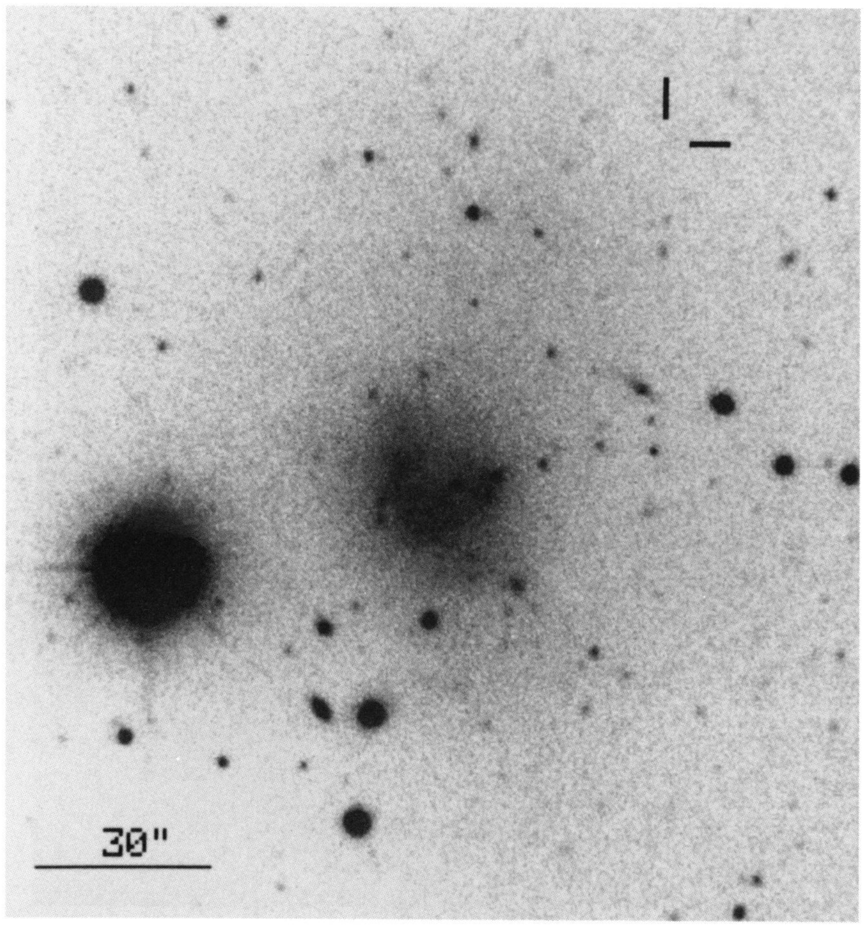

FIG. 1*d*

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intensity of the H I map, approximately halfway between UGC 7636 and NGC 4472. The detected H I emission feature has a central heliocentric velocity $v_H = 472$ km s^{-1}, a full velocity width at half-power $\Delta v_{50} = 29$ km s^{-1}, and a peak flux density of 23.5 mJy, agreeing well with the Westerbork data convolved to a circular beam of 3′. The flux integral is $F = 0.7$ Jy km s^{-1}, which gives an H I mass of $1.65 \times 10^7 h^{-2} M_\odot$. This is a lower limit, since the Westerbork data show that the H I is more extended than 3′. The Arecibo profile also shows a hint of emission at low levels with a velocity extent of ~100–150 km s^{-1}.

More sensitive Arecibo observations of NGC 4472 by Bregman, Roberts, & Giovanelli (1988) still do not reveal any H I emission and establish an upper limit of $2.7 \times 10^6 h^{-2} M_\odot$. CO emission, however; has been detected in NGC 4472, corresponding to an H_2 mass of $5.3 \times 10^6 h^{-2} M_\odot$ (Huchtmeier et al. 1988). UGC 7636 has also been subsequently reobserved at Arecibo by two different groups. Hoffman et al. (1987) find weak H I emission with $v_H = 468$ km s^{-1}, $\Delta v_{50} = 36$ km s^{-1}, and $F = 0.167$ Jy km s^{-1}, corresponding to an H I mass of $3.9 \times 10^6 h^{-2} M_\odot$, with a peak flux density of 5 mJy. Schneider et al. (1990) find similar results: $v_H = 469 \pm 9$ km s^{-1}, $\Delta v_{50} = 25 \pm 15$ km s^{-1}, and $F = 0.28 \pm 0.14$ Jy km s^{-1}, corresponding to an H I mass of $6.6(\pm 3.3) \times 10^6 h^{-2} M_\odot$, with a peak flux density of 10 mJy.

It is clear that a single-dish H I measurement with a telescope beam large enough to include the whole UGC 7636–NGC 4472 system was necessary to tie down the total H I content in the region. The NRAO 140 foot (43 m) telescope at Green Bank with its beamwidth of ~22′ is ideal for such a measurement. The H I observations were performed during the period 1992 March 5–6. We used a two-channel, dual polarization 21 cm prime-focus receiver with a system temperature of ~20 K. A bandwidth of 20 MHz was used with a 1024 channel autocorrelator split in two. The two polarizations were detected independently and averaged to improve sensitivity. The channel spacing was ~8 km s^{-1}, and the effective resolution after Hanning smoothing was ~16 km s^{-1}. The observations were made in the standard total-power (position-switching) mode, with 6 minutes off-source/6 minutes on-source integrations. Taking into account the two polarizations, a total integration time of 6 hr on source was obtained. The calibrator signal levels and telescope pointing errors were checked by observing standard calibrators listed in the 140 foot Telescope Observer's Manual. A gain of 3.4 mJy mK^{-1} was derived.

The resulting spectrum, which has an rms noise of 3.5 mJy, is presented in Figure 3. The derived H I parameters are the following: $v_H = 470 \pm 5$ km s^{-1}, $\Delta v_{20} = 133 \pm 10$ km s^{-1}, $\Delta v_{50} = 70 \pm 10$ km s^{-1}, and $F = 1.947 \pm 0.358$ Jy km s^{-1}, corresponding to an H I mass of $4.6(\pm 0.8) \times 10^7 h^{-2} M_\odot$. The peak flux density is 27.2 mJy, and the error on the flux density is calculated as in Schneider et al. (1990). The H I profile can be fitted by the sum of two Gaussians: a narrow component with $v_H = 470$ km s^{-1} and a FWHM of 23 km s^{-1}, and a much broader component with the same line center and a FWHM of 110 km s^{-1}. Thus our H I observations suggest that there is a spatially extended H I component (more extended than ~3′) at low flux density (the peak flux density being ~16 mJy), spanning a large velocity range, from $v \sim 380$ km s^{-1} to $v \sim 540$ km s^{-1}, and containing nearly 3 times as much neutral hydrogen as given by the Arecibo measurement at midpoint between UGC 7636 and NGC 4472.

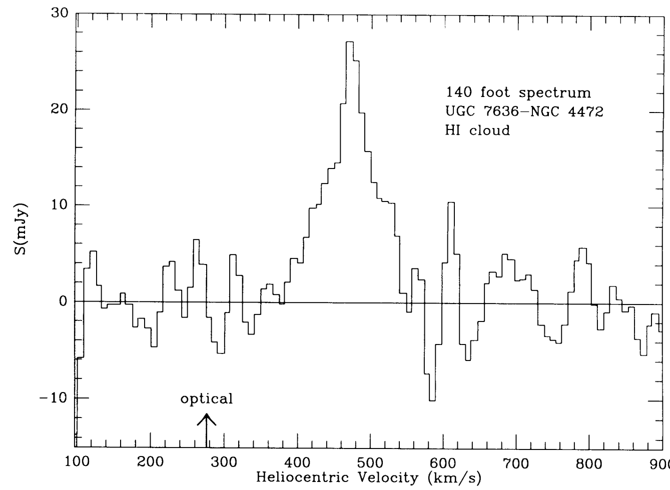

FIG. 3.—H I profile of the whole UGC 7636–NGC 4472 system obtained with the NRAO 140 foot telescope (BWHP = 22′). The profile can be fitted by the sum of a narrow Gaussian (FWHM = 23 km s^{-1}) and a broad Gaussian (FWHM = 110 km s^{-1}), both centered at $v_H = 470$ km s^{-1}. The optical heliocentric velocity of 276 ± 78 km s^{-1} (Huchra 1992) is indicated by an arrow.

The spectrum, along with a new H I Westerbork map of the complex (Sancisi 1992), allows us to estimate the contamination effect from the H I cloud for the Arecibo observations of UGC 7636. The new Westerbork map shows that the neutral gas is concentrated in a main clump ~1′.5 in size and about 2′ away from the dwarf. At this distance, the beam intensity decreases by a factor of ~4 from peak intensity at the main clump, giving a contamination peak flux density of ~7 mJy at the location of UGC 7636. This matches the peak flux densities measured by Hoffman et al. (1987) and Schneider et al. (1990) in the direction of UGC 7636. Furthermore, the neutral gas observed in that direction has the same velocity ($v_H = 469$ km s^{-1}) as that of the H I complex as a whole (Fig. 3), but it is quite different from the optical heliocentric velocity of 276 ± 78 km s^{-1} of the dwarf, as measured by Huchra (1992) from several absorption lines (Hβ, Mg II, Fe II, and Na I). We thus believe that all of the observed flux in the direction of UGC 7636 is due to contamination and that UGC 7636 is devoid of neutral hydrogen.

3. DISCUSSION

What is the possible origin of the H I gas between the two galaxies? Is it plausible that this is stripped gas from the dwarf irregular, as suggested by Sancisi et al. (1987)? If we take into account all the H I gas seen by the 140 foot telescope and the photometry in this paper, we get $M(\text{H I})/L_B = 0.26\ M_\odot/L_{B\odot}$, which is the low range of the values obtained by Thuan (1985) for field dI's and by Hoffman, Helou, & Salpeter (1988) for Virgo dI's. We thus conclude, in agreement with Sancisi et al. (1987), that the H I seen between the two galaxies has been removed from UGC 7636.

What stripping process has been responsible for the gas removal? As pointed out by Sancisi et al. (1987), it is likely that the neutral hydrogen has been stripped from the dwarf galaxy by the ram pressure exerted by the X-ray halo surrounding NGC 4472. The dwarf galaxy has a radial velocity of 707 km s^{-1} with respect to NGC 4472, the X-ray gas has a density of $\gtrsim 10^{-3}$ cm^{-3} (Fabian 1985), and with typical stellar and gas surface densities for dwarf irregulars (Tully et al. 1978), the sudden ram-pressure stripping condition (Gunn & Gott 1972) is easily satisfied.

Such a ram-pressure stripping model would not, however, by itself explain the presence of the red tail and countertail, or the disturbed morphology of the inner parts of the dI. We also need to invoke tidal interaction between the stripped dwarf galaxy and the elliptical galaxy. Such a model would naturally account for the observed tide-countertide symmetry. Using a mass of $4.6 \times 10^{12}\ M_{\odot}$ for NGC 4472, as derived from the X-ray observations (Forman et al. 1985), and a projected angular distance between the two galaxies of 5.′6, we calculate a lower limit of $\sim 20''$ for the tidal radius. This is consistent with the excess light above the exponential fit to both the B and I profiles for $r \gtrsim 30''$ (Fig. 2) and which we attribute to light from the tidal tail and countertail.

We believe the tail and countertail to be stellar, made of stars pulled out from the outer parts of the dI galaxy. They have a $B-I$ color of 1.4, corresponding to a spectral type of G8 V (Johnson 1966, with corrections from Bessell 1979) and similar to the color of the outermost parts of the dI. The inner regions of UGC 7636 have slightly younger stellar populations. They have $B-I = 1.1$, corresponding to the color of a F8 V star, a spectral type which is also consistent with the UBV colors measured by Gallagher & Hunter (1986). This also agrees with the optical spectrum of the dI galaxy, obtained by Huchra (1992), which shows Hβ, Mg II, Fe II, and Na I in absorption (but no emission), implying the presence of an intermediate-age stellar population.

The blue patch at the tip of the tail has $B-I \lesssim 0$, a color consistent with that of an H II region. We speculate that the thermal pressure from the hot X-ray gas plays a role in triggering gravitational collapse and star formation from density enhancements in the stripped gas.

The double component nature of the H I profile also supports the ram-pressure stripping hypothesis. H I bridges and tails usually show small velocity widths ($\Delta v \sim 30$ km s^{-1}). Thus the large velocity width ($\Delta v_{50} \sim 110$ km s^{-1}) of the low-intensity extended H I component can only be understood in the context of a ram-pressure stripping model.

Because of the alignment of the dI, H I cloud, and major axis of NGC 4472 and the orthogonality to the nuclear radio source in NGC 4472, Sancisi et al. (1987) speculate that the H I gas is falling into the elliptical galaxy and feeding the "monster" in its heart. This may be difficult to reconcile with the new stringent upper limits of H I gas ($\lesssim 2.7 \times 10^6\ h^{-2}\ M_{\odot}$) in NGC 4472. As for the CO gas, its distance from the center of the H I cloud ($\sim 2'$), and their difference in velocity (~ 434 km s^{-1}) with no overlap in the velocity dispersions, make its association with the H I cloud unlikely (Huchtmeier et al. 1988). Recent CO observations of the H I cloud by the same authors did not reveal any signal (Huchtmeier et al. 1992).

What will become of UGC 7636? If the H I observed along the line of sight to UGC 7636 is external to the dwarf and the dI is gas-free, can it evolve into a dE? Until recently, there were three main objections to an evolutionary connection between dI's and dE's. The first two—(1) that many dE's have globular cluster–like nuclei, whereas most dI's do not, and (2) that the flattening distributions of dE's and dI's differ—may have found a solution (Sandage & Hoffman 1991). The third, that the metallicity distributions of dI's and dE's, as measured by their near-infrared colors, are substantially different (Thuan 1985), still remains. Thus the fate of UGC 7636 is unclear. In any case, the rate of production of gas-poor dI's is too low to account for the large population of dE's in the Virgo Cluster (Gallagher & Hunter 1989).

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