Dust Streamers in the Virgo Galaxy M86 from Ram Pressure Stripping of its Companion VCC 882

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**ABSTRACT**

The giant elliptical galaxy M86 in Virgo has a \(\sim 28\) kpc long dust trail inside its optical halo that points toward the nucleated dwarf elliptical galaxy, VCC 882. The trail seems to be stripped material from the dwarf. Extinction measurements suggest that the ratio of the total gas mass in the trail to the blue luminosity of the dwarf is about unity, which is comparable to such ratios in dwarf irregular galaxies. The ram pressure experienced by the dwarf galaxy in the hot gaseous halo of M86 was comparable to the internal gravitational binding energy density of the presumed former gas disk in VCC 882. Published numerical models of this case are consistent with the overall trail-like morphology observed here. Three concentrations in the trail may be evidence for the predicted periodicity of the mass loss. The evaporation time of the trail is comparable to the trail age obtained from the relative speed of the galaxies and the trail length. Thus the trail could be continuously formed from stripped replenished gas if the VCC 882 orbit is bound. However, the high gas mass and the low expected replenishment rate suggest that this is only the first stripping event. Implications for the origin of nucleated dwarf ellipticals are briefly discussed.

*Subject headings:* galaxies: interactions — galaxies: individual (M86) — galaxies: kinematics and dynamics — galaxies: clusters

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1. Introduction

M86 (NGC 4406) is a bright elliptical (E3/S0) galaxy located in the Virgo Cluster at a distance of $\sim 18.3$ Mpc (Capaccioli et al. 1990). It has a redshift of $-227$ km s$^{-1}$ (Binggeli et al. 1985), while the mean heliocentric velocity of the cluster as a whole is 1050 km s$^{-1}$ (Binggeli et al. 1993). M86 is thought to be on an orbit passing through the core of the cluster approximately every 5 billion years (Forman et al. 1979). It is an X-ray object and appears to be a weak radio source (Laing et al. 1983; Fabbiano et al. 1992; Rangarajan et al. 1995). A plume of X-ray, HI, and infrared emission from M86 suggests that its interstellar medium was swept back by the ram pressure from its motion through the intracluster medium (Forman et al. 1979; Fabian, Schwarz, & Forman 1980; Takeda, Nulsen, & Fabian 1984; Bregman & Roberts 1990; Knapp et al. 1989; White et al. 1991). There is also an optical asymmetry to M86 that gives it a slightly enhanced emission along the plume (Nulsen & Carter 1987).

Here we discuss a nucleated dwarf elliptical galaxy, VCC 882 (NGC 4406B; Binggeli et al. 1985), that lies just to the northeast of M86, inside its projected stellar halo. Deep CCD images show a 28 kpc long dust trail inside M86 that appears to follow VCC 882 in its orbit. This trail is possibly the result of ram pressure stripping of gas originally inside VCC 882 that was removed by the high pressure of its motion through the hot gaseous halo of M86. The gas mass obtained from the extinction in the trail is consistent with this former connection to VCC 882. Other evidence for an interaction between M86 and VCC 882 could be an isophotal twist in the central 8 to 80 arcsec of M86 (Bender & Mollenhoff 1987), and the asymmetric outer isophotes of M86 (Nulsen & Carter 1987).

Gas stripping is pervasive within this core region of the Virgo cluster. Three spirals are close to the M86/VCC 882 pair in projection: NGC 4438, NGC 4388, and NGC 4402. There is also a nearby dwarf galaxy, IC 3355. The spirals have been severely stripped of their outer HI disks (Warmels 1986; Hoffman, Helou, & Salpeter, 1988; Cayatte et al. 1990), but the dwarf looks normal. The peculiar negative velocity of M86 is also shared by NGC 4402, NGC 4438, and IC 3355, as if at least some of these galaxies are comoving like a group through the Virgo cluster (Kotanyi & Ekers 1983). Detailed studies of one of these galaxies, NGC 4438, suggest that ram pressure from its motion through the Virgo intracluster medium has visibly distorted its outer disk (Arp 1966), pushing the gas and star formation off the normal plane, and producing a short diffuse trail of radio continuum and X-ray emission (Kotanyi & Ekers 1983; Kotanyi, van Gorkom & Ekers 1983). A second galaxy in this group, NGC 4388, has been studied by Pogge (1988), Petitjean & Durret (1993) and Veilleux et al. (1999), with mixed results on a stripped origin for extraplanar material. The spiral galaxy NGC 4569, at an equal distance from M87 but on the eastern...
side, has a negative velocity too, along with an anemic classification (van den Bergh 1976) and depletion in HI (Cayatte et al. 1990). Another dwarf galaxy, IC 3475, is closer in projection to M87 than IC 3355 and is highly stripped of HI (Vigroux et al. 1986), while another anemic spiral, NGC 4548, is about twice as far from M87 as these others and has a distorted outer HI disk (Vollmer et al. 1999).

Ram pressure seems to have stripped the Virgo spiral NGC 4694 also. This galaxy is far to the east of the core region in Virgo. It has a 36 kpc long trail of HI streaming off to the west, with a linear velocity gradient along the trail that smoothly connects it with the galaxy (van Driel & van Woerden 1989). A very faint dwarf galaxy is also in the trail, where the HI column density peaks.

All of these cases suggest stripping from the motion of a galaxy through the hot, low-density, intracluster medium inside Virgo. The case discussed here differs because VCC 882 was apparently stripped by its motion through the much denser hot gas associated with the elliptical galaxy M86. Its relative speed is just as large as in the other cases, exceeding 1000 km s\(^{-1}\), but the ram pressure it felt must have been much larger because of the higher ambient density.

A similar case is the Virgo dwarf galaxy UGC 7636, which was apparently stripped as it moved through the giant elliptical, NGC 4472. The evidence for this is: a gas cloud to the side of UGC 7636 (Sancisi, Thonnard & Ekers 1987) that has the right mass to have been formerly part of UGC 7636 (Patterson & Thuan 1992; Irwin & Sarazin 1996); a 30 kpc long optical trail of luminous debris adjacent to the cloud and the dwarf (McNamara et al. 1994); absorption of the elliptical galaxy X-ray radiation by the HI cloud (Irwin & Sarazin 1996), and an oxygen abundance in an HII region of the cloud that is consistent with the abundance expected for UGC 7636 (Lee et al. 2000).

Previous photometric studies of Virgo cluster galaxies were made by Binggeli et al. (1985, 1993), Bender & Mollenhoff (1987), and Caon et al. (1994). Katsiyannis et al. (1998) co-added thirteen Schmidt exposures to produce a deep R-band image of the Virgo southeast region, from which they studied extended and overlapping halos. The dust trail discussed here did not appear in these other images.

2. Observations and Data Reduction

We obtained 92 images in B, V, and I over an approximately 1 square degree field in the southeast center of the Virgo Cluster using the Burrell Schmidt 0.6-m telescope at Kitt Peak National Observatory on 17-22 March 1999. The plate scale is 1.6 arcsec per pixel,
or about 142 pc per pixel at the assumed distance of 18.3 Mpc. The images were reduced using standard IRAF procedures. Flat fields were made from global sky flats taken over the entire observing run. The images were mosaicked to produce combined images with total exposure times of approximately 6.5 hours in each band.

Figures 1a and 1b show a mosaic of the central square degree of the images in B band. The left-hand image is low-contrast, showing the giant ellipticals M84 and M86 as well as the small companion VCC 882, which is normally lost in the bright light of M86. The right-hand image is shown with high contrast to emphasize the outer extents of the large galaxies.

Enhanced images of M86 are in Figure 2. The top left frame shows the logarithm of the intensity in B band with the angular scale indicated. Dark dust features are labeled. Feature A is 2.05 arcmin east of center, and Feature B is 3.7 arcmin southeast of center, midway between two bright foreground stars. These features are more prominent in the other enhanced images. In the top right, which is a (B-I) color map, Feature A has a fork at its mid-point and a faint extension, marked C, towards VCC 882. The lower left frame is an unsharp-masked image, made by smoothing the original with a Gaussian filter 5 pixels wide and subtracting this from the original. Most of the stars have been removed from this image by replacing the corresponding pixels with the average surrounding background. A star at the top of the eastern dust feature remains, as well as another due west of the center of M86 and one near VCC 882. The lower right-hand frame is an "embossed" B-band image made in Adobe Photoshop; the three-dimensional perspective is the result of an apparent "illumination" from the west. Here, the dust features are black against the gray background.

Previous published images of M86 did not show the dust features present in Figure 2. They are too faint to appear on high-contrast prints. Bregman & Roberts (1990) mapped this region in HI and reported a private communication with J. L. Tonry, who noticed dust patches 100” east of center. These are probably what we see here. The associated gas did not show up in H I emission because it was below Bregman & Roberts’ detection limit.

At the assumed distance of 18.3 Mpc, Features A and B lie at projected distances of 10.9 kpc and 19.7 kpc from the center of M86. The latter is comparable to the 19.5 kpc radius of M86 at a surface brightness of 25 mag arcsec\(^{-1}\) (de Vaucouleurs et al. 1991). The outermost halo of M86 shown in the right-hand image of Figure 1 has a much larger radius of 62 kpc. Feature A is approximately 130” (= 11.5 kpc) long from north to south, and its average width is 6.4” (= 570 pc). Feature B is ~ 63” (= 5.5 kpc) long and ~ 19” (= 1.7 kpc) wide, while Feature C is ~ 27” (= 2.4 kpc) long and ~ 4.8” (= 430 pc) wide. The total length of the trail is 28 kpc.
In order to estimate the extinction of the dust features, we determined the magnitude difference between them and their surrounding regions in each passband. East-west intensity cuts were made at 28 points along the length of the trail; 17 of these cuts that are on Feature A are shown in Figure 3. The midpoint of the cut was at the approximate position of the trail. The dashed lines are averages of all 17 cuts. The magnitude differences between the dust and the surrounding regions varied from 0 to 0.2 in B band and from 0 to 0.15 in V band, with uncertainties of about 0.02 mag. The dust features do not show up well in I band.

Figure 4 shows the magnitude differences in the dust features for the B and V bands as a function of position from south to north. The ratio of these magnitude differences, $\Delta m_B / \Delta m_V$, is shown at the top. Least squares fits to feature A are shown as dotted lines. The endpoints of the curves are the southeastern dust Feature B and the northernmost extension, Feature C, near VCC 882. The magnitude differences decrease from south to north in both B and I bands. The ratio of the magnitude differences in B and V bands is slightly larger than in a Whitford reddening law, where it would be 1.3. The data are not accurate enough to tell if this ratio changes along the length of the trail. It should decrease with greater depth inside the halo of M86 because foreground stars wash out the color difference in the trail, but such a decrease can be offset by changes in intrinsic extinction. The opacity and depth of the dust trail are estimated in Section 3 from simple radiative transfer.

Figure 5 shows the B and I-band radial profiles along the major and minor axes of VCC 882. The profiles were made after first removing the underlying light from M86 by rotating the image 180° and subtracting it from the original. The profiles are well-fit by an exponential, which is the case for many Virgo dwarf ellipticals (Vader & Chaboyer 1994; Ryden et al. 1999). The scale length is $3.8'' = 340$ pc. The (B-I) color profiles along the major and minor axes are shown at the bottom of Figure 5 as solid and dashed lines. The southern side of VCC 882, nearest M86, is bluer than the northwest side, while the color profile along the major axis is symmetric and flat.

The isophotal contours of VCC 882 are in Figure 6. They are symmetric like the color profile, also showing no evidence of a tidal tail. In contrast, the interaction of the dwarf galaxy UGC 7636 and the giant elliptical NGC 4472 shows a blue tidal tail in the dwarf (Patterson & Thuan 1992). An ellipse fit for VCC 882 gives a position angle of 116° ± 4° and an ellipticity of 0.26 ± 0.02. The inner 2'' region in Figure 6 shows an isophotal twist.
3. Grain Size, Opacity and Geometric Depth

The magnitude difference between the dust feature and the surrounding field can be converted into an opacity and a relative depth through the M86 halo stars if the intrinsic ratio of $\Delta m_B/\Delta m_V$ is known. Denoting this ratio by $C$ (= 4/3 for a Whitford reddening law), we can write the observed intensities in V and B bands in terms of the intensities of the halo light behind and in front of the cloud, $I_0$ and $I_1$, respectively, and in terms of the opacity in V, $\tau_V$:

$$I_{V}^{\text{cloud}} = I_0 e^{-\tau_V} + I_1 ; \quad I_{B}^{\text{cloud}} = X I_0 e^{-C\tau_V} + X I_1$$

where $X$ is the ratio of B to V intensity to the side of the cloud:

$$I_{V}^{\text{side}} = I_0 + I_1 ; \quad I_{B}^{\text{side}} = X I_0 + X I_1.$$  \hspace{1cm} (2)

The magnitude differences may be written in the form $I_{V}^{\text{cloud}}/I_{V}^{\text{side}} = 10^{-0.4\Delta m_V}$. Thus we can express the opacity $\tau_V$ in terms of the magnitude differences:

$$\frac{1 - e^{-C\tau_V}}{1 - e^{-\tau_V}} = \frac{1 - 10^{-0.4\Delta m_B}}{1 - 10^{-0.4\Delta m_V}}.$$  \hspace{1cm} (3)

and we can express the relative depth of the cloud in the M86 halo as

$$\frac{I_1}{I_0} = \frac{10^{-0.4\Delta m_V} - e^{-\tau_V}}{1 - 10^{-0.4\Delta m_V}}.$$  \hspace{1cm} (4)

Figure 7 shows the V-band opacity and the relative depth of feature A for four values of $C$, using the linear fits to $\Delta m_V$ and $\Delta m_B$ that are in figure 4. The opacity generally decreases to the north, and the depth increases. The $C$ values are all required to be larger than the maximum of $\Delta m_B/\Delta m_V$, because this maximum is the value $C$ would have for a foreground cloud. In the figure, the value of $C$ is given in terms of this maximum, which is 2.36. The solution is not reliable when $C$ is close to the maximum, as shown by the sudden decrease of the depth in the northern part of the trail for the $C = \max(\Delta m_B/\Delta m_V)$ case. Large values of $C$ suggest that the dust grains are smaller in the trail than they are in the Milky Way. The measurements are too inaccurate to be conclusive, however.

4. Discussion

The dwarf galaxy VCC 882 appears to have lost much of its interstellar medium during a recent passage through the X-ray emitting gas of M86. The variation of extinction
and depth along the trail of this debris, and the positive relative velocity of VCC 882, suggest that the orbit of the dwarf took it from the lower-left foreground of M86 to the upper middle or background. Ram pressure stripping is the mostly likely cause for the gas removal, rather than tidal stripping, because the stellar distribution in the dwarf is hardly affected by the encounter, and ram-pressure stripping affects only the gas.

The total mass of the dust features was estimated by assuming a standard HI column density of $1.9 \times 10^{21}$ cm$^{-2}$ for $A_V=1$ mag (Bohlin, Savage & Drake 1978), and multiplying the resulting column density by the total area of the features. For a magnitude difference of $A_V=0.1$ (Fig. 4), the above measurements give a total mass of $3.4 \times 10^7$ M$_\odot$. If the dwarf is deficient in dust, as is common for small galaxies with low metallicities, then the gas mass in the trail will be larger. For a metallicity of [Fe/H]$=-0.59 \pm 0.42$ (Brodie & Huchra 1991), a proportionately lower extinction-to-gas ratio would increase the trail mass by a factor of $\sim 4$ to $\sim 1.4 \times 10^8$ M$_\odot$. We shall use this mass below.

If the radiative transfer model is correct, then the opacity in the trail can be larger than 0.1 mag; Figure 7 suggests it might be as large as 1 mag. The gas mass would then increase in proportion. We do not consider this model to be accurate, however, because of measurement errors in the magnitude differences and because the results are very sensitive to the unknown ratio $C$. More accurate measurements of the trail should improve this situation.

The timescale for the stripping can be estimated from the trail length, which is $\sim 28$ kpc, and the relative speed of VCC 882 inside M86, $v_{rel} = 1328$ km s$^{-1}$ (the heliocentric velocity of VCC 882 and M86 are 1101 km s$^{-1}$ and -227 km s$^{-1}$, respectively). The ratio of these numbers, 15 My, is a measure of the timescale for the trail to be deposited, aside from projection effects.

There is no measure of the mass of VCC 882, but we estimate the absolute magnitude in B band to be $\sim -16$ mag based on a comparison of our counts with photometric sources in the field. For comparison, observations by Binggeli, Sandage, & Tammann (1985), Harris (1991), and Cohen (1988) convert to absolute B magnitudes of $-14.6$, $-16.2$, and $-15.2$, respectively, using a distance of 18.3 Mpc. Our estimate of $\sim -16$ mag makes the galaxy luminosity $L_B \sim 3.8 \times 10^8$ L$_\odot$. If the gas in the trail was formerly part of the VCC 882 galaxy, then the ratio of the HI mass to the stellar luminosity was about unity, which is comparable to that for dwarf irregular galaxies (Roberts 1969; Swatters 1999) but high for nucleated ellipticals. This makes the proposed VCC 882 predecessor resemble ESO 359-G29, which is a gas-rich nucleated, dwarf elliptical (Sandage & Fomalont 1993). For a normal stellar population with $M/L_B \sim 2$ M$_\odot$/L$_\odot$ (Sandage & Fomalont 1993; Hirashita, Takeuchi, & Tamura 1998), the galaxy mass would be $M_{gal} \sim 8 \times 10^8$ M$_\odot$. This, combined
with the exponential scale length of $R_{\text{gal}} = 340$ pc, gives a characteristic virial speed of $GM_{\text{gal}}/(5R_{\text{gal}})^{1/2} = 45$ km s$^{-1}$.

The presence of globular clusters around VCC 882 (Cohen 1988), as well as the symmetric isophotal contours in the outer parts of this galaxy (Fig. 6), suggest that ram pressure stripping of the gas may not have been accompanied by significant tidal disruption of the stars. However, tidal disruption detaches stars and globular clusters slowly from the gravitational pull of VCC 882; it need not have moved the stars very far yet from the galaxy center. If we multiply the 15 My interaction time by the 45 km s$^{-1}$ virial speed inside VCC 882, we get a plausible drift distance of $\sim 675$ kpc, to within a factor of $\sim 3$ uncertainty from projection effects. This is not a large enough distance for the globulars to have migrated significantly from the center of VCC 882, considering that globulars are usually seen in the outer parts of galaxies anyway. Thus the dwarf could have been exposed to a significant tidal force from M86, but we would not necessarily have noticed the effects of this force yet.

The ram pressure force on the gas can have a very different effect than the tidal force on the stars. The average density in the X-ray halo of M86 is $n \sim 0.01$ cm$^{-3}$ (Thomas et al. 1987), and the VCC 882 orbital speed discussed above is $v_{\text{rel}} = 1328$ km s$^{-1}$. Thus the average ram pressure on the VCC 882 gas is $P = n\mu v_{\text{rel}}^2 \sim 3 \times 10^6$ K cm$^{-3}$ for mean atomic weight $\mu = 2.2 \times 10^{-24}$ g. Such a pressure can strip the ISM from VCC 882 all at once if it exceeds the gravitational binding energy density that the gas would have had there. This energy density comes from the former gas density multiplied by the square of the escape velocity in the dwarf. This condition for stripping may be written

$$\rho_{\text{external}}v_{\text{rel}}^2 > \rho_{\text{internal}}v_{\text{escape}}^2,$$

which is comparable to the conditions written by Gunn & Gott (1972) for disk stripping and Takeda et al. (1984) for spheroid stripping. We take the escape speed to be $2^{1/2}$ times the virial speed derived above.

The effective density that the gas had when it was inside VCC 882, if this is where it came from, can be estimated from the current gas mass $M \sim 1.4 \times 10^8$ M$_{\odot}$ in the trail and from the exponential scale length $R_{\text{gal}} = 340$ pc of the galaxy. This naively gives a density of $3M/(4\pi R_{\text{gal}}^3) \sim 26$ cm$^{-3}$ for a spherical distribution. This is high for an average ISM density, but it is not supposed to be the real density, only the effective density for the stripping calculation. With this density, the gravitational energy density gives a self-binding pressure of $1.7 \times 10^7$ K cm$^{-3}$, which is $\sim 5 \times$ larger than the ram pressure.

We get about the same result if we consider a more realistic disk-like structure for the gas before it was stripped. Then the expression for self-binding pressure is $2\pi G\sigma_{\text{tot}}\sigma_{\text{gas}}$. 
(Gunn & Gott 1972) for total and gaseous column densities $\sigma_{tot}$ and $\sigma_{gas}$. For an exponential disk with central surface density $\sigma_0$ and an exponential scale length $R_{gal}$, the total mass out to infinity is $2\pi\sigma_0 R_{gal}^2$. Thus $\sigma_{tot} = M_{tot}/(2\pi R_{gal}^2)$, $\sigma_{gas} = M_{gas}/(2\pi R_{gal}^2)$, and the self-binding pressure is $(GM_{gal}/R_{gal}) M_{gas}/(2\pi R_{gal}^3)$. This is $(5/3) \rho_{gas} v_{esc}^2$ for $\rho_{gas} = 3M_{gas}/(4\pi R_{gal}^3)$ as above. Thus the stripping condition given by equation (5) with an effective galactic gas density crudely derived for a sphere the size of the exponential scale length is the same to within 60% as Gunn & Gott’s condition for a disk with the gas distributed exponentially.

In either case, the results suggest that the ram pressure from the motion of VCC 882 through M86 was not overwhelming compared to the internal gravitational energy density of the former interstellar medium in that galaxy. If it were, it would probably have led to a more rapid loss of gas from the dwarf, in one or two big clumps (as for UGC 7636). Instead, the stripping was apparently mild, and the morphology of the stripped gas more filamentary, like a long trail of debris removed somewhat steadily.

In fact, this morphological dependence on stripping strength is in agreement with general theory. Stevens, Acreman, & Ponman (1999) found that long gas trails like the one we observe here result if the stripping pressure is modest rather than overwhelming, and if the galactic stars continuously replenish the interstellar medium at normal rates through winds and supernovae. Earlier calculations by Lea & De Young (1976) got a trail for this case too; they explained it as the result of expansion of galactic gas into the low pressure zone downstream in the trail. Takeda, Nulsen & Fabian (1984) found a rapid initial loss of gas for their models, but this was followed at long times by a trail of more steady ablation consisting of gas from the stellar replenishment. Balsara, Livio & O’Dea (1994) got a trail in the mass-replenishment case too, but found also that stripping occurred in bursts. For steady state models, trails occur when there is a low rate of gas replenishment and a high ram pressure (Portnoy, Pistinner, & Shaviv 1993).

The VCC 882 case may have had stripping bursts too, in addition to a more steady gas loss that formed the overall trail. Figure 2 suggests that the trail is not perfectly uniform, but has three prominent condensations. These are approximately equally spaced, and consistent with the suggestion by Balsara, Livio & O’Dea (1994) and Stevens, Acreman & Ponman (1999) that the bursts of mass loss would be periodic. The timescale for these bursts should depend on the turbulent or sound crossing time inside the dwarf galaxy, out to the shocks at the interacting surfaces (cf. Lea & De Young 1976), because internal adjustments and pulsations in the interstellar medium of the dwarf have this characteristic scale. The positions of these shocks depend on the flow speed, so the oscillation timescales should also scale with the flow crossing time outside the galaxy, which is $2R_{replenish}/v_{rel}$. 

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Here $R_{\text{replenish}}$ is the mass-replenishment half radius defined by Stevens et al. (1999). Specific timescales given in these previous models range from 3 to $5 \times 10^7$ years, which was several flow-crossing times (see also Abadi, Moore, & Bower 1999). Here the flow-crossing time is much shorter, $2R_{\text{gal}}/v_{\text{rel}} \sim 0.5$ My, so several flow times is perhaps slightly over 1 My. Considering that the whole trail may be only 15 My old (uncertain because of projection effects), this oscillation timescale is short enough to be consistent with the occurrence of three condensations along the trail behind VCC 882.

Other aspects of the trail morphology might result from variable pressures in the M86 halo, i.e., increasing with depth, or from Kelvin-Helmholtz instabilities along the trail of gas. The wiggles in Feature A cannot result from the rotation of VCC 882 because the rotation period at one exponential scale length is $\sim 50$ My, which is longer than the expected trail formation time.

The long term evolution of the trail is presumably dominated by evaporation and mixing with the hot halo of M86. The evaporation time given by Veilleux et al. (1999) provides a useful guide:

$$t_{\text{evap}} = 1000n_{\text{trail}}R_{\text{trail,pc}}^2 \left( T_{\text{M86}}/10^7 \, K \right)^{-5/2} (\ln \Lambda/30) \, \text{yr};$$

(6)

$\Lambda$ is the Coulomb logarithm. The trail density, $n_{\text{trail}}$ is unknown, but we can use a column density of $1.9 \times 10^{20}$ cm$^{-2}$ from the estimated extinction of $A_V = 0.1$ mag to give $n_{\text{trail}}R_{\text{trail,pc}} = 30$ (half the total because $R$ is a radius rather than the full depth of the trail). For $R_{\text{trail,pc}}$ comparable to the observed half-width of $\sim 250$ pc, the evaporation time is $\sim 7.5$ My, which is half the estimated trail age. Thus the trail length could be determined in part by evaporation.

It is conceivable that VCC 882 is bound to M86 and produces a continuous trail from replenished gas that always evaporates by the time it reaches 10 – 20 My downstream. This can be checked from the orbit speed in the potential of M86. If we assume that the two galaxies are currently separated by their projected distance of $D = 86.9'$ = 7.7 kpc, and that VCC 882 is in a parabolic orbit with a speed of $v_{\text{rel}} = 1328$ km s$^{-1}$ (ignoring projection effects), then the mass of M86 becomes $0.5Dv_{\text{rel}}^2/G \sim 1.6 \times 10^{12}$ M$_{\odot}$. The log of the blue luminosity of M86 is 10.65 (Tully 1988), which then gives an M/L ratio of 35 M$_{\odot}$/L$_{\odot}$. Although the average M/L for elliptical galaxies is 5 to 10, the M/L ratio for M86 was calculated to be 63 based on mass estimates from the X-ray temperatures and densities (Forman et al. 1985). Our value is consistent with their result, considering the uncertainties here. This suggests that much of the apparent speed of VCC 822 could be from its motion inside M86. The visible trail could be only the non-evaporated remnant of a longer trail that has periodically removed fresh gas from VCC 882 as it plunged into the denser regions of M86.
This situation is similar to the model proposed by Takeda et al. (1984) for elliptical galaxies in clusters, applied here on a smaller scale. However, for VCC 882, the gas mass in the trail is probably too large to be entirely the result of stellar wind accumulation in an orbit time around M86. For the replenishment rate of $\frac{dM}{dt} = 1.6 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ used by Balsara et al. (1994), the time for $1.4 \times 10^8 M_{\odot}$ of gas to accumulate inside an $8 \times 10^8 M_{\odot}$ galaxy is $10^{10}$ years. This would have to be the orbit time if the stripping process were repetitive, but it is such a long time compared to the Hubble time that VCC 882 would have to be on its first orbit. If the gas accumulation time is not shorter than this, then the trail behind VCC 882 is probably a first stripping event. Even longer replenishment times were assumed for elliptical galaxies by Gaetz, Salpeter & Shaviv (1987).

The distinction between these two models of first-time and repetitive stripping is relevant to the problem of the origin of nucleated dwarf ellipticals. If VCC 882 is now experiencing its first stripping event, then it is just now becoming a gas-poor elliptical galaxy and its formation mechanism would have been one involving stripping from a gas-rich dwarf irregular (Lin & Faber 1983), or preferably a BCD, considering its compact bright nucleus (Davidge 1989; Sandage & Hoffman 1991; Vader & Chaboyer 1994). If the gas accumulation rate is faster than the Balsara et al. estimate by a factor of 10, then VCC 882 could have formed as an elliptical long ago by other mechanisms and now be shedding only the gas mass that comes from evolved stars. The concentration of dE,N galaxies in the center of the Virgo cluster suggest an early formation anyway (Gallagher & Hunter 1989), consistent with dwarf formation models in a cold dark matter universe (Silk, Wyse, & Shields 1987).

The origin of dE’s in Virgo is unclear although their properties are well studied. Nucleated dE’s like VCC 882 concentrate toward the center of Virgo, unlike the non-nucleated dE’s and the dI’s (van den Bergh 1986; Ferguson & Sandage 1989). This suggests either an early origin for the dE’s or stripping from a previous gas-rich state. The centralized dE,N’s are also brighter and larger than the peripheral dE’s (Ichikawa et al. 1988), so stripping from a common ancestor will not produce both types of dE’s. The nucleated dE’s like VCC 882 have more globular clusters per unit luminosity than non-nucleated dE’s (Harris 1991), and this also suggests a primordial origin for the dE,N’s, unless the globulars were made during the stripping event. The exponential light profile in VCC 882 is typical for dE’s, which are like dI’s in this respect (Faber & Lin 1983; Caldwell 1983; Binggeli, Sandage & Tarenghi 1984), but the dE’s have more metals than the dI’s (Thuan 1985) so either the dE’s had a distinct origin or early stripping events triggered substantial amounts of star formation. No star formation is seen in VCC 882, however; there is only a slight B-I color gradient along the minor axis (Fig. 5). dE’s are also distinct from E’s and globular clusters on correlation diagrams considering galactic structure parameters.
(Binggeli, Sandage & Tarenghi 1984; Kormendy 1985), but not considering color (Caldwell 1983; Bothun & Caldwell 1984; Wirth & Gallagher 1984; Zinnecker et al. 1985),

These properties of dE,N galaxies suggest that most of them acquired their morphologies early on, possibly passing through an early BCD phase to get the bright nucleus and/or globular clusters through intense star formation. Indeed, dE,N nuclei resemble bright globulars (Phillips et al. 1996). But in this case the presence of what appears to be a trail following VCC 882 is an anomaly. This galaxy could not have been a BCD only ~ 15 My ago, which is the stripping time considering the trail length and relative velocity of M86, because that would make VCC 882 too blue now. It might have had a mixed morphology before, like ESO 359-G29 (Sandage & Fomalont 1993) or several other dwarf galaxies (Vigroux et al. 1986; Davidge 1989; Sandage & Hoffman 1991; Vader & Chaboyer 1994). Or it could have an anomalously high gas replenishment rate, which would make the trail come from stripped stellar ejecta in a more continuous flow. The lack of obvious blue stars or young stellar clumps in what was supposedly a gas-rich system only several tens of millions of years ago is difficult to understand. Perhaps the trail did not come from VCC 882 at all.

Observations of the metallicity, dust-to-gas ratio, grain properties, and velocities in the trail would be useful, as would more detailed studies of the current stellar populations in VCC 882. High resolution X-ray observations of the region around and behind VCC 882 would be interesting too, to distinguish the trail from the plume and other X-ray emitting gas connected with M86.

5. Conclusions

Deep B, V, and I images of the southeast core region of the Virgo cluster reveal a dust trail in the central region of M86, spanning 28 kpc with a thickness of ~ 500 pc. The dust appears to connect to the nucleated dwarf galaxy VCC 882 located just north of M86. We estimate that the dust has a V-band extinction of 0.1 mag, with a total mass of $10^8 \, M_\odot$. This dust and the associated gas may have been ram-pressure stripped from VCC 882 over the last 10-20 My as the dwarf galaxy passed through the hot X-ray emitting gas of M86. The mass of gas is somewhat consistent with its former presence inside VCC 882, and the morphology of a trail is consistent with theoretical predictions for relatively weak ram pressures and periodic outflows. The similarity between the evaporation time of the trail and the dwarf orbit time suggest that evaporation is important. The length of the trail could even be determined by steady evaporation at the back end.

A problem with this interpretation is that VCC 882 is a classical nucleated dwarf. It
seems to have no recent star formation as if it just had a gas disk, and the gas mass estimate is much too high for such a morphology. If the trail really did come from VCC 882, then it would have had a mixed morphology before the stripping, like several other rare cases that have been studied elsewhere. More observations will be required to determine the origin and history of this gas.

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Fig. 1.— B band images of the central region of the Virgo cluster, with two contrast levels. The image bpi has been reduced here by 4 to save space for astro-ph.
Fig. 2.— Enhanced images of M86 with VCC 882 to the northeast. Top left: logarithmic intensity in the B band; top right: B-I color image; bottom left: unsharp-mask restoration of small-scale structure in the B band; bottom right: embossed representation of the B band image. The image bpi has been reduced here by 4 to save space for astro-ph.
Fig. 3.— Intensity strips across Feature A in three passbands, B at the top, V in the middle and I at the bottom. The dust filament is approximately at the relative distance 0.
Fig. 4.— Magnitude differences between the trail and the surrounding regions are plotted as a function of distance along the trail, from south to north. The three plotted points on the left are Feature B, the cluster of points in the middle is Feature A, and the three points on the right are Feature C.
Fig. 5.— B and I-band profiles of relative intensity along the major and minor axes of VCC 882. The shift between the profiles is arbitrary. The major axis profile is an average over 11 adjacent profiles spaced by one pixel in the minor axis direction, and the minor axis profile is an average over 21 profiles spaced by one pixel in the major axis direction. The underlying light from M86 was remove. The profiles are exponential with a major axis scale length of 3.8″ = 340 pc. The (B-I) color profiles along the major and minor axes are also plotted at the bottom of the diagram, using the scale on the right.
Fig. 6.— Isophotal contours of VCC 882 in B band. No distortion from a stellar tidal tail is evident. *The image bpi has been reduced here by 4 to save space for astro-ph.*
Fig. 7.— Radiative transfer model fits for the opacities (solid lines) and relative depths (dashed lines) of the dust trail in the stellar halo of M86. The linear fits to the magnitude differences in Fig. 4 are used. The parameter $C$ is the intrinsic ratio of $B$ to $V$ extinction, equal to 1.3 for a Whitford law. Here it is much higher, taken to be the indicated factors times the maximum observed value of the $B$-to-$I$ ratio, which is 2.36. The large value of $C$ suggests the dust grains in the trail are smaller than in the local interstellar medium.
Relative Distance from south (arcsec)

Opacity

\[ C = 2 \times \max(\Delta m_B / \Delta m_V) \]

Relative Depth

- Opacity
- Depth

Relative Distance from south (arcsec)