# The Evolution of Gas and Stars in the merger galaxy NGC 1316 (Fornax A)

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## ABSTRACT

We present optical and archival X-ray data on the disturbed morphology radio elliptical NGC 1316 (Fornax A) that displays numerous low surface brightness shells, loops and tails. An extended (81x27$''$ or 9x3 kpc) emission line region (EELR) at a projected distance of 35 kpc from the nucleus has been discovered in a $\sim$90x35 kpc, $\sim$3.0x10$^9$ $L_{B\odot}$ tidal tail. The position and extreme size of the EELR suggest it is related to the merger process. We suggest that the ionization mechanism of the EELR is shock excitation, and the gas is remnant from the merger progenitor. X-ray emission is detected near two tidal tails. Hot, $\sim$5 x 10$^6$K gas is probably the predominant gas component in the tidal tail ISM. However based on the current tidal tail (cold + warm + hot) gas mass, a large fraction of the tidal tail progenitor gas may already reside in the nucleus of NGC 1316. The numerous and varied tidal tail system suggests that a disk-disk or disk-E merger could have taken place $\geq$ 1 Gyr ago, whilst a low mass, gas rich galaxy started to merge $\sim$ 0.5 Gyr ago.

*Subject headings:* galaxies: structure — galaxies: photometry — galaxies: peculiar — galaxies: individual — galaxies: interactions — X-rays: galaxies

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## 1. Introduction

NGC 1316 (Fornax A, PKS 0320-37, Arp 154) is one of the closest, D = 22.8 Mpc (adopting $v_0$=1713 km $s^{-1}$, Sandage and Tammann 1981, hereafter RSA, and $H_0$ = 75 km $s^{-1}$ $Mpc^{-1}$) and brightest radio galaxies in the sky. Its catalogue morphological type is uncertain, being described as Sa pec (merger?) in RSA. It is located on the outskirts of the Fornax cluster, and is projected 3.7° from the centrally located cluster giant elliptical NGC 1399. Extensive optical observations of Schweizer (1980), hereafter S80, and Schweizer (1981) show NGC 1316 ($M_B \sim -22.7$) possessing a surprisingly small core radius and high central surface brightness for its luminosity. These unusual core properties alone may suggest a previous merger event (Kormendy 1987) has taken place. S80 showed NGC 1316 to be a D-type galaxy with an elliptical-like spheroid surrounded by a large envelope. Photographic plate imagery shows the envelope possessing numerous low surface brightness arcs or shells and loops, including a large loop that extends $\sim 25'$ S–SW ($\sim$170 kpc adopting $9''$/kpc) from the galaxy nucleus. Long-slit spectroscopy by S80 shows a rapidly rotating ($v \sin i \sim 350$ km $s^{-1}$) disk of ionized gas in the centre of the galaxy with a rotation axis almost 90° from the stellar rotation axis and a single giant H II region was discovered $6.7'$ S of the nucleus.

NGC 1316 also shows activity that may be related to its dynamical history and environment. It displays low-ionization emission-line spectra in its nucleus (Veron-Cetty and Veron 1986; Phillips *et al.* 1986), as well as a steep spectrum radio core with dual–opposing jets (Geldzahler and Fomalont 1984). It has a double-lobe radio continuum structure (Ekers *et al.* 1983) with a diameter of $\sim 35'$ that exists primarily outside of the optical galaxy. HST FOC imaging by Fabbiano *et al.* (1994) shows that NGC 1316 possesses a UV-bright, unresolved nucleus. *ROSAT* HRI observations of hot gaseous emission in the central region of NGC 1316 by Kim *et al.* (1997) suggest a hot ($10^7$K) ISM exists with $M_{gas} \sim 10^9$ $M_\odot$ and sets a $3\sigma$ upper limit $<9 \times 10^{39}$ erg $s^{-1}$ for a nuclear point-like source. Shaya *et al.* (1996) presented HST Planetary Camera V and I images that confirmed the existence of a small, 34 pc, core radius and found a central non-isothermal luminosity profile. The star cluster population appears to be quite normal in terms of colour and luminosity, with little sign of a young population, in contrast to other studies of merger galaxies (eg. NGC 1275, Holtzman *et al.* 1992; NGC 7252, Whitmore *et al.* 1993; NGC 4038/9, Whitmore and Schweizer 1995).

The origin of tidal tails such as those seen in NGC 1316 is firmly established. Toomre and Toomre (1972) and Toomre (1977) proposed that gravitational interactions between disk galaxies could form tidal features. Further, Toomre (1977) suggested that such disk-disk mergers could ultimately resemble ellipticals. Theoretical studies of equal mass disk-disk mergers by Barnes (1992) have strengthened the case of a merger origin for some ellipticals, whilst recent models (Barnes and Hernquist 1996) have included gas dynamics showing that large central concentrations of gas can form in the cores of merger remnants. Such predictions have been verified by the detection of large amounts of molecular gas in merger galaxies such as NGC 520 (Sanders *et al.* 1988), NGC 4038/9 (Stanford *et al.* 1990) and NGC 7252 (Dupraz *et al.* 1990).

Multi-wavelength observations of mergers can provide important constraints on the types of progenitors, the stellar and gaseous properties of tidal features and merger remnant and the ultimate fate of the remnant. Hibbard *et al.* (1994) presented optical, radio and X-ray observations of the merger remnant NGC 7252. Large amounts of H I exist in the tidal tails, showing inflow into the merger core although there is no H I in the main stellar body. X-ray emission is detected, centred on the main stellar body only. Computed X-ray luminosities suggest that the emission in NGC 7252 is larger than expected for a spiral, and lower than expected for an elliptical of the same blue luminosity. The lack of atomic hydrogen in the main body of the remnant, combined with the presence of warm ionized gas in the nucleus, and possible hot, $\sim 10^{6-7}$K, gas inferred from X-ray measurements, suggests an efficient mechanism converts H I into other gaseous phases. Hibbard and Mihos (1995) made N-body simulations of NGC 7252 in order to explain the H I observations. The kinematics of the H I showed a velocity reversal along the tails that could be successfully modelled as material in the base of the tails falling back to smaller radii of the merger remnant. A comprehensive H I, H II and R-band study of five mergers (including NGC 7252) is presented in Hibbard and van Gorkom (1996). Several trends are evident along the merging sequence including the presence of H I in the disks of the early mergers, and the scarcity of H I in the remnant bodies of the more evolved systems. Efficient gas conversion appears to be a fundamental property along the disk-disk merger evolutionary sequence.

We present very deep CCD observations of NGC 1316 made with the CTIO Schmidt, and *ROSAT* archival X-ray images. In this paper the discovery of an extended, emission line region, at large radii from the nucleus of NGC 1316, yet located within a prominent low surface brightness tidal tail is presented. X-ray emission is detected, possibly for the first time, associated with two tidal tails. We shall discuss the stellar and gaseous properties of the two prominent tidal tails, the probable excitation mechanism of the extended emission line region, and the probable history of merger events in the system. The observations are described in ∮II. Reduction and analysis of the data is given in ∮III. A discussion of the results is given in ∮IV.

## 2. Optical Observations and Data Reduction

The CCD images presented in this paper were taken with the CTIO/University of Michigan Curtis Schmidt 0.6/0.9m telescope. The detector was a Thomson 1024x1024 CCD. The pixel size is 19$\mu$m square (1.835″) however vignetting limits the useable field size to about 30′. Multiple bias and dark images were taken. Flatfields were generated from twilight sky exposures each night. B band ($\lambda_c$ = 4324Å, FWHM=1156Å; CTIO Harris set #2) exposures were taken on the night of 1994 November 10/11. The night was not photometric. Individual exposures were 900s with small shifts between successive exposures. The total exposure time was 11,700s. Narrowband (H$\alpha$+[N II]) exposures were taken on the night of 1994 November 11/12. The night was photometric. Individual exposures were typically 1200s with small telescope shifts between exposures. Total exposure times were 8100s each for the redshifted H$\alpha$+[N II] ($\lambda$ 6563 + $\lambda\lambda$ 6548,6583) emission line filter ($\lambda_c$ = 6606Å, FWHM=76Å), and continuum filter ($\lambda_c$ = 6693Å, FWHM=81Å). Based on the half power points of the 6606Å line filter and assuming emission centred at 6563Å the filter will be sensitive to emission over the velocity range of 250–3700 km s$^{-1}$.

Images were bias subtracted, flatfielded, and added after registration by centroiding on bright stars. Since the night of 1994 November 10/11 was not photometric, B band standard star observations were not taken. The observations were calibrated using previous aperture photometry listed in Lauberts and Sadler (1984). Twelve previous B band photoelectric measurements with aperture diameter sizes ranging from 30.0 to 203.3″ were used to derive a zeropoint of the CCD data with a dispersion of 0.04 mag. The spectrophotometric standard HZ 4 was used to calibrate the narrow band images based on AB magnitudes (Oke 1994, priv. comm). The adopted magnitudes for HZ 4 were $AB_{6606}$=15.01 and $AB_{6693}$=14.81. The H$\alpha$+[N II] image was derived by subtracting a scaled, sky subtracted continuum image from the sky subtracted emission line image. PSF widths of stars in the on-line and continuum images were measured and they agreed within measuring errors. The adopted scaling was calculated from a linear least square fit to residuals of 25 field stars calculated from several scaling factors. Mean pixel values of the final H$\alpha$+[N II] image at large radii from the nucleus were consistent with zero. The H$\alpha$+[N II] image was smoothed with a Gaussian filter of $\sigma$ = 3 pixels. A B-6693Å colour map was constructed from the B and narrowband red continuum filter ($\lambda_c$ = 6693Å, FWHM=81Å) image. PSF widths of stars were matched via slight smoothing, and images were registered via centroiding on bright stars.

## 3. Analysis

### 3.1. B band images and NGC 1316 model

Figure 1 shows the NGC 1316 B band median filtered (stacked) image produced from 13 900s individual images. The galaxy ∼6.4′ N of NGC 1316 is NGC 1317 ($v_0$=1893 km s$^{-1}$ from RSA) that appears very regular, with no sign of structural disturbance. Figure 1 clearly shows the shells, ridges and loops of material at large radii. A prominent tidal tail originates SW of the main body of NGC 1316, then extends to the NW, ending in a straight feature. This is $L_1$ denoted by S80 (see also the sketch map, Figure 2 of S80). A second prominent tail, E of the nucleus, was denoted $L_2$. Other ripple features closer to the nucleus and fainter loops ($L_3$ and $L_4$ in S80, N and SW of $L_2$ respectively) are seen. In this paper we will concentrate on the two most prominent tails, $L_1$ and $L_2$.

This median image shows that the NW portion of $L_1$ is relatively narrow and quite straight, extending SE–NW. Progressing towards the SE, the loop then bends toward a P.A. of ∼90° and becomes much wider. The faint light morphology suggests that this section of $L_1$ is a distinct plateau from the main body of NGC 1316. $L_2$ is structurally more simple than $L_1$, and appears as a loop of material curving into the central region of NGC 1316. To isolate $L_1$ and $L_2$ from the envelope of NGC 1316, an isophotal model of NGC 1316 was made using IRAF [2] *ellipse* and *bmodel* tasks. Features such as NGC 1317 and the nuclear dust lane were masked from the fit. As well, clipping of the highest 10% of pixels in each isophotal fit was implemented to ignore faint light features such as the loops and shells themselves and any faint stars and galaxies that remained undetected by eye. The elliptical model extended to just outside the furthest extent of $L_1$ and $L_2$. The accuracy of the model is poor within $1'$ of the nucleus due to the existence of the nuclear dust lane, however this does not effect the modelling near the tidal tails. The images displayed very good field flattening with small errors in the sky values ($\pm$0.4%) across the image.

Figure 2 shows the B band residual light derived from the median image (Figure 1) after isophotal model subtraction. This image clearly shows the complexity of low light features in the outer envelope of NGC 1316. The projected size of $L_1$ is $\sim$90x35 kpc and the broadening of $L_1$ in the SE and its "plateau" nature as suggested by Figure 1 is confirmed. Its southern edge is quite sharp, although the main SE–NW component of $L_1$ can not be mistaken for a shell due to its extreme width and nearly uniform brightness. The apparent width of $L_1$ may be a projection effect, since tidal tails are usually flattened systems (Toomre and Toomre 1972). The majority of $L_1$ spans less than two magnitudes in surface brightness (25–27 B mag. arcsec$^{-2}$). $L_2$ is slightly shorter in projected size and much more loop-like than $L_1$, and shows a small variation in surface brightness (brighter at its S edge) yet is fainter overall than $L_1$.

The white (deficit) region in the nucleus of length $2'$ at a P.A. of $\sim$160° is the nuclear dust lane. Several extended, clumpy residual regions are seen within 2–$3'$ (NE, NW and SW) of the nucleus, as well as many shells. These regions are not artifacts of the isophotal model subtraction. The residual region to the NW at a P.A. of –40° contains the plume 'P' noted by S80 and subsequently suggested by Graham (1987) as a region of blue stars. The sketch map of Figure 2 in S80 suggests that $L_2$ joins this plume region, however it also seems possible that $L_2$ ends more abruptly in another residual region, NE of the nucleus, at a P.A. of 35°. A third residual region, $2.5'$ SW of the nucleus could be associated with $L_1$. Overlayed on Figure 2 are lines showing the axis of stellar rotation at P.A. = 140° as determined by Bosma *et al.* (1985) and the direction of the two outer radio lobes (Ekers *et al.* 1983) at P.A. = 110°.

Tests showed that the parameters used to exclude extraneous faint features in the isophotal modelling were more important than flat fielding errors when determining the errors in the residual light components. By varying the amount of pixel clipping in each isophote (from our adopted 10%) and constraining the residual pixel value to be zero at large distances from the tidal features, we estimate our errors in the residual light of $L_1$ and $L_2$ to be $\pm$30%. To estimate the stellar luminosity of $L_1$ the residual light was summed, after careful exclusion of bright (foreground) stars. An aperture of 90 x 37 kpc was used. An $L_B$ ($L_1$) = 3.1x$10^9$ $L_{B\odot}$ or 2.2% of $L_B$ (NGC 1316) is found. We have done a similar analysis to determine the optical luminosity of $L_2$. A 31 x 18 kpc aperture was used and $L_B$ ($L_2$) = 2.6x$10^9$ $L_{B\odot}$ was derived. Profile fits to the broadband surface brightness (excluding the loops and ripples) of NGC 1316 support the findings in S80 that NGC 1316 follows an $r^{1/4}$-law very closely, suggesting that the main stellar body has relaxed to an equilibrium configuration. If $L_1$ and $L_2$ were formed by major merger events, with original luminosities well in excess of our calculated values above, our isophotal model could be overestimating the spheroidal light. This problem is inherent to any evolved merger system. Later results and discussion will however propose that the $L_1$ tidal system is probably a recent merger event, and therefore the derived luminosity is representative of the original pre-merger value.

### 3.2. The discovery and properties of the EELR

Figure 3 shows NGC 1316 with H$\alpha$+[NII] emission in greyscale overlayed with B band (total) contours of 23, 24, 25 and 26 mag. arcsec$^{-2}$. The newly discovered extended emission line region is labelled EELR, the giant H II region ($2.6'$ SE of the EELR) found in S80 is labelled SH2, and $L_1$ is also denoted. The positions of the EELR and SH2 relative to NGC 1316 are given in Table 1. The nuclear gas disk is seen, as is H$\alpha$+[NII] associated with NGC 1317. The EELR

[2] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

is situated ∼5.3′ (35 kpc projected distance) SW of the nucleus of NGC 1316 and is located in the previously described plateau region of $L_1$. Comparison with the Figure 2 sketch map of S80 shows that the EELR is near a major dust lane. Inspection of the B band residual image shows strong extinction in the vicinity of the EELR that is structurally similar to the EELR. The position angle of the EELR, ∼45°, is almost perpendicular to the predominant direction (SE–NW) of $L_1$. Very faint Hα+[NII] is also seen between the nuclear gas disk and NGC 1317, yet none is seen near $L_2$.

The SW quadrant of NGC 1316 is shown in Figure 4. Contours show Hα+[NII] emission, whilst greyscale depicts B band residual light (summed B image - isophotal model), clearly showing the intensity and structure of $L_1$. Several bright foreground stars are also seen in projection in $L_1$. The position of the EELR is at the central E edge of $L_1$. Interestingly, SH2 may be located in $L_1$ as well. There are no other bright, extended Hα+[NII] regions in $L_1$. The association between $L_1$ and the B band residual region, 2.5′ SW of the nucleus is shown more clearly, and suggests that it could be part of $L_1$. After excluding a foreground star, this region has a similar surface brightness to the main part of $L_1$. The other residual B band regions (NE and NW of the nucleus) are shown, as well as smaller (than the EELR) Hα+[NII] regions 2′ N of the nuclear gas disk and extending to the W. A close-up view of the EELR is given in Figure 5. The greyscale depicts Hα+[NII] emission, and contour levels at 2.0 and 4.0 x$10^{-17}$ erg $cm^{-2}$ $s^{-1}$ $arcsec^{-2}$ are also shown. A disturbed morphology is suggested, with its long axis extending along the NE-SW direction. The size of the ionized gas region is 81x27″ or 9x3 kpc. Central concentrations are evident along the major axis of the EELR and close-by, faint blobs of emission are also seen. The integrated flux of the EELR, $f_{H\alpha+[NII]}$ is 8.1x$10^{-14}$ erg $cm^{-2}$ $s^{-1}$.

### 3.3. The hot gas environment near $L_1$, $L_2$ and the EELR

A *ROSAT* Position Sensitive Proportional Counter (PSPC; Pfeffermann *et al.* 1987) image of NGC 1316 (FWHM ∼ 25″) was extracted from the U.S. *ROSAT* data archive. This data has been previously used in a study of the X-ray emission associated with the outer radio lobes by Feigelson *et al.* (1995) who showed that the emission, predominantly beyond the field of view of our images, (see their Figure 2) can be explained by Inverse-Compton scattering. The total exposure time was 25.5 ksec. Figure 6 shows contours of PSPC Broadband (0.1-2.4 keV) emission at 3, 5, 10 and 20$\sigma$ above background overlayed on the B band residual image, shown in greyscale. The PSPC data was binned to a pixel size of 15″ (approximately half of the PSPC FWHM; the PSPC instrumental pixel size is 0.5″) and smoothed with a Gaussian filter of $\sigma$ = 2 pixels. The emission is dominated by X-rays from the main body of NGC 1316, however the X-ray emission at large radii is quite complex.

There is substantial X-ray emission cospatial with the higher surface brightness regions of $L_1$. The EELR is positioned (see arrow in Figure 6) on the N edge of this X-ray emission that extends S then W of NGC 1316. Other X-ray emission, that is cospatial with parts of $L_2$ (excluding the emission probably originating from the bright star SE of the main region) is seen. A third region of emission extends NW from NGC 1316, where there is little or no residual B band light at large radii. The X-ray emission that extends N from NGC 1316 overlaps with NGC 1317. There is no evidence of X-ray emission near the other loops or tails in the system.

An analysis of the PSPC data within 3′ of the nucleus (not including the emission near $L_1$ or $L_2$) has been done by Kim *et al.* (1997). The X-ray spectrum is consistent with hot gaseous emission, with an $L_X$ ∼ 2 x $10^{41}$ erg $s^{-1}$ (for the Kim *et al.* 1997 adopted distance of 27.2 Mpc), and a possible hard component that could be due to low-mass binaries, contributing 20-30% of the flux. We concentrate on the X-ray emission at intermediate radii that has not been studied. The good correspondence of X-ray emission with both $L_1$ and $L_2$ tidal tails suggests a physical association. The origin of the emission could be binary sources and SNR in the tails and/or hot gas resulting from the merger process or from the evolution of the ISM in the tails. To investigate the origin of the X-ray emission, PSPC spectra have been extracted from the tidal tail regions (for the apertures used see Table 2). The background was taken well away from source emission (N. of NGC 1317), and vignetting corrections were applied to the data. The total PSPC spectral counts were 712±71 and 280±47 for the $L_1$ and $L_2$ regions respectively. Given the limited statistics of the data for the $L_2$ region, we concentrate on finding acceptable XSPEC spectral fits for the $L_1$ region emission. Table 2 summarizes our spectral fitting results.

We find that a single component Raymond and Smith (Raymond and Smith 1977; R-S hereafter) gaseous thermal model yields kT = 0.55 keV (with XSPEC 90% limits of 0.40-0.83 keV for 3 interesting parameters), $N_H$ = 2.3 (1.2-3.5) x $10^{20}$ cm$^{-2}$, (consistent with the line of sight $N_H$ = 2 x $10^{20}$ cm$^{-2}$; Fabbiano *et al.* 1992), and a very low metal abundance of 5.8 x $10^{-3}$ (0 - 4.1 x $10^{-2}$) of solar. The fit returns a $\chi^2$ of 17.5 for 25 degrees of freedom (d.o.f.). A statistically similar fit to the spectra can be achieved by using a single component Bremsstrahlung model. This model could represent a population of discrete X-ray sources (ie. binaries) in the tidal tails. The fit yields kT = 0.54(0.39-0.80; for 2 interesting parameters) keV, $N_H$ = 2.7(1.7-3.8) x $10^{20}$ cm$^{-2}$ (again consistent with the line of sight value), and a $\chi^2$ of 19.2 for 26 d.o.f. Both single component models return similar X-ray luminosities (see Table 2) of ~2 x $10^{40}$ erg s$^{-1}$. Other model fits have been attempted although none are as good as the single model fits above. An R-S model with fixed line of sight absorption and solar abundance returns an unacceptable $\chi^2$ of 67.3 for 28 d.o.f. A combined R-S (solar abundance) and Bremsstrahlung (kT = 5 keV; a temperature typically used to describe a hard X-ray binary component) model with fixed line of sight absorption, gives a soft R-S temperature of 0.16 keV and returns a $\chi^2$ of 27.9 for 28 d.o.f.

The range of kT suggested by the single model fits (see Table 2) shows that the X-ray emission of $L_1$ is significantly softer than that expected from a population of evolved stellar sources (see Fabbiano 1989 and refs. therein) suggesting the emission is from a hot ISM. This is not surprising since the expected emission from a population of binary X-ray sources is $L_X$ ~6 x $10^{38}$ erg s$^{-1}$ in $L_1$ (using the average $L_X$-$L_B$ relation of spirals in Fabbiano *et al.* 1992), which is a factor ~10 less than the above calculated luminosities. We adopt an area of 45 x 35 kpc (consistent with the area of X-ray emission in $L_1$) and a depth of 5 kpc, which assumes that the hot gas is coexistent with the tidal tail, and that the tail is seen face-on, consistent with most tails being flat or ribbon-like (Toomre and Toomre 1972). We adopt the cooling function of Wang and Helfand (1991) used for the LMC and a hot gas $L_X$ ~2 x $10^{40}$ erg s$^{-1}$ to derive an electron density of $n_e \sim 2.4 \times 10^{-3}\ \eta^{-1/2}$ cm$^{-3}$, where $\eta$ is the gas volume filling factor. The mass of hot, ~5 x $10^6$K gas in $L_1$ is then $\sim 5 \times 10^8\ \eta^{-1/2}\ M_\odot$. Uncertainties in the volume would suggest an error of 2-3 could exist in our mass estimate. The implied shock velocity for this temperature of gas is ~380 km s$^{-1}$, much higher than observed for the H I infall velocity at the base of the tidal tails in NGC 7252 (Hibbard *et al.* 1994).

## 4. Discussion

### 4.1. Stellar and gaseous content of $L_1$ and $L_2$: Clues to the nature of the progenitors

We can attempt to derive the stellar and gas contents of the $L_1$ progenitor based on the properties of the $L_1$ tidal tail. We have determined that the luminosity of $L_1$ is 3.1x$10^9$ $L_{B\odot}$ with an error of ±30%. There is no evidence of recent star formation due to passage through NGC 1316 (see Section 4.2 for a discussion about the global colour of $L_1$). The structural characteristics of $L_1$ (plateau, ridges or ripples and the sharp southern edge), imply that the progenitor was a dynamically "colder" galaxy than NGC 1316 (Quinn and Hernquist 1987). For the following discussion we shall assume that the derived luminosity of $L_1$ is representative of the total luminosity of its progenitor galaxy. Arguments given later in this section and in section 4.3 will propose that $L_1$ is substantially different structurally and in gas content from the other tidal tails that are more likely to be indicative of a major disk-disk or disk-E merger.

We can estimate an original H I mass for an $L_1$ progenitor based on the gas fraction estimates of spirals. Adopting the H I estimates in Table IV of Haynes and Giovanelli (1984) and allowing the possible morphological types of the $L_1$ progenitor to range from Sa-Sab through Scd-Sd, would suggest an initial H I mass ranging from 8.7x$10^8$-2.8x$10^9$ $M_\odot$. This gas mass is substantially more than that detected in observations. Early searches for H I gave upper limits only for NGC 1316. Reif *et al.* (1982) list an upper limit of 4.5 Jy km s$^{-1}$, whilst Jenkins (1983) derives a similar (to Reif *et al.* 1982) H I mass limit of <2x$10^8$ $M_\odot$. A VLA H I observation (van Gorkhom 1996 priv. comm.) detects several $10^7$ $M_\odot$ of H I near SH2 but only an upper limit of ~1x$10^7$ $M_\odot$ for the region near the EELR. We can also estimate the amount of H I that could be associated with the dust lane near the EELR. We assume a Galactic gas-to-dust ratio of $M_{gas}/M_{dust}$ = 100, and $N_H$ = 5.8 x $10^{21}$ $E_{B-V}$ atoms cm$^{-2}$ (Bohlin *et al.* 1978). $A_B$ is measured directly from our B band image and isophotal model, whilst we assume the dust is optically thick across $5.9 \times 10^7$ pc$^2$. We adopt an $R_B = 4.10$ (Goudfrooij *et al.* 1994b) and derive $M_{HI} = 1.1 \times 10^8$ $M_\odot$, that is substantially larger than the upper limit found near the EELR, but still less than the gas mass predicted from a spiral progenitor.

We determine the ionized gas content of the EELR. We derive L(H$\alpha$ ) = $8.2 \times 10^5$ $L_\odot$ or $3.2 \times 10^{39}$ erg s$^{-1}$ which is is a factor of $\sim$10 less than the expected L(H$\alpha$ ) for a $3.1 \times 10^9$ $L_{B\odot}$ late-type spiral based on the L(H$\alpha$ )-$l_B$ regression fits of Trinchieri *et al.* (1989). We then convert this L(H$\alpha$ ) to a mass, and determine $M_{HII} = 7.5 \times 10^3$ $M_\odot$. A summary of the EELR dust and gas properties is given in Table 3. Therefore, based on a late-type spiral progenitor for $L_1$ the H II content could be diminished by a factor of $\sim$10, and the H I content, allowing for the range of spiral types, may be diminished by $\sim$30-100. As discussed in Section 3.3, $\sim$5 x $10^8$ $M_\odot$ of hot, 6 x $10^6$K, gas could also exist near $L_1$. This could be the first detection of hot gas associated with tidal tails. The presence of a hot ISM may suggest heating by strong shocks (consistent with a merger velocity of a few hundred km s$^{-1}$). This hot gas may shock heat any cold gas that is falling into the central regions, and can at least partially explain the dearth of H I. We estimate a cooling time, $\tau_c \sim 1$ x $10^9$ $\eta^{1/2}$ yrs, which is larger than our estimated merger lifetime (see Section 4.2) of 0.5 Gyr. The amount of total ISM is in excess of that expected from the outgassing of an evolving stellar population (Faber and Gallagher 1976) over the lifetime of the merger. We assume that the stellar population in the tidal tail is similar to early-type galaxies as assumed in Faber and Gallagher (1976), which is supported by the smooth optical stucture in the tail and the elliptical-like colour (see Section 4.2) across the majority of $L_1$. We derive an outgassed mass of $\sim$3 x $10^7$ $M_\odot$ based on the estimated $L_B$ of $L_1$ and a 0.5 Gyr lifetime, being the estimated time since the start of the merger encounter. Hence the bulk of the observed gas must be from the pre-merger progenitor.

The existence of a hot ISM in a tidal tail is an important discovery. Other tidal tail systems do not show X-ray emission suggesting a low or nonexistent hot gas content. The PSPC observation of NGC 4038/9 (Read *et al.* 1995) detects emission related to the two interacting disks that can be explained by almost equal amounts of discrete source and diffuse emission originating from $\sim$4 x $10^6$K gas. The Hibbard *et al.* (1994) PSPC observation of NGC 7252 shows emission centred on the merger remnant body only. Our observations show that in $L_1$ (and possibly $L_2$) a hot gas phase exists that is separate to the central hot gas associated with the main stellar body. The shock velocity needed to produce the $\sim$5 x $10^6$K gas in $L_1$, $\sim$380 km s$^{-1}$, suggests a rapid interaction velocity well in excess of the gas infall velocities in NGC 7252 and may help explain the paucity of H I. We suggest that the extreme size (9 x 3 kpc) of the EELR, the large hot gas content and the extensive and unusual tail morphology (similar to low mass merger models of Hernquist and Quinn 1989) of $L_1$ support it being the $\sim$0.5 Gyr old remnant of a low mass, gas rich disk galaxy.

The $L_2$ tail is fainter and much smoother than $L_1$ although the S section has a slightly higher surface brightness than the rest of the tail. We do not detect any H II emission nor is any H I detected. If the X-ray content in $L_2$ is similar to that in $L_1$, and adopting a gas volume of 30 kpc x 15 kpc x 5 kpc, by simple scaling of the ratio of PSPC counts, $L_2$ may contain $\sim$1 x $10^8$ $M_\odot$ of hot gas (see Table 4 for a summary). The smooth structural appearance may suggest a progenitor that is dynamically hotter than the $L_1$ progenitor. We suggest that $L_2$ is not necessarily associated with the event that formed $L_1$ but could be related to a previous disk-disk or disk-E merger. The likely merger history and tidal tail progenitors will be discussed further in Section 4.3.

### 4.2. The probable ionization mechanism of the EELR

The large size, 9 kpc x 3 kpc (a factor $\sim$5 larger in surface area than SH2) and special (projected) position of the EELR in the high surface brightness region of $L_1$, argues against it simply being a giant H II region, and connects its existence with the $L_1$ merger event. Theoretical simulations of low mass mergers (Weil and Hernquist 1993) show that stellar and gaseous (T=$10^4$K) components *rapidly* segregate with the gas flowing quickly into the nucleus of the primary galaxy whilst the stellar tidal tail evolves. As an example, one model simulation, Figures 2, 3 and 6 of Weil and Hernquist (1993), shows that by a timestep of 60 units, a substantial amount of merger gas has reached the central regions of the primary galaxy, whilst the stellar merger component continues to display low surface brightness shells and loops out to a timestep of 200 units. Hence at least in this case it is possible that a large fraction of the gas rapidly segregates from its stellar body within 30% of the total time that such stellar merger signatures (shells, loops, tails) are visible.

The stellar light extent of $L_1$ would *suggest* it is substantially dynamically evolved. We derive an age estimate of $L_1$ of $\sim$5x$10^8$ yrs based on the low mass merger models of Hernquist and Quinn (1988) and Hernquist and Quinn (1989). We compute our age estimate via Equation 2.1 of Hernquist and Quinn (1988), inputting mass estimates for NGC 1316 and the $L_1$ progenitor, and then comparing the timescale of appearance of similar model structures to that seen in $L_1$. The error in this age estimate is probably a factor of 2, given the uncertainties of the geometry of the encounter and the long lifetime of the fine structures. If our age estimate is correct then the evolved nature of the stellar component of $L_1$ should favour a scenario in which the majority of progenitor gas already resides in the nucleus of NGC 1316. Whilst we detect a substantial amount of warm (the EELR) and hot gas, it is possible that the present warm and H I gas content is a factor $\sim$10 and $\sim$30-100 smaller (see Section 4.1) respectively than their original values. CO observations of NGC 1316 by Sage and Galletta (1993) detect $\sim$1 x $10^9$ $M_\odot$ of $H_2$ that is coextensive with dust in the central ionized gas disk. Velocities suggest that the ionized and molecular gas are corotating, and the observations support an external origin for the warm gas and $H_2$. Therefore it is possible that a large fraction of the incoming galaxies original gas has settled into the nucleus of NGC 1316, in agreement with the rapid segregation predictions of Weil and Hernquist (1993).

There is no indication of a concentrated, stellar remnant within $L_1$. Inspection of the B-6693Å colour map shows that the *predominant* colour of $L_1$ is similar to non-disturbed areas of NGC 1316 at similar radii. Small blue regions are seen but do not dominate the $L_1$ colour. Hence there appears to be no compelling evidence for a present epoch, high star formation rate. The argument for photoionization of the EELR by young stars or hot old stars appears weak due to the lack of any unusual colour near the EELR. Based on the above, and the existence of the nearby structurally similar dust lane, we suggest that the most probable ionization mechanism of the EELR is shock excitation of remnant cold gas of the $L_1$ progenitor. Spectroscopic observations are required to determine this conclusively and establish its dynamical properties.

### 4.3. A merger (or more?) in progress

The complicated structure of NGC 1316 hinders an accurate reconstruction of its merger history. The small amount of H I does not allow a dynamical study to be done as in Hibbard and Mihos (1995) for the tidal tails in NGC 7252, and hampers attempts to predict the merger progenitor types. S80 proposed the infall of several gas-rich galaxies over the past $\sim$2x$10^9$ yrs to explain the system. Similarities between numerical models and observed systems of disk-disk mergers and some features of NGC 1316 also suggest that it could be an old remnant of a major disk-disk merger. It is also possible that both processes are occurring. In the case of a major disk-disk merger the lack of well defined bright tidal tails at large radii (eg. as seen in NGC 7252, Schweizer 1982; NGC 4038/9, Toomre and Toomre 1972) and the lack of H I in the tidal tails would support it being a substantially evolved merger system. The central surface brightness profile (excluding the loops and ripples) of NGC 1316 was found to follow an $r^{1/4}$-law very closely, hence the main stellar body has relaxed to an equilibrium configuration. This again supports an evolved system. The existence of nuclear $H_2$ and warm gas and a central hot ($10^7$K) ISM (Kim *et al.* 1997) and a possible mass of $\sim$6 x $10^8$ $M_\odot$ of $\sim$5 x $10^6$K gas associated with two tidal tails would support an efficient and evolved conversion of H I into other phases as seen in other merger systems (Hibbard and van Gorkom 1996).

The very faint (S80 estimates 27-28 mag. arcsec$^{-2}$ in B) loop of stellar material (denoted $L_5$ in S80) that extends 25$'$ S-SW of the galaxy (outside our CCD field of view but shown in Figure 9 in S80) and the shorter length loop $L_2$ that are opposing, may be associated with one merger event. Whilst two equal length tails are typically associated with the classical picture of a disk-disk merger (Toomre and Toomre 1972), it is possible (Balcells 1997) to produce two different length and surface brightness tails (ie. $L_2$ and $L_5$) by the merger of a single spiral with a pre-existing elliptical given a special impact trajectory. However, without such special impact parameters, the narrowness of the $L_2$ and $L_5$ features is hard to explain by an interaction with a dynamically hot elliptical that should typically produce broad features. $L_2$ has no detectable H I or H II which argues for it to be substantially evolved, whilst the gaseous content of $L_5$ is unknown although S80 does describe variations in its structure that may suggest associations of young stars. Shorter tails can also be produced via a bulge-dominated progenitor, which is also consistent with the low cold and warm gas content in $L_2$.

The properties of $L_1$ suggest that it is a singular merger event. The structure of the tidal tail is remarkably similar to structures produced in the low mass merger models of Hernquist and Quinn (1989). The existence of a 9 x 3 kpc, $\sim 10^4$ $M_\odot$ of $\sim 10^4$K gas (the EELR) is unusual in a tidal tail. The position of the EELR in the highest surface brightness region of $L_1$ and its disk-like shape suggest that it could be the remnant of a cold gaseous disk. The gas content and optical structure and brightness range of $L_1$ are very different to both $L_2$ and $L_5$ again suggesting different origins. Could $L_1$ be related to a previous disk-disk or disk-E merger event? Schweizer and Seitzer (1992) have suggested that delayed splashbacks of material can occur for several Gyr after an initial merger event. A splashback event would probably show extensive, disturbed stellar light (and possibly cold and warm gas) at large radii which is not seen. The centrally located position of the EELR, and the clean, compact stellar structure of $L_1$ argues against it being a splashback event. The broader shape of $L_1$ to that of $L_2$ and $L_5$ should argue for a merger event with an evolved, hot system. We believe the observational evidence support $L_1$ being a $\sim$0.5 Gyr old remnant of a gas rich galaxy on a high velocity encounter with the halo of NGC 1316.

The varied and numerous fine structures and gaseous properties of NGC 1316 may also be consistent with separate merger events. However, a recent study suggests that a major disk-disk merger can produce fine structure features that have been previously associated with low mass mergers. Balcells (1997) has observed NGC 3656 and finds two, low surface brightness tails, and argues for a major disk-disk merger origin of shells and a minor axis dust lane. In NGC 3656 however, the tidal tails are similar in brightness and extent, and are very different to the complex and numerous tidal tail system of NGC 1316. The NGC 1316 tidal tail system comprises 5 tails or loops of varying morphology, which argues for more than one merger event. The existence of nuclear molecular gas and a warm gas disk, and special nuclear (small core radius, high surface brightness) properties also suggest that earlier merger events may have taken place before the $L_1$ event began. The location of NGC 1316 in a cluster may also provide opportunities for multiple mergers. Adopting a mean expansion velocity of 200 km $s^{-1}$ for the $L_5$ tail infers a timescale of $\sim$1 Gyr. This is similar to the timescales of the merger remnants NGC 7252 and NGC 3921 (Schweizer and Seitzer 1992). The faintness and low H I contents of $L_2$ and $L_5$ tails compared to the tails of NGC 7252 and NGC 3921 may imply an even longer timescale for a disk-disk or disk-E merger. In contrast, using the same encounter velocity for the $L_1$ tail, a $\sim$5 x $10^8$ yr dynamical age is derived which agrees with our previous age estimate for $L_1$ based on the models of Hernquist and Quinn (1988). If the shock velocity, $\sim$380 km $s^{-1}$, inferred from the hot gas temperature of the $L_1$ region is representative of the encounter velocity then the above estimate of the $L_1$ age may even be too large, by a factor of $\sim$2. Hence, whilst a significant amount of mass in NGC 1316 could have been deposited by an early disk-disk or disk-E merger, optical and X-ray observations presented here suggest that a recent, ongoing low mass, gas rich galaxy is still in the process of merging.

We would like to thank Arturo Gomez for assistance at the CTIO Schmidt, Bev Oke for providing spectrophotometric scan information, and Jacqueline van Gorkom for supplying information about her VLA observations of NGC 1316. We thank Brian McNamara for comments on an early draft of the manuscript. We also thank the referee for many constructive comments that greatly improved the paper. The IRAF and VISTA image and spectral reduction packages were used in this work. This work was supported by NASA grant NAGW–2681 (LTSA).

Table 1

Coordinates and Offsets of Features.

| | R.A. (1950) | Dec. (1950) | $\Delta$ R.A. ($''$) | $\Delta$ Dec. ($''$) |
|---|---|---|---|---|
| NGC 1316[a] | 03 20 47.2 | $-37$ 23 08 | | |
| EELR | | | 148W | 271S |
| SH2 | | | 44W | 380S |

[a]The position of NGC 1316 is that given for the bright optical core in Schweizer (1981). All other positions are relative offsets from the optical nucleus based on the CTIO Schmidt CCD images.

Table 2

X-ray Properties of the $L_1^a$ region.$^{\dagger}$

| Model | $N_H$ ($\times 10^{20}$ cm$^{-2}$) | Abundance (units of $\odot$) | $kT_{R-S}$ (keV) | $kT_{Brem.}$ (keV) | $\chi^2$/d.o.f./$\chi^2_{red.}$ | Flux (erg cm$^{-2}$ s$^{-1}$) | $L_X$ (erg s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| R-S | 2.3(1.2-3.5) | 5.8E-03(0-4.1E-02) | 0.55(0.40-0.83) | ... | 17.5/25/0.70 | 2.7(1.6-4.8)E-13 | 1.7(1.0-3.0)E40 |
| Brem. | 2.7(1.7-3.8) | ... | ... | 0.54(0.39-0.80) | 19.2/26/0.74 | 2.8(1.7-4.6)E-13 | 1.7(1.1-2.9)E40 |

[a] 712±71 PSPC (0.1 - 2.4 keV) counts were extracted for the $L_1$ region in a 375″ x 300″ aperture centred on 03 20 33.8 -37 29 00 (1950), compared to 280±47 for the $L_2$ region in a 210″ x 330″ aperture centred on 03 21 24.1 -37 24 41 (1950). Background was taken from a 750″ x 360″ region, north of NGC 1317, centred on 03 20 38.5 -37 10 15 (1950).

† Errors in brackets are 90% confidence for 3 interesting parameters (R-S model) and for 2 interesting parameters (Brem. model).

Table 3
Estimated and Measured Masses of the EELR.

| Mass | Amount |
| --- | --- |
| $M^{\dagger}_{\rm HI}$ | $1.1 \times 10^{8}$ $M_{\odot}$ |
| $M^{\ddagger}_{\rm HI}$ | $<1 \times 10^{7}$ $M_{\odot}$ |
| $M_{\rm HII}$ | $7.5 \times 10^{3}$ $M_{\odot}$ |

$M^{\dagger}_{\rm HI}$ estimated from observed dust extinction and assumes $M_{gas}/M_{dust} = 100$.

$M^{\ddagger}_{\rm HI}$ is upper limit from observation.

$M_{\rm HII}$ assumes a 33% contribution to $f_{H\alpha+[NII]}$ from [NII] (based on 14 spirals, mainly Sc's; Kennicutt 1983), and $L(H\alpha) = 2.96 \times 10^{16}$ $f_{H\alpha}$ $D(\mathrm{Mpc})^2$ $L_{\odot}$, and $M_{\rm HII} = 2.33 \times 10^{3} \left( \frac{L(H\alpha)}{10^{39}\,\mathrm{erg\,s^{-1}}} \right) \left( \frac{10^{3}\mathrm{cm^{-3}}}{n_e} \right) M_{\odot}$ (Osterbrock 1974, Case B recombination theory; Goudfrooij *et al.* 1994a), $n_e = 10^{3}$ cm$^{-3}$ (assuming an electron temperature of $\sim 10^{4}$K).

Table 4
Optical luminosities and estimated hot gas masses of $L_1$ and $L_2$.

| | $L_1$ | $L_2$ |
|---|---|---|
| $L_B$ | $3.1 \times 10^9 \pm 30\%\ L_{B\odot}$ | $2.6 \times 10^9 \pm 30\%\ L_{B\odot}$ |
| $M_{X,gas}$ | $\sim 5 \times 10^8\ M_\odot$ | $\sim 1 \times 10^8\ M_\odot$ |

$M_{X,gas}$ for $L_2$ is estimated assuming a similar X-ray content to $L_1$ and a gas volume of 30 x 15 x 5 kpc.

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Fig. 1.— B band image of NGC 1316. NGC 1317 is 6.4′ N of NGC 1316. Schweizers (1980) $L_1$ loop is W and SW of NGC 1316 and $L_2$ loop is E of NGC 1316.

Fig. 2.— B band residual image of NGC 1316. Loops $L_1$ and $L_2$ are denoted. The axis of stellar rotation and the direction of the outer radio lobes are indicated.

Fig. 3.— A H$\alpha$+[N II] image of NGC 1316 and environment (greyscale) overlayed with B band surface brightness contours of 23,24,25 and 26 mag. arcsec$^{-2}$. The EELR, SH2 and $L_1$ are indicated.

Fig. 4.— SW quadrant of NGC 1316. B band residual shown as greyscale. Overlayed is H$\alpha$+[N II] shown in solid contours (2.0 and 4.0x10$^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ ).

Fig. 5.— A subimage of Figure 3 showing the EELR in H$\alpha$+[N II] (greyscale). Overlayed are H$\alpha$+[N II] contours at flux levels of 2.0 and 4.0x10$^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ .

Fig. 6.— B band residual light (greyscale), overlayed with *ROSAT* PSPC Broadband (0.1 - 2.4 keV) 3, 5, 10 and 20 $\sigma$ contours. The arrow shows the position of the EELR.