ONGOING MASS TRANSFER IN THE INTERACTING GALAXY PAIR NGC 1409/1410

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ABSTRACT

I present two-band Hubble Space Telescope (HST) STIS imaging and WIYN spectral mapping of ongoing mass transfer in the interacting galaxy pair NGC 1409/1410 (where NGC 1410 is the Seyfert galaxy also cataloged as III Zw 55). Archival snapshot WFPC2 imaging from the survey by Malkan and coworkers showed a dust feature stretching between the galaxies, apparently being captured by NGC 1409. The new images allow estimates of the mass being transferred and the rate of transfer. An absorption lane typically 0′25 (100 pc) wide, with a representative optical depth $\tau_B = 0.2$, cuts across the spiral structure of NGC 1410, crosses the 7 kpc projected space between the nuclei, wraps in front of and, at the limits of detection, behind NGC 1409 and becomes a denser ($\tau_B = 0.4$) polar feature around the core of NGC 1409. The combination of extinction data in two passbands allows a crude three-dimensional recovery of the dust structure, supporting the front/back geometry derived from colors and extinction estimates. The whole feature contains on the order of $2 \times 10^8 M_\odot$ in dust, implying about $3 \times 10^8 M_\odot$ of gas and requiring a mass transfer rate averaging $\approx 1 M_\odot$ yr$^{-1}$, unless we are particularly unlucky in viewing angle. Curiously, this demonstrable case of mass transfer seems to be independent of the occurrence of a Seyfert nucleus, since the Seyfert galaxy in this pair is the donor of the material. Likewise, the recipient shows no signs of recent star formation from incoming gas, although NGC 1410 has numerous luminous young star clusters and widespread H$\alpha$ emission.

Key words: galaxies: individual (NGC 1409, NGC 1410) — galaxies: interactions — galaxies: star clusters

1. INTRODUCTION

Galaxy interactions are clearly linked to bursts of star formation and, in more restricted ways, to the triggering of nuclear activity. What physical mechanisms mediate these connections remains unclear, since there are multiple well-motivated and plausible processes. Among these, mass transfer between the galaxies in an interacting system has long been discussed, but evidence for its occurrence has remained largely circumstantial. Such transfer could play a particular role in dumping gas into the inner regions of a galaxy, since the angular momentum barrier, which restricts the inward transport of disk gas, may be greatly reduced if the gas comes from another galaxy with the appropriate encounter geometry.

The conditions for mass transfer have been examined analytically as well as numerically. Sotnikova (1990) considered the fate of dense interstellar medium (ISM) clouds crossing between galaxies and heated by both conduction and radiation in a hot intergalactic medium, finding that the clouds could survive long enough to reach the second galaxy, and that a stream of clouds from galaxies in low-eccentricity orbits could reach a quasi–steady-state configuration. Her numerical simulations (Sotnikova 1988) indicated that this situation is reached much faster when the spiral spin and orbit are parallel than the antiparallel case, in roughly an orbital timescale of the binary system.

Wallin & Stuart (1992) presented an extensive study of mass transfer from restricted n-body simulations, including over 1000 encounter geometries to map the systematics of mass transfer. The largest amounts finally captured by the second galaxy are found for encounters with the orbital plane close to the donor’s disk plane, with this favoritism enhanced by the strong dependence on orientation of periapsis for non-planar encounters. The intuitive increases in mass transfer for closer periapsis and larger mass ratio also hold. These simulations do not give much detail on how the companion captures the mass but should be robust as to the totals bound in its potential well. These results fit with patterns in the 86 simulations described by Howard et al. (1993), where the particles were tracked but there was no modeled companion structure to interact in detail with the incoming particles.

The observational signatures of mass transfer can be hidden in the complex kinematics and star formation behavior of gas-rich interactions and mergers. Thus, it has long been recognized that such effects are easiest to see in pairs of mixed morphology, since large amounts of cool gas in the early-type E/S0 members of these systems very likely originated in the gas-rich companion (as set forth by Domingue et al. 2003). This has been particularly discussed in the context of emission lines, far-infrared emission, and blue (post-starburst) optical colors for these galaxies, as possible evidence of past gas transfer (de Mello et al. 1995, 1997). This would also account for the Holmberg effect, a correlation between colors of pair members, even for early-type members (Holmberg 1958; Demin et al. 1984; Madore 1986; Reduzzi & Rampazzo 1995). Marziani et al. (2003) present kinematic evidence of ongoing or recent dumping of gas in the pair Arp 194 and stress that mass transfer itself is necessary but not sufficient for cross-fueling of nuclear activity or starbursts.

An unusually clear example of current mass transfer appeared in the HST WFPC2 snapshot survey of active galactic
nuclei (AGNs) and starburst galaxies by Malkan, Gorjian, & Tam (1998). Their data for NGC 1409 showed a dust lane crossing between NGC 1409 and its close companion (and Seyfert galaxy) NGC 1410, also known as III Zw 55 (although there has been some ambiguity in the literature as to which member of the pair is which). This feature extends even beyond the region shown in Figure 1 of Malkan et al. (where the galaxy identified there as the Seyfert galaxy NGC 1410 is in fact its earlier type and more quiescent companion NGC 1409). Such cases highlight the value of dust absorption as a tracer of the ISM, also exploited by several groups analyzing HST imagery of the nuclei of early-type galaxies (Martel et al. 2000; Tran et al. 2001; Martini et al. 2003).

The extensive tidal envelope of stars around NGC 1409/1410 provides backlighting to trace this feature and estimate the total mass and transfer rate involved. To allow such a study, two-color STIS imagery was obtained with a higher signal-to-noise ratio in each band. The results are described here, along with mapping in Hα and [N ii], which constrains the encounter geometry and timing through the velocity field.

We see the NGC 1409/1410 pair deep into a strong encounter, as shown by the presence of a substantial stellar envelope extending well beyond the two galaxy cores, to a radius of at least 15 kpc. The nuclei are projected at a separation of only 7 kpc suggesting that there may have been significant tidal loss of stars from both galaxies. The spiral NGC 1410 in particular is rather small in linear size, with the nearly face-on loss of stars from both galaxies. The spiral NGC 1410 in only 7 kpc suggests that there may have been significant tidal contamination in the extended emission occurring in this region are much smaller than in the star-forming disk of NGC 1410, emission-line contamination is unlikely to be an issue in these results.

The white-light image (in the 50CCD mode) is shown in Figure 1 to illustrate the geometry of the NGC 1409/1410 pair, the extensive diffuse envelope of scattered stars, and the third companion spiral seen to the north of the strongly interacting pair. The stellar envelope provides smooth background light to trace the dust between and beyond the two pair members.

The observations, sequence root o5ev01, include full-orbit (2767 and 2815 s) sets of exposures, two in each filter for cosmic-ray rejection. The filter change introduces a small scale change between the two images, evaluated from the locations of 11 unresolved or compact objects. The angular size of the red F28X50LP pixels is larger than the white-light 50CCD pixels by a factor 1 + 7.9 × 10⁻⁴, amounting to 0.8 pixels across the frame. This was corrected for differential analysis by transforming the red image to the coordinate system of the white-light data.

To analyze the extinction properties of the dust feature, a blue-light image was constructed as a scaled difference between the white- and red-light data sets. This allowed the use of the very sensitive STIS CCD for multicolor measurements, since the exact shape of the blue passband is less important than that the shape be known. The preflight estimates of the relative throughputs of the two filters in their overlap region had to be substantially revised, since using the initial throughput values led to unphysical negative flux in the difference. The F28X50LP filter was designed to replicate the white-light 50CCD configuration with only a gray shift longward of a sharp cutoff to the blue. To the extent that this was realized in fabrication, the count rate at each pixel can be expressed in terms of the white-light rate $C_W$ and that in the red F28X50LP filter $C_R$ to give a differential blue rate $C_B$ according to

$$C_B = C_W + C_R / f,$$

where $f$ is the mean transmission ratio of red and white-light passbands longward of the cutoff wavelength. The in-flight calibration, now incorporated into the STSDAS crefer files, gives $f = 0.873$ averaged across the 6000–9500 Å range. This fits with astrophysical constraints from the range of color and...
direction of color gradient in the early-type galaxy, which show that $f$ must lie in the range $0.83–0.93$. Figure 2 shows the effective passbands of the two filters and their scaled difference.

An image in the blue passband was produced following equation (1). To avoid confusion with standard photometric passbands, the original and derived images will be referred to simply as white-light, red, and blue. To show the overall structure of the system, the central portion of the STIS field is shown in Figure 3, comparing the blue and red images.

Some analysis techniques can make more appropriate use of the observed white and red passbands, since they are statistically independent and free of the correlated noise that can result from measuring subtle features in a difference image. Similarly, some points can be made more clearly using the disjoint passbands of the red and blue images. To allow approximate scaling of the extinction results from these broad passbands, the effective extinction was evaluated using a model old stellar population (appropriate for NGC 1409 and probably for most of the stellar envelope as well), in photon units. These very broad bands have the potential for nonlinear extinction behavior (that is, significant changes in effective wavelength with reddening). In practice, these numerical tests indicate that such shifts are still small for extinctions $A_V < 1$ and slopes near that of a normal Galactic extinction law ($A_V/E_{B-V} = 3.1$). The blue passband behaves very much like $V$; its extinction ranges from 1.01 to 0.97$A_V$ over the range $A_V = 0–4.0$, varying in a nearly linear fashion. The red passband has extinction $0.58–0.54A_V$ over the same range, again changing almost linearly with $A_V$. The much broader white-light band shows more pronounced color behavior with increasing reddening, with extinction from $0.68–0.59A_V$ for $A_V = 0–4.0$ in a roughly quadratic way, as the redder part of the passband becomes more important at large extinctions. However, the extinctions that matter in this work are small enough that these are not major complications.
2.2. Spectroscopic Mapping

To help us understand the kinematics and interaction history of NGC 1409/1410, the velocity field in Hα and [N ii] emission was measured using the 3.5 m WIYN telescope and DensePak fiber array. As described by Barden, Sawyer, & Honeycutt (1998), the array includes a 7 × 13 configuration of fibers in a roughly hexagonal packing covering a 35′′ × 45′′ region, set for these observations with the long axis at P.A. 0°. Four outlying fibers allow sky subtraction far from the galaxy centers. During 2000 December 6/7, two 30 minute exposures were obtained in each of four positions, with 60 minute exposures at each position obtained on the following night when the transparency was more stable. A final 60 minute exposure was obtained with an offset of 15′′ east and 16′′ north, to cover the fainter third galaxy just east of NGC 1410. This galaxy, centered at (J2000.0) α = 03h41m11.60s, δ = −01°17′40″.4 from the STIS coordinates, ended up not being well centered in any of the fibers. The fiber location nearest its core does show features at about the 3 σ level that match Hα and [N ii] emission at \( \text{c}z = 7808 \pm 28 \text{ km s}^{-1} \) (heliocentric), which is at least plausible given the values of 7710 and 7596 for NGC 1409 and NGC 1410, respectively, and the evidence that the envelope of tidally stripped stars from the interaction encompasses this galaxy as well as the two brighter ones.

The positions centered on NGC 1409/1410 were dithered in a parallelogram pattern, with each leg offset by about 2″, to fill the gaps between the 3″ fiber apertures. The instrumental resolution with these fibers was 1.6 A, well sampled by the 0.68 Å pixel\(^{-1}\) scale. The spectral range observed was 6000–7400 Å. Velocity maps were produced from the Hα and [N ii] \( \lambda \Delta 6583 \) measures; for each observation, emission was detected in 21–28 fibers, for a total of 198 velocity measures from the higher quality 60 minute exposures. The velocity maps were constructed on a 1″ grid, with overlapping aperture data averaged at each pixel and numerical 0″1 subpixels used to track aperture outlines until the final averaging. Registration to the direct images used reconstruction of continuum images from the spectral measurements, giving positions of the galaxy nuclei in the DensePak coordinate system. The velocity field is shown in Figure 4.

The nucleus of M32 was observed in four exposures of 10 minutes each in a single fiber to provide a reference old-population spectrum. These data are used in deriving a cross-correlation velocity scale and in subtracting a typical bulge contribution from the nucleus of NGC 1409.

3. THE NGC 1409/1410 ENCOUNTER: GEOMETRY, TIMING, AND VELOCITY SCALE

The WIYN spectroscopic results give a velocity field (at least for ionized gas) showing the relative velocities and senses of rotation for NGC 1409 and NGC 1410. The northeastern side of NGC 1410 is approaching, with the line of nodes in approximately position angle 140°. For NGC 1409, the disk rotation is less clear, since much of the gas may be associated with the dust lane or other tidal debris. The velocity field in Figure 4 shows the gradient across NGC 1409 approximately along the minor axis. The absorption-line results from these spectra are limited, but they do show a gradient across the nucleus in the sense that the northeastern side is receding. For the sense of orbital motion, the Hα results and the central absorption-line velocity for NGC 1409 agree in showing NGC 1409 to be receding relative to the center of mass, with NGC 1410 approaching. The faint tails of starlight extending beyond the STIS field (see the inset to Fig. 1) indicate the rotation senses of the disks in the plane of the sky, since tidal tails act as a kind of material arm and wind up with the sense of disk rotation. The long and prominent one-sided tail wrapping north of NGC 1409 shows that the disk must share this sense of rotation in projection (clockwise), fitting with a polar passage, and putting the eastern side of the disk in front. Together, the morphology and kinematics suggest that the orbital plane is viewed from its eastern side and not too nearly edge-on. The northern tidal tail also indicates that there was a previous close passage through the disk plane of NGC 1409.

If the spiral pattern in NGC 1410 is trailing, the western side is in the foreground. Only the tidal tail provides compelling evidence as to which orientation about the plane of the sky the disk of NGC 1409 has, since its internal structure shows parts of a ring rather than spiral features. NGC 1409 probably lies behind NGC 1410 from our perspective, since the dust feature crosses in front of NGC 1409, something that would require very special geometry if it were to be seen far from the plane of the sky.

The observed velocity difference between the nuclei is 181 km s\(^{-1}\). There are indirect arguments suggesting that we see this system within about 30″ of the orbital plane, so that this is a modest underestimate of the relative velocity. NGC 1409 is the receding member. The emission-line velocity field does follow this trend; since dust and gas are generally associated, the dust is likely to show this same behavior, which fits with its apparently becoming bound to NGC 1409.

The dominant grand-design pattern in NGC 1410 is easiest to understand if this disk is experiencing a near-planar direct (prograde) encounter, which favors the orbital plane being viewed from its eastern side. This would be a geometry most favorable to the loss of mass from its disk during the encounter. In contrast, NGC 1409 is undergoing a roughly polar encounter, which would favor the acquisition of material into a polar ring.
Figure 5 shows a sketch of the inferred geometry of the disks and relative orbit, incorporating the constraints from velocity field, central velocities, and tidal structure. To put a timescale to the encounter and mass-transfer event, the characteristic orbital time (that is, assuming circular orbits) for the two galaxies can be estimated from $T = \frac{2}{C^2} \frac{D}{v}$ for a deprojected linear separation $D$ and space-velocity difference $v$. Including the orbital inclination to the line of sight $i$ and phase angle $\phi$ along the orbit, measured from the plane of the sky, gives $T = \frac{2D}{C^2} \cos i \cos \phi / \Delta v (1 - \cos^2 i \sin^2 \phi)^{1/2}$ in terms of the projected linear separation $D_\perp$ and observed velocity difference $\Delta v$ (e.g., Karachentsev 1987). The observed $\Delta v = 181 \text{ km s}^{-1}$ suggests that the correction for projection is not large, since for even more luminous pairs the projected velocity differences are greater than this only $20\%$ of the time (from Karachentsev 1987). Taking the typical value of $250 \text{ km s}^{-1}$ as the maximum for galaxies at this combined luminosity (following Karachentsev, in his Table 5), the projection effects suggest $\cos i \cos \phi > 0.72$, so that $T = (1.7 - 2.7) \times 10^8 \text{ yr}$. The small projected separation of this pair and the extensive halo of diffuse starlight indicate that the members are well into the spiraling stage preceding a final merger, so that this circular-orbit timescale is only a rough scaling value.

4. AN INTERGALACTIC DUST BRIDGE

The NGC 1409/1410 system shows a striking lane of dust crossing between the galaxies. The connection to the spiral...
pattern of NGC 1410 and polar wrapping around NGC 1409 make it clear that the direction of ISM transfer is from the spiral NGC 1410 to the early-type disk of NGC 1409.

The extent and structure of the dust bridge in the NGC 1409/1410 system may be most simply shown in median-windowed images and color maps. Figure 6 (top) shows a median-windowed image, obtained upon dividing the original white-light image by a version median-filtered over a 200 box. From this display, the dust lane clearly crosses continuously between the galaxies, probably connecting to a feature that crosses the southern spiral arm of NGC 1410 and curving so as to suggest that it passes behind most of the starlight in NGC 1409. This linkage might then reappear as the near-polar dust structure seen closer to the nucleus of NGC 1409. This image also highlights nonaxisymmetric structure in the smooth disk of NGC 1409, in the form of a narrow stellar bar and connected arcs. The dust lane between the galaxies has only moderate observed attenuation, with a maximum light loss in this area of 13%. It is not completely smooth, with multiple filaments and offsets particularly apparent as it curves north of NGC 1409. The dust lane passes in front of the northern part of NGC 1409, especially well seen where the dust crosses the bar feature. It may pass behind the southern arm of NGC 1410. The median-windowed images in each passband were the starting point for generating maps of residual intensity in the dust lanes, in which the median-windowed images were interpolated roughly perpendicular to the dust lanes to make a background model, retaining the ratio of observed to model images.

Many of the same features appear in a color map (Fig. 6), obtained as the simple ratio of blue to red images. The signal-to-noise ratio in the dust bridge is reduced, but structures near the center of NGC 1409 are traced much more clearly since changes in the background illumination do not affect the color. In front of NGC 1409 there are two distinct dust features, one

Fig. 4.—DensePak emission-line velocity field, shown as contours aligned with the STIS white-light image. Velocities are plotted in the observed frame (before heliocentric or galactocentric correction). The individual fibers in the array have 3" diameter; this map results from the combination of four dithered pointings to fill the interfiber gaps. The only feature that changes when slight superresolution is used (equivalent to a smaller pixel footprint in the drizzle algorithm) is the sharpness of the velocity transition crossing the center of NGC 1409. The entire system shows a single monotonic progression in radial velocity except for a small island just above 7800 km s$^{-1}$. 

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with a braided appearance wrapping across the bar and the other a narrower lane crossing almost exactly in front of the nucleus.

To the extent that the dust properties and the distribution of starlight, in particular color gradients, are known, the combination of color and intensity information can be used to reconstruct the three-dimensional location and intrinsic optical depth of dust features. I neglect scattering into the observed beam at this stage, since the optical depth in the NGC 1409/1410 features is modest, so that observational error dominates over this neglect. Let a pixel have residual intensity \( R \) with respect to the unabsorbed starlight, as determined either by simple interpolation or modeling of the entire image structure. When a single, spatially resolved dust feature is responsible for the flux deficit, this implies a relation between the optical depth at its optical depth \( \tau_0 \) through

\[
R_k = X + e^{-k\tau_0}(1 - X),
\]

where the extinction curve enters through \( k \), which is the ratio of \( \tau_0 \) to the value at a fiducial wavelength such as the V band. An example using two bands is shown in Figure 7, where error bounds for 1% precision in residual intensity \( R_k \) are shown restricting the possible values of \( X \) and \( \tau_0 \) from data in the \( B \) and \( R \) passbands.

These expressions should be used at high enough spatial resolution to avoid the averaging effects of dust structures within the resolution element, which artificially flattens the extinction curve and introduces nontrivial weighting of unresolved structures by their transmission. WFPC2 imaging of overlapping galaxy systems shows that linear resolution of a few tens of parsecs substantially reduces these effects (Keel & White 2001a, 2001b). The STIS pixel size corresponds to 26 pc (at 105 Mpc from \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \)), satisfying this condition.

For disk dust in luminous spirals, there is evidence that the slope of the optical extinction curve is close to the typical Galactic value. Among the four backlit spirals studied using \( HST \) imagery by Keel & White (2001a, 2001b), the only one showing a significant departure from a Galactic extinction curve is the late-type object silhouetted in front of NGC 1275, where the unusual environment may have altered the grain population. Dust in the arms of NGC 2207 gives similar results from \( HST \) images, albeit with significant errors from the less favorable geometry (Elmegreen et al. 2001). In the nearby spiral M31, star-by-star spectroscopy indicates that the optical behavior is much like the Milky Way (rather than, for example, the SMC slope associated with its lower metallicity), as found by Bianchi et al. (1996). These observations motivate the use of a Galactic slope associated with its lower metallicity, as found by Bianchi et al. (1996).
A dust bridge in NGC 1409/1410. It can also suggest whether this bridge is spatially continuous with the other polar features around NGC 1409, if fading of the dust extinction is accompanied by a graying trend, which suggests that it is also wrapping behind most of the starlight. In practice, the reddening curve is steeper than expected for the STIS effective passbands and a Galactic extinction law, limiting what we can learn about its spatial location from the photometric results alone. This can be shown using the region where the dust passes in front of the bar of NGC 1409 and is thus plainly in the foreground of most of the starlight (with the difference in $X$ between here and the middle of the dust feature being roughly a factor 9 from relative starlight intensities). For a given depth of the dust feature into the starlight and modest values of $\tau$, changing $\tau$ for different places in the dust feature will give a roughly linear locus in the color–residual intensity plane (Fig. 8). The slope of points in this part of the dust lane is inconsistent with “normal” reddening curves ($A_V/E_B = 3.1$), implying more reddening per unit extinction (or that the STIS passbands have not been correctly evaluated). The slope expected for a Galactic relation is the ratio of $k$ (as in eq. [4]) for the two bands, about 0.93 in this case. A linear relation was fitted to the data from this foreground region (region 1), incorporating the typical photometric errors from pixel scatter in both coordinates and using the procedure from Press et al. (1992, p. 660) as implemented in the GSFC IDL library, giving a slope 0.800 ± 0.019. The dust lane between galaxies and backlit by the diffuse envelope light (region 2) gives a slope 0.835 ± 0.012. If the slope from region 1 represents the actual dust properties for these bands, the slope is equal to the ratio of $k$ values in the limit of small $\tau$. For finite $X$, the locus of values of $R_1$ and $R_2$ for changing $\tau$, as would be found in a single structured dust feature, follows a family of curves whose mean slope in a given range of $R_1$ steepens.

![Residuals from 2\arcsec median](image1.png)

![White/red count ratio](image2.png)

Fig. 6.—Dust structure as revealed in residual intensity from a median-filtered version (top), using a 2\arcsec median window, and a color map (bottom) shown as the ratio of white and red images. The intensity scale bars on the right of each image run from 0.5 to 1.6 times the model intensity for the median-windowed upper image and from 0 to 2 in count-rate ratio for the bottom color image. In the lower panel, bluer areas are white. The small red regions at each nucleus are an artifact of the rebinning required to match these two images in scale. The region and orientation are the same as shown in Fig. 3. For retrieval of the dust location and properties, the regions listed in the text are bracketed. Region 1 is where the lane crosses in front of the disk of NGC 1409 to the right, while region 2 is the region between the galaxies where the dust is backlit by the diffuse stellar envelope of the binary system.
with $X$. This happens as nonlinear structure in the $R$-$\tau$ relation occurs at higher values of $R$ for dust seen deeper into the starlight. In this case, the best fit occurs for $X = 0.4 \pm 0.1$, a slight improvement over the intuitive conclusion that dust is most visible for $X < 0.5$.

This information then allows a correction to the apparent extinction, giving typical values of $A_V$ and hence column density. A map of $R$ at either wavelength becomes a map of $\tau$ according to

$$e^{-\tau} = \frac{R - X}{1 - X}$$

(and ideally the same for each wavelength observed to within errors of measurement and elimination of structure in the starlight). Integration over the resulting map of $\tau$ can give characteristic dust masses and column densities. In this case, I follow Domingue et al. (1999) in using a mix of graphite and silicate grain properties, which yields a column density of $1.11 \times 10^{-10} \tau \text{ g cm}^{-2}$. The mean map for the main dust lane as converted to $\tau_B$ was formed by averaging results from the white and red images. Region 1 is unaffected by this scaling, being in front of nearly all the starlight. The largest extinctions, scaled to $\tau_B$, reach 0.55 in region 2 and 0.35 in region 1 (where the extinction is visually more dramatic because of the brighter background intensity). This conversion gives a dust mass of $7 \times 10^5 M_\odot$ in region 2, with about $2 \times 10^5 M_\odot$ in region 1.

Additional dust features are of interest to the question of whether the dust wraps behind NGC 1409 and reappears as the polar lanes in one continuous structure. For region 3, where the lane appears faintly in the median-windowed image and might be turning behind much of the starlight, the $R_Y$-$R_B$ relation is still steeper than for region 2. How much steeper is poorly determined, since the fit has a slope formally greater than unity. This would then be farther back than the reference curve $X = 0.7$ in Figure 8. That would give this part of the lane optical depth (and mass) similar to region 2 and support the continuity of dust around NGC 1409. The structure in front of the central region of NGC 1409 is in front of the bulk of the starlight ($X < 1$) by inspection. It has $R_B \approx 0.4$ at its deepest points, much like regions 1 and 2. These results are consistent with the suspicion that there is a single continuous dust lane crossing from the disk of NGC 1410 and wrapping in front of the northwestern edge of NGC 14109, turning behind it, and reappearing in front on the western side near the nucleus to form a polar structure. The total dust mass involved is about $2 \times 10^6 M_\odot$, including the unseen portion, which would lie behind the disk of NGC 1409. For a typical gas-to-dust ratio of 160 by mass (e.g., Sodroski et al. 1994), the accompanying gas phase material would total $\approx 3 \times 10^8 M_\odot$.

The time spent crossing along this path would be of the same order as the orbital timescale, implying a mean mass-transfer rate of $1.1-1.4 M_\odot \text{yr}^{-1}$.

5. STAR FORMATION

The members of this pair differ as much in star formation rate as in morphology and color. NGC 1410 shows substantial recent star formation, including a population of luminous blue star clusters (Figs. 1 and 6). Of these, 10 are isolated enough for simple aperture photometry. Roughly transforming to the $V$ band gives them observed magnitudes of $22.9-24.4$, or absolute magnitudes of $-12.2$ to $-10.7$. These are luminous but by no means unprecedented, falling within the range of the brightest clusters seen in more local interacting systems (Whitmore et al. 1999; Keel & Borne 2003) in which only a handful of clusters appear brighter than $M_V = -12$. Clusters are short lived at this luminosity (a few $10^7$ yr), indicating that their formation is ongoing at the timescale of the interaction. Similarly, the line emission from the disk of NGC 1410 (away from the Seyfert nucleus) indicates brisk star formation. Equivalent widths in H$\alpha$ from 10 to 30 $\AA$ are found throughout the region within about 6$''$ of the core (and excluding the active nucleus itself). This corresponds to a flux of $7.6 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$, or an H$\alpha$ luminosity of $9 \times 10^{40} \text{ ergs s}^{-1}$. Using the formulation by Kennicutt (1983) for a Salpeter initial mass function, this corresponds to a star-formation rate of $0.8 M_\odot \text{yr}^{-1}$ in the spiral disk of NGC 1410.

Fig. 7.—Sample retrieval of simultaneous bounds on depth $X$ of a dust region into the starlight distribution and its optical depth $\tau_B$, as in eq. (4). For this example, the residual intensity measured in the standard $B$ and $R$ bands is taken to have 1% precision. A standard Milky Way extinction law was assumed, which gives $k_B = 1$, $k_R = 0.57$. Lines are shown for the measured $R$ and the error bounds in each case; the allowed region from $B$ is shaded. The error region for the combined measurements is the intersection of this shaded region with the upper and lower error bounds from the $R$ measurement.

Fig. 8.—Measuring depth of dust features into the starlight when the pixel signal-to-noise ratio is too low for the approach used in Fig. 7 to be useful. The points show pixels in region 1 silhouetted in front of the disk of NGC 1409, taken to define the reddening curve and thus the $X = 0$ behavior. The plotted curves are for $X = 0.1$, 0.4, 0.7, given that reddening slope, and show the departures in the mean behavior as fitted for region 2 between the galaxies.
These points are in stark contrast to the lack of either associated line emission or stellar clusters in NGC 1409 (since even the brightest old globular clusters would be just at the threshold of these observations). The line emission show in Figure 4 is kinematically decoupled from the rotating disk of NGC 1409 and is therefore suspect as an indicator of any UV stellar flux. The broadband color, smooth image, and characteristic old stellar features in the spectrum of NGC 1409 limit its overall star formation rate to only a few percent of what we see in NGC 1410. Whatever the fate of the gas reaching NGC 1409, it is not fueling star formation at the epoch we observe. A star formation rate of less than 0.05 \( M_\odot \) yr\(^{-1} \) would stand out in these data.

6. NUCLEAR ACTIVITY

NGC 1410 is a well-known type 2 Seyfert galaxy and, as a member of such a strongly interacting pair, has been included in many samples of AGNs designed to test for links between nuclear activity and interaction. It is therefore ironic that in this clear instance of mass transfer, it is the Seyfert galaxy that acts as the donor, with a much more quiescent galaxy receiving the material. Nuclear activity in NGC 1409 is much weaker, if present. The WIYN spectrum of its nucleus is compared with NGC 1410, with and without correction for the starlight continuum, in Figure 9. The continuum was subtracted using M32 as a template, rebinned to match redshifts, and broadened by a Gaussian of FWHM = 11.4 \( \text{Å} \) (520 km s\(^{-1} \)), the best fit for the combined velocity dispersion and central rotation gradient in the NGC 1410 spectrum. NGC 1409 shows typical LINER emission with [\text{N} \text{II}] \( \lambda \lambda 6583/\text{H}_\alpha \) near unity. Such emission, while often associated with other signs of genuine nuclear activity at low luminosity, is common enough not to be a particular indication of anything special happening in the core of NGC 1409.

7. SUMMARY

\textit{HST} STIS images in two broad passbands have been used to trace a dust lane marking mass transfer in the interacting galaxy pair NGC 1409/1410. The combined color and extinction behavior support the impression that there is a single feature crossing the 7 kpc gap between NGC 1410 and NGC 1409, then wrapping behind NGC 1409 and reappearing on the opposite side to become a small lane crossing its disk over the pole. The depth into the starlight derived from the two-color data and the residual intensity yield estimates of the dust mass, totaling about 2 \( \times 10^6 \) \( M_\odot \), and likely accompanied by 3 \( \times 10^8 \) \( M_\odot \) of gas. At the characteristic orbital velocities in this system, this suggests a mean rate of mass transfer slightly above 1 \( M_\odot \) yr\(^{-1} \) onto NGC 1409.

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Fig. 9.—Nuclear activity in NGC 1409 and NGC 1410. The observed spectrum of the nucleus of NGC 1409 is at the top; the type 2 Seyfert nucleus of NGC 1410 scaled down by a factor of 2.5 is in the middle. At the bottom is the net emission spectrum of the NGC 1409 nucleus after subtracting a broadened M32 spectrum, to show the H\(\alpha \) emission properly. Weak LINER emission appears at \( \approx 1\% \) of the level seen in NGC 1410.

This mass-transfer calculation may be too simple, since the feature may be more exactly described as an isochrone than a pipeline. It is striking that only in a small region has material been launched away from NGC 1410, perhaps indicating that a special location in the system was needed to start such a transfer. This fits with the fact that the dust lane appears to cross the spiral pattern of NGC 1410.

In light of the mechanisms discussed to account for star formation and nuclear activity in interacting galaxies, it is ironic that the Seyfert galaxy NGC 1410 is the donor, rather than the recipient, of mass transfer. The recipient NGC 1409 shows no signs of any fate of the gas reaching its disk. Limits to its rate of star formation stand at a few percent of the inflow rate, and its nuclear activity is limited to a modest LINER. Either the flow has yet to actually reach the dense inner regions, or some additional trigger must set in after a critical density or mass of infalling gas is achieved. If flows such as these drive starbursts in interacting systems, such a cycle is needed to drive star formation rates an order of magnitude greater than the estimated flow rate in NGC 1409/1410.
