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NEUTRAL HYDROGEN ASSOCIATED WITH SHELLS AND OTHER FINE STRUCTURE IN NGC 2865: A DYNAMICALLY YOUNG ELLIPTICAL?

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ABSTRACT

We report the discovery of neutral hydrogen in a second elliptical galaxy with shells, NGC 2865. Very Large Array images reveal an association between the neutral hydrogen (H I) and the fine structure (shells, tails, and loops) in the galaxy. Similar to what we previously observed in NGC 5128 (Centaurus A), most of the $6 \times 10^8 \, h^{-2} \, M_\odot$ of cold gas is found in a broken ring in the outer regions of NGC 2865 (beyond $\frac{1}{2}D_{25}$) and is displaced *to the outside* of the shells and loops. The measured velocities cover a range of 500 km s^{-1} around the systemic velocity. The velocity field of the outer H I has the same sense and magnitude (and line of nodes) as that of the stars in the elliptical body. Although NGC 2865 appears to be a relaxed elliptical galaxy, deep images, photometry, and spectroscopy suggest that the galaxy might be the recent (less than 7 Gyr) product of a major disk-disk merger—a "dynamically young elliptical." Our H I data support this hypothesis. Nevertheless, the association between gas and stellar fine structure, with gas displaced outward from the stars in projected position, implies gas motions not predicted by any of the current merger scenarios.

Using the H I ring and assuming nearly circular motion, we measure M/L_B at large radii ($4 \times \frac{1}{2}D_{25}$). We find $M/L_B = 33 \pm 4 \, h$, a factor of 5 greater than the value of M/L_B found for the central regions, indicating the presence of a dark halo.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 2865) — galaxies: interactions — galaxies: ISM — galaxies: structure

1. INTRODUCTION

Where are the remnants of mergers past? What do the merged pairs look like in their next few galactic years? Toomre & Toomre (1972) first suggested that many elliptical galaxies are the featureless end products of disk-disk collisions over a Hubble time–a hypothesis that has survived considerable theoretical and observational scrutiny (Barnes 1994; Schweizer 1990). When King posed the above questions to Toomre (1977), however, it was not the relaxed elliptical that he had in mind but rather a galaxy that would still show signs of unrest, albeit without the telltale features of two disk galaxies undergoing a merger. Indeed, many of today's ellipticals betray hints of a recent violent encounter, displaying fine structure: faint tails and jets, shells, kinematic peculiarities and isophotal distortions. Citing as evidence a correlation between the amount of fine structure and *UBV* colors, Schweizer & Seitzer (1992, hereafter SS) suggest that ellipticals with significant fine structure are "dynamically young," or formed by a disk-disk merger within the last 7 Gyr.

Although statistical studies place the transition region between mergers and relaxed remnants within the realm of the optically peculiar E, S0 (and even Sa) galaxies, it is difficult to find one well-supported example of a galaxy that was formed by a disk-disk merger several billion years in its past (note, however, NGC 6776 [Sansom, Reid, & Boisson 1988]; ESO 341-IG04 [Bergvall, Ronnback, & Johansson 1989]). This is due in large part to the fact that surprisingly little is known about the composition and kinematics of the fine structure in most galaxies. The low surface brightness of shells, tails, and jets means that accurate photometry and spectroscopy of these stellar features are difficult to obtain. Indirect studies of nuclear IR (Wilkinson, Browne, & Wolstencroft 1987b), radio continuum (Wilkinson et al. 1987a), emission lines (Carter et al. 1988), and kinematics of nuclear stars (Bettoni 1992) provide little information because the link between global properties and fine structure is not well understood.

We employ a different method to identify and study dynamically young ellipticals and S0 galaxies, motivated in part by the serendipitous discovery of neutral hydrogen (H I) associated with the shells in the radio galaxy Centaurus A (Schiminovich et al. 1994) and recent imaging of H I in and around several other optically peculiar (shell) galaxies. Relic H I found in galaxies that are typically gas-poor suggests a recent merger/accretion event. H I and optical data can be used to assess the extent to which gas is spatially and morphologically correlated with the stellar fine structure in a particular galaxy. Our principal assumption is that a correlation between gas and stars implies a physical relationship, an "association," which therefore enables us to use the gas morphology and dynamics to probe the event that created the fine structures.

In subsequent sections, we present images of H I associated with the fine structure in the shell elliptical galaxy NGC 2865 and discuss their implications.[1]

[1] Throughout this Letter we adopt a distance to NGC 2865 of 26.1 h^{-1} Mpc ($1' = 7.6 \, h^{-1}$ kpc) based on an optical systemic velocity (heliocentric) of 2611 km s^{-1} (de Vaucouleurs et al. 1991 [RC3]).

2. PREVIOUS WORK

NGC 2865 is a genuine elliptical galaxy. It is classified as an E3+ in RC3 (de Vaucouleurs et al. 1991) and as an E4 in RSA (Sandage & Tammann 1981). The nucleus of the galaxy appears relaxed; Forbes et al. (1994) find no evidence for double nuclei. CCD surface photometry in *BVI* (Reid, Boisson, & Sansom 1994) and $B_J R_G$ (Jørgenson, Franx, & Kjærgaard 1992) bands reveal surface brightness profiles consistent with an $r^{1/4}$ law (de Vaucouleurs 1948) out to $\sim 60''$ and $\sim 30''$, respectively, with no satisfactory exponential law fit. NGC 2865 shows maximum isophote flattening at an intermediate radius ($\epsilon = 0.28$ at $r = 15''$; Jørgenson et al. 1992), thereby placing it in van den Bergh's (1989) sample of "pure" elliptical galaxies. The luminosity and velocity dispersion of NGC 2865 satisfy the Faber-Jackson (1976) relation for ellipticals (Lake & Dressler 1986). R_G band photometry (Jørgenson et al. 1992) and velocity dispersion measurements (Lake & Dressler 1986) also place NGC 2865 within the fundamental plane for elliptical galaxies (Djorgovski & Davis 1987).

In deep images, however, NGC 2865 is genuinely peculiar. The galaxy, shown in Figure 1 (Plates L2–L4), displays a significantly disturbed morphology. Isophote fits reveal boxy isophotes within $r < 40''$ and disky isophotes at larger radii (Reid et al. 1994). A member of the Malin & Carter (1983) catalog of shell galaxies, NGC 2865 contains a chaotic system of ~ 7 shells out to 2'.5, some wrapping almost 180° around the center of the galaxy. (These shells are illustrated schematically in Fig. 1*c*). A westward protrusion identified as a "stellar jet" or "polar ring" (Whitmore et al. 1990) extends 1' from its nucleus. Fort et al. (1986) estimate that 11%–22% of the total luminosity of NGC 2865 is contained in the shells and "jet." Farther out, a faint loop is visible in the northwest, and a plume or taillike extension can be seen to the southeast. Nevertheless, NGC 2865 has no companions of similar luminosity, although two gas-rich dwarfs are seen nearby (see § 3 below).

An important kinematical feature of NGC 2865 was identified by Bettoni (1992), who studied the stellar kinematics along the major, minor, and two intermediate axes of the galaxy. Out to 30'' along the major axis, Bettoni finds a high rotation velocity for the inner stars. Radial velocities rise to 250 km s^{-1}, corresponding to $v/\sigma \sim 1.3$–1.4, exceptionally high for an elliptical.

Photometry of NGC 2865 yields colors bluer than those of most ellipticals, even those with extensive fine structure. SS employ *UBV* color *residuals* of ellipticals to date the occurrence of recent bursts of star formation, and make the assumption that such activity has been merger-induced. We used photometric measurements from RC3 to determine the color residuals of NGC 2865, using the methods and results described by SS. The extinction-corrected, effective (half-light aperture) $U-B_{e,0}$ and $B-V_{e,0}$ indices are 0.37 and 0.81, respectively. After subtracting the color-magnitude relationship for ellipticals (SS), we find $\Delta U-B_{e,0} = -0.15$ and $\Delta B - V_{e,0} = -0.13$. These color residuals are bluer than all except one of the galaxies (NGC 3156) in the SS sample of 35 ellipticals with varying degrees of fine structure, although not as blue as the late-stage mergers NGC 3921 and NGC 7252. According to the SS models, a disk-disk merger may have formed NGC 2865 between 1 and 4 Gyr ago.

In fact, stellar spectroscopy of the nuclear regions of NGC 2865 (Bica & Alloin 1987) shows a bump at 4600 Å and a corresponding strengthening of the Balmer lines, features that might correspond to an intermediate-age burst of star formation. Carter et al. (1988) confirm this result, and, using stellar templates, they estimate that 30% of the nuclear luminosity comes from A stars. By performing population synthesis with galaxy templates and making comparisons with Galactic clusters, Bica & Alloin (1987) derive a burst age of 1.2 ± 0.3 Gyr.

3. OBSERVATIONS

We observed NGC 2865 in 1993 October with the Very Large Array (VLA). To maximize surface brightness sensitivity, we used the array in its most compact configuration. An extended north arm was used because of the galaxy's low declination. Instrumental parameters are given in Table 1. With 63 channels of continuum-subtracted visibility data we made a CLEANed (Clark 1980) H I image cube, from which we obtained the total H I intensity and velocity field maps shown in Figure 1. We find $6.0 \pm 0.6 \times 10^8\ h^{-2}\ M_{\odot}$ of H I in NGC 2865, almost all of which is situated in a discontinuous ring 1'.5–4' from the galaxy center ($h = H_0/100$ km s^{-1} Mpc^{-1}). In addition, an uncataloged gas-rich edge-on dwarf companion sits nearby 7' to the southeast and contains $2.4 \pm 0.2 \times 10^8$ $h^{-2}\ M_{\odot}$ of H I. The dwarf companion is relatively undisturbed, showing no evidence of present tidal interaction with NGC 2865. A second uncataloged companion (not shown in Fig. 1), 10' to the west of NGC 2865, has an H I mass of $1.2 \pm 0.1 \times 10^8\ h^{-2}\ M_{\odot}$. The amount of H I detected in NGC 2865 and its southern companion is consistent with single-dish observations ($\sim 1 \times 10^9\ h^{-2}\ M_{\odot}$; Huchtmeier 1994).

We find that most of the gas is associated with the outermost shells and loops. East of the galaxy center, the H I follows the curve of the outer stellar shell 1 (shell numbers refer to Fig. 1*c*) and peaks over the same range of angles spanned by the shell (P.A. 65°–140°). The correlation is not perfect; the gas is displaced, peaking 30''–45'' *to the outside* of the shell. At P.A. 155° there is a discontinuity or "jump" in the H I column density between shell 1 and shell 2. The gas again follows shell 2, slightly offset by up to 30'', leading up to the jet (3) where, once again, we observe a discontinuity in the H I distribution. The deep image overlay (Fig. 1*b*) shows a correlation between gas and stars in the northwest loop, where, as with the shells, the outer "claw" of H I is displaced to the outside of the stars and is offset to the east of the brightest clump of stars in the loop. Figure 1*b* also reveals H I following the faint extension to the

TABLE 1

INSTRUMENTAL PARAMETERS

Parameter	Value
Field center	R.A. $09^h21^m15^s$, decl. −22°56'54''
Observing date	1993 October 11
Observation time	4 hr
Array configuration	DnC
Shortest spacing	35 m
Longest spacing	3 km
Number of antennas	27
Number of frequency channels	63
Velocity of band center	2604 km s^{-1}
Velocity resolution	21 km s^{-1}
Velocity coverage	1323 km s^{-1}
Primary beam (FWHP)	30'
Synthesized beam (FWHP)	72''.5 × 40''.0
Beam position angle	−8°
Weighting	Natural
Observed rms noise (1 σ)	0.5 mJy beam^{-1}
Equivalent T_b for 1.0 mJy beam^{-1}	0.21 K

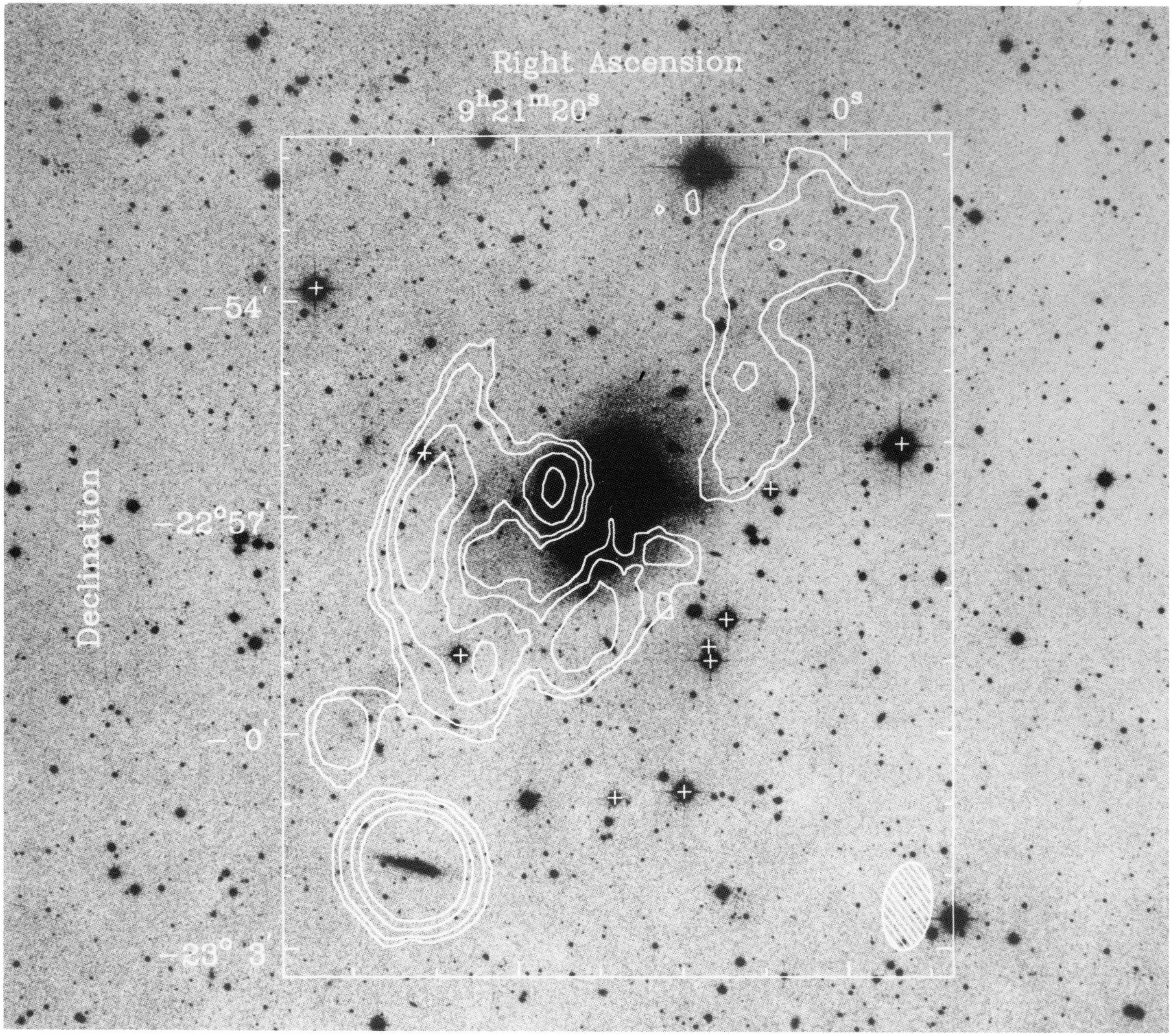

FIG. 1*a*.—A morphological association between gas and stars is evident in the total H I overlay on an optical image of NGC 2865. Inner shells, diffuse outer shells, and "jet" are clearly visible in the optical image. The H I peaks to the outside of the southern and eastern outer shells and to the outside of the northern loop. The H I 7′ southeast of the galaxy center corresponds to an edge-on dwarf companion, or shred. The H I contour levels are 1.9, 3.8, 7.6, and 11.4 × 10^{19} cm^{-2}. The optical image is from photoamplified AAT IIIa-J plates. The 73″ × 40″ VLA beam is shown in the lower right-hand corner of the image.

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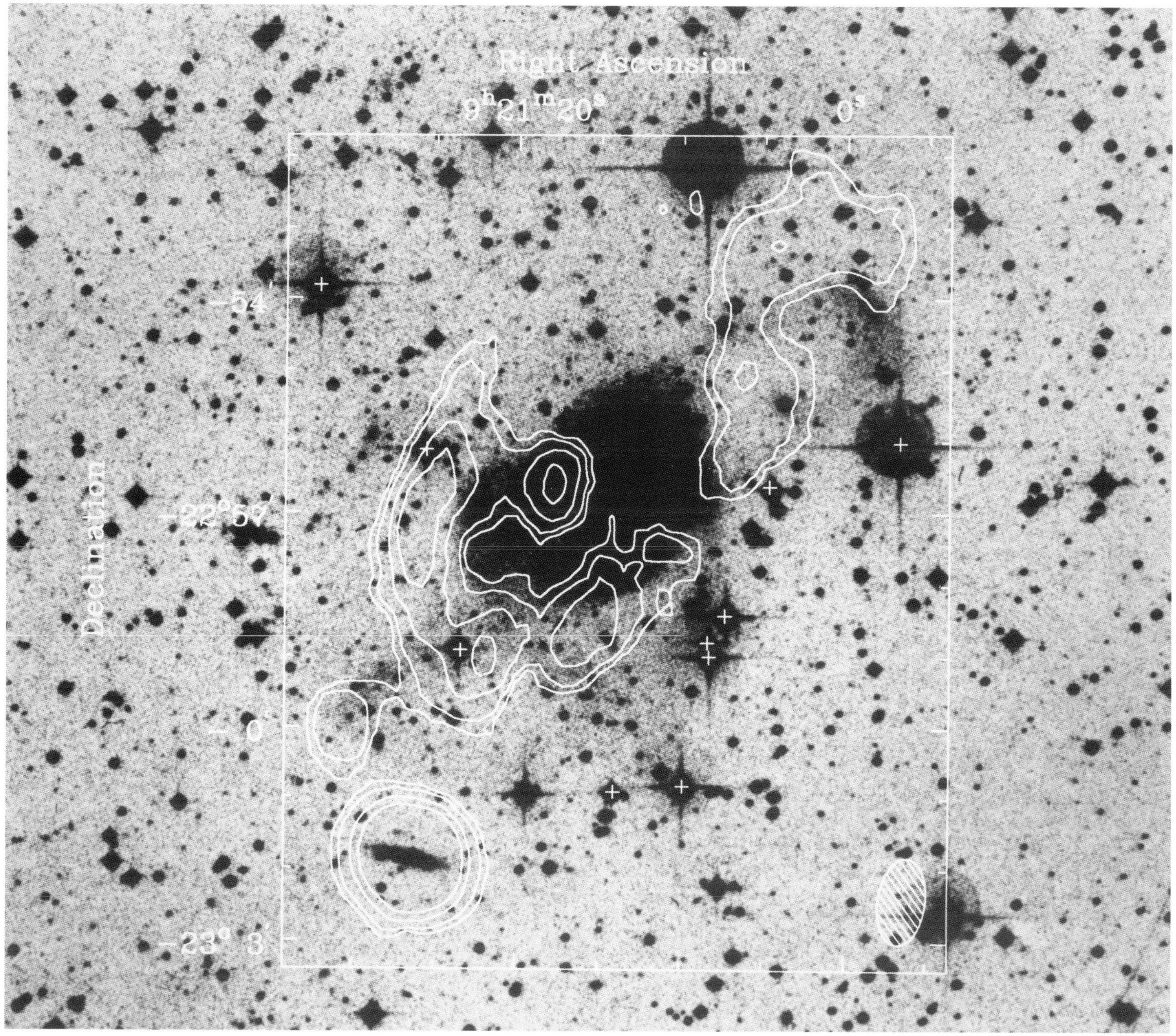

FIG. 1*b*.—Total H I map of NGC 2865 overlaid on a deep optical image. In addition to the gas-shell association, the deep optical image reveals an elongated loop 4′ northwest of the center and a faint stellar ribbon that projects outward to the southeast. As with the shells, the H I follows the curvature of the loop but is not spatially coincident. The southern spur of H I appears to be extending toward the dwarf companion. Nevertheless, the velocity field does not support such a connection. H I contours are the same as in (*a*). The optical image was made by combining photoamplified images from seven deep UK Schmidt IIIa-J plates and reveals features with a surface brightness of about 27.5 mag arcsec^{-2}.

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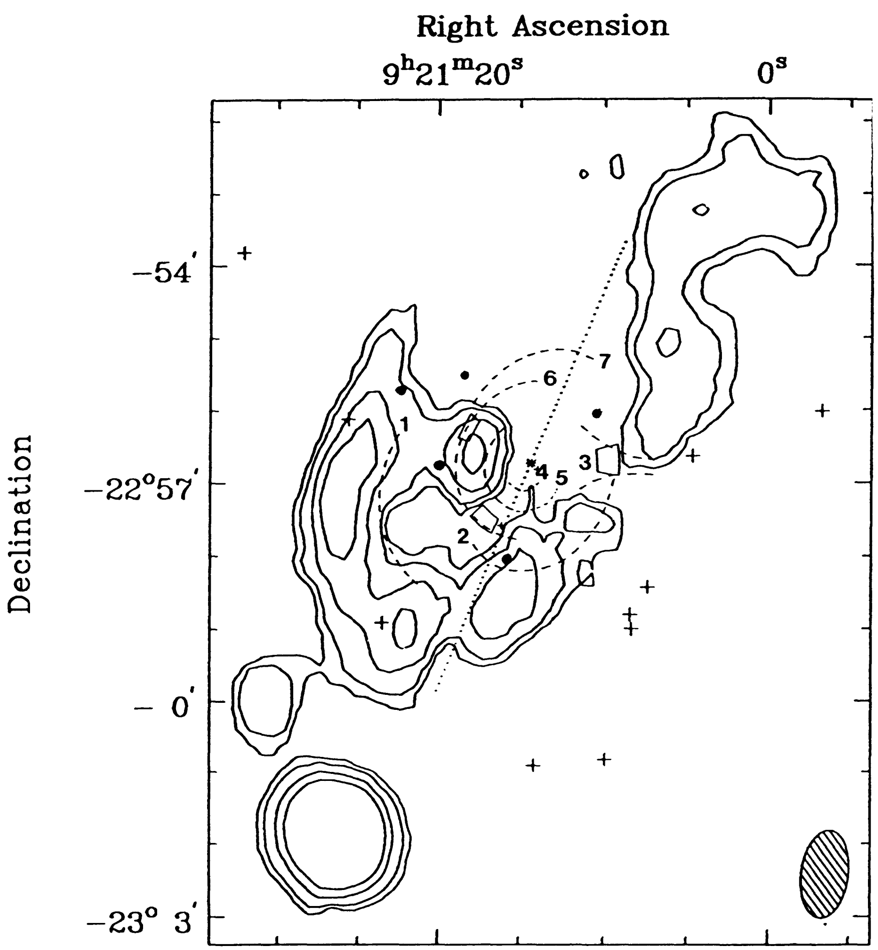

FIG. 1c

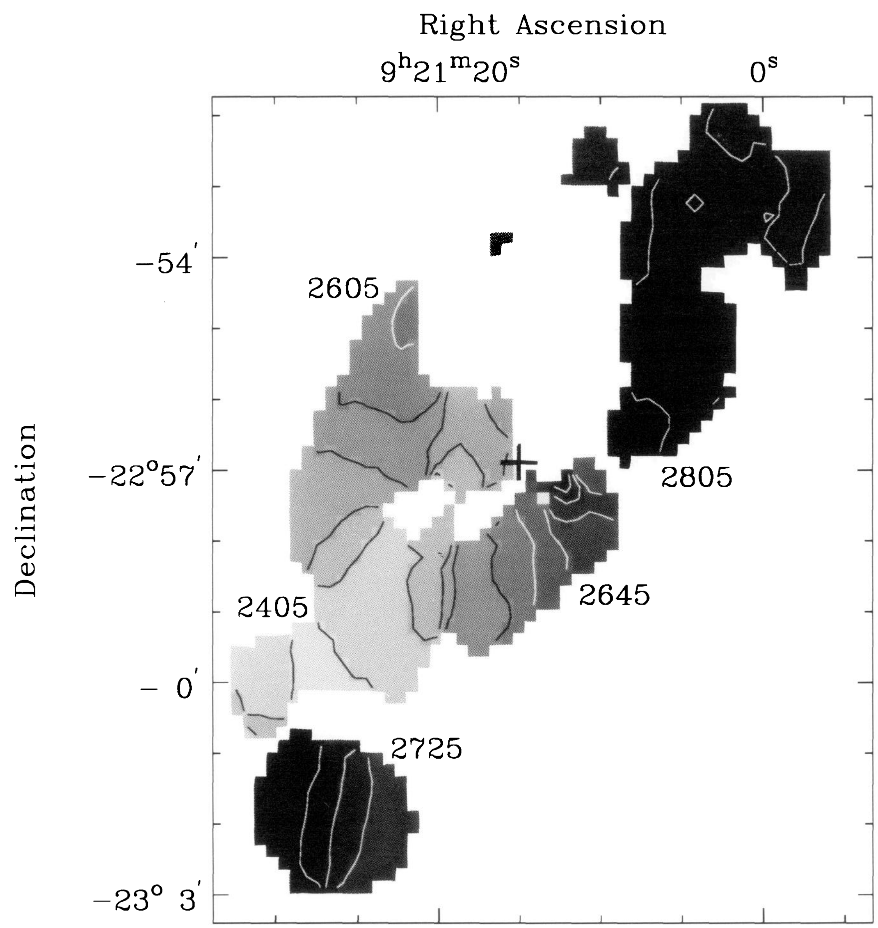

FIG. 1d

FIG. 1c.—Total H I map of NGC 2865 overlaid on a schematic of the shells (Fort et al. 1986), showing that, with the exception of the blob near the center, the H I is only associated with the outermost shells of NGC 2865. In contrast to Cen A, there is little H I in the center. A significant break in the H I appears at the position of the optical jet. Dashed lines correspond to edges of shells. Dashed lines west of the center mark the position of the optical jet. Shells and jet are numbered 1–7. The northwest loop and the southeast extension are not indicated. Solid rectangles denote regions where Fort et al. (1986) made photometric measurements. The dotted line corresponds to the major axis of NGC 2865. H I contours are the same as in (*a*).

FIG. 1d.—Intensity-weighted velocity field map of NGC 2865. The velocity field shows a large velocity gradient, and the southern half displays a surprising regularity. The velocity field also reveals that the southeast spur of H I and the neighboring dwarf are not kinematically connected. The plus sign denotes the optical center of the galaxy. Gray scale and contours indicate the mean velocities of H I along the line of sight at each position on the sky. Contours are spaced every 40 km s^{-1} (approximately 2 channels). H I was detected in channels covering a velocity range between 2400 and 2850 km s^{-1} (heliocentric). The optical systemic velocity is 2611 km s^{-1} (RC3).

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southeast. The peak of the H I coincides with a stellar edge in the southeast plume.

For some of the inner H I clumps, optical connections are less apparent. The northwest inner H I "claw," which sits inside the northwest loop, is morphologically similar to the northwest stellar edge of the main body (not previously identified as a shell). The innermost blob of H I overlaps several of the inner shells (5, 6, and 7), but high-resolution observations are required to determine whether the stars and gas might be associated. No H I is detected to the northeast (shells 6 and 7), but because this was a short exploratory observation, we may be sensitivity-limited; in channel maps, weak emission appears to complete the broken ring of H I.

Unlike the total-intensity map, the velocity field, shown in Figure 1*d*, displays a surprising regularity; the velocity gradient in the approaching side of the galaxy is smoothly varying and continuous. Figure 2 shows an H I position-velocity plot, with stellar velocity data from Bettoni (1992) plotted in the inner regions. Contours show H I velocity versus position along the major axis of the H I distribution (P.A. 315°). The detected H I neatly conforms with the expected position-velocity relationship for a thick ring or disk with a flat rotation curve. The velocity of the northern "claw" of H I follows the general sense of rotation. Most notably, there appears to be a remarkable similarity between the outer H I and the stellar velocities measured within 30″ along the optical major axis (P.A. 330°).

Making the assumption that the gas is rotating in circular orbits centered on the nucleus, with no apparent expansion or contraction, we can fit rotation curves to the intensity-weighted velocity field (Begeman 1989). We performed fits to the data using both the entire field and the approaching half only, and solved for different sets of four parameters (systemic velocity, rotational velocity, inclination, and position angle). Satisfactory fits were found between 2′ and 4′, giving circular velocities near 240 ± 15 km s^{-1}, an inclination of $65° \pm 5°$ at a position angle of $310° \pm 5°$, close to the major axis of the galaxy. The systemic H I velocity, 2640 ± 15 km s^{-1} (heliocentric) is slightly higher than the optical systemic velocity 2611 ± 13 km s^{-1}. These results are merely suggestive; despite our ability to obtain satisfactory fits, we have no evidence to support the assumption of coplanar, circular rotation.

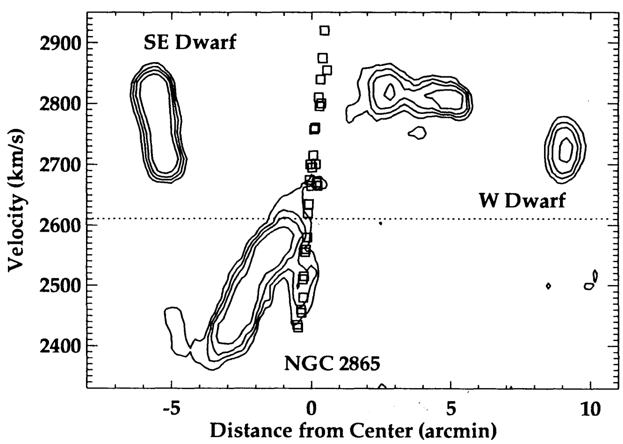

FIG. 2.—Position-velocity plot of NGC 2865 showing the kinematic signature of a rotating ring. Contours show H I velocity vs. position along the major axis of the H I distribution (P.A. 315°). Contour levels are 3 σ, 5 σ, 7 σ, and 10 σ. Squares denote stellar kinematics along the major axis of the main body (P.A. 330°) (Bettoni 1992). Contours and squares illustrate the agreement between stellar and H I kinematics. The dotted line indicates the optical systemic velocity (RC3). We do not know why the optical spectroscopy along the major axis appears to suggest a higher systemic velocity.

4. DISCUSSION

One striking aspect of the association between gas and stars in NGC 2865 is the similarity to what we found in Cen A (Schiminovich et al. 1994). Here, as in Cen A, we observe gas distributed in a partial ring, displaced to the outside of the outermost shells and rapidly moving with the same sense as the main body (although, unlike Cen A, the inner stars move at the *same velocity* as the gas). This similarity strengthens the case for correlation between gas and stars in each galaxy, since neither is a true anomaly.

4.1. *Testing the Merger Hypothesis*

The fate of gas and stars in disk-disk mergers has been studied extensively by Hibbard (1995). Hibbard et al. (1994) and Hibbard & Mihos (1995) observed and simulated NGC 7252, a late-stage merger in the Toomre sequence, and identified several features that directly apply to our study. Simulations show that material from the tidal tail has been falling back into the main body and will continue to do so for many gigayears, forming loops, rings, and shells around the remnant. Hibbard et al. (1994) find H I only in the outer parts of the remnant, with most of the gas spatially coincident with the stellar tails. The absence of H I in the center of the remnant suggests that the returning gas has likely been converted into other phases, possibly fueling a central starburst (Dupraz et al. 1990).

We observe little gas in the center of NGC 2865, and nuclear gas has not been detected in other phases. However, a post-starburst spectrum is observed in the nucleus. If the nuclear gas were efficiently converted into stars, we might expect to see H I only in the outer parts of the galaxy. Thus, it is quite possible that at an earlier stage the H I content of NGC 2865 was much greater than the 6×10^8 h^{-2} $M_\odot$ of H I ($M_{\rm H\,I}/L_B \sim 0.05$) we currently observe. In fact, taking the 11% lower limit that Fort et al. (1986) derived for the total fractional luminosity of light from the shells (we see H I associated only with the faint outer fine structure), we find that $M_{\rm H\,I}/L_B \sim 0.5$ in the outer regions, giving a ratio close to that observed in spirals (Giovanelli & Haynes 1988).

As described above, the stellar kinematics within 30″ matches the outer gas kinematics, indicating that the main body and the gas "ring" might have formed from the same event. This can best be explained by a major merger of nearly equal mass progenitors (e.g., Hernquist & Spergel 1992); we would not expect the velocity field resulting from the accretion of a small gas-rich galaxy to so closely match the field of the primary. This is consistent with the measurements of the fine-structure luminosity in NGC 2865 by Fort et al. (1986), which appear to rule out formation of these features through the destruction of a low-mass (less than 10% of the primary) companion. Citing these results, Prieur (1988) writes that for NGC 2865 the absorbed companion could likely have had a mass of the same order of magnitude as that of the galaxy—a major merger.

The timescales for this system are consistent with the merger model. Stellar spectroscopy and *UBV* photometry set 1 and 4 Gyr as the lower and upper limits on the age of the encounter. Gas-settling timescales are at least several orbit times (Rix & Katz 1991). If the H I gas clumps are rotating, then 1–4 Gyr corresponds to ~2–8 orbits. This is few enough orbits that we would not have expected the gas clumps to have completely dissipated and settled into rings. (Some settling appears to have occurred; the approaching half of the velocity field is reminiscent of a prototypical "spider" distribution for spirals. In channel maps, low-level emission hints at velocity continuity up into the receding loop.)

There are, however, problems with the merger scenario. While we do observe stars and gas forming loops, shells, and rings, we do not observe gas "raining back" into the center of NGC 2865 as Hibbard et al. (1994) find for NGC 7252. Instead, we observe gas slightly displaced to the outside of the shells and loops, farther from the center than the collisionless stars. Weil & Hernquist (1993) and Barnes & Hernquist (1991) find in numerical simulations that most of the gas that passes through the inner regions of a merger loses its angular momentum in collisions and quickly falls to the center of the newly formed remnant. It is possible that the outermost gas has remained on nonintersecting orbits and kept its angular momentum, but then when and why was the outer gas displaced from the stars?

We are puzzled by the displacement between H I and shells in NGC 2865 and in the similar example of Cen A. While we have added to the growing list of observational evidence in support of a recent merger formation of the shell elliptical galaxy NGC 2865, we view these conclusions with caution because current merger simulations do not reproduce the observed displacement. Because we appear to be observing NGC 2865 at a unique time, when gas and stars are segregating but still maintain a degree of association, a better understanding of how gas and stars settle during the several billion years following an encounter may eventually allow us to determine more accurately the age of the merged remnant. We may then use the H I observations of NGC 2865 not simply to determine whether the galaxy is dynamically young but also to establish exactly when and how two disks collided to form it.

4.2. *Mass-to-Light Ratio*

H I in the outer regions of elliptical galaxies offers an excellent opportunity to study the mass distribution at large radii ($r > \frac{1}{2}D_{25}$) (e.g., Knapp 1987). However, in contrast to the case of spiral galaxies, few ellipticals contain detectable amounts of H I; a mere handful of cases employ H I dynamics as a probe of the potential. In NGC 2865 we find the cold gas rotating farther than $4 \times \frac{1}{2}D_{25}$ from the center, nearly twice as far out as some of the previously best-studied examples (e.g., IC 2006, Schweizer, van Gorkom, & Seitzer 1989; Cen A, Schiminovich et al. 1994).

Assuming circular rotation around a point mass, we find $4.0 \pm 0.5 \times 10^{11}\ h^{-1}\ M_{\odot}$ within $30\ h^{-1}$ kpc. This yields, for an L_B of $1.2 \times 10^{10}\ h^{-2}\ L_{\odot}$, an M/L_B ratio of $33 \pm 4\ h$. This can be compared with the mass-to-light ratio near the center of the galaxy (Binney 1982), calculated using the effective radius and surface luminosity derived from an $r^{1/4}$ fit to the B_J surface photometry of Jørgenson et al. (1992) as well as the central velocity dispersion measured by Bettoni (1992). Given $r_e = 1.9\ h^{-1}$ kpc and $I_e = 0.034$ ergs s^{-1} cm^{-2}, we find $M/L_B = 6\ h$ in the central regions. The significant change in M/L_B out to large radii requires the presence of a massive dark halo around NGC 2865.

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