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EVIDENCE FOR A PHYSICALLY ASSOCIATED COMPANION GALAXY TO I Zw 18

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ABSTRACT

Using the William Herschel Telescope ISIS spectrograph, deep long-slit spectra were obtained of the ionized gas across the blue compact dwarf galaxy I Zw 18 and in an irregular galaxy located 15″ to the northwest. Heliocentric radial velocities of Hα and Hβ emission lines were measured over a 50″ length spanning the main body of I Zw 18 all the way to a central bright emission knot of the companion galaxy. This emission shows a smoothly varying double-sinusoidal variation in radial velocity over the length of the slit, which corresponds to about 2.5 kpc in the plane of the sky for an adopted distance of 10 Mpc for I Zw 18. Our primary result is that the radial velocity of an Hα knot near the center of the companion galaxy is the same as the systemic radial velocity of the ionized gas in the center of the main body of I Zw 18. We also observe a smoothly varying velocity field in the ionized gas between, which we interpret to be strong evidence for the two stellar systems' physical closeness to each other.

Subject headings: galaxies: individual (I Zw 18) — galaxies: interactions — galaxies: irregular — galaxies: starburst

1. INTRODUCTION

The blue compact dwarf (BCD) galaxy I Zw 18 (Zwicky 1966) has the lowest O/H abundance known for a star-forming galaxy. Consequently, several detailed observational and theoretical investigations of I Zw 18 have been made in recent years. Deep ground-based imagery of I Zw 18 and nearby objects have been reported by Davidson, Kinman, & Friedman (1989, hereafter DKF89) and by Dufour & Hester (1990, hereafter DH90). Numerous ground-based spectroscopic studies of the two H II regions in I Zw 18 have been published, the most recent being by Skillman & Kennicutt (1993, hereafter SK93), which gives references to prior studies. The most extensive theoretical study of the chemical and star formation history of I Zw 18 to date is by Kunth, Mateucci, & Marconi (1995), which concluded that I Zw 18 could not have experienced more than two bursts of star formation, with durations no longer than 10–20 Myr each.

Morphologically, I Zw 18 has a "peanut-shaped" main body, consisting of two bright centers of star formation, separated by 5″.8. Near the main body, to the north and west, are several diffuse features noted from the deep ground-based imagery of DKF89 & DH90. Recent imagery with *HST* resolves I Zw 18 into stars (Meurer et al. 1995; Hunter & Thronson 1995; Dufour et al. 1996a, 1996b), with the brightest being $V \approx 22.0$. The deep *HST* WFPC2 imagery of Dufour et al. found that the nearest of the diffuse features—feature C—appears to be a blue irregular galaxy (Im) located only 15″ northwest of the main body of I Zw 18. Their images show that this system is resolved into stars (e.g., Fig. 3 in Dufour et al. 1996a), with the brightest having $V \approx 24.5$, and contains two emission nebulae. For clarity we will hereafter call feature C the "companion" and refer to the BCD main body as "I Zw 18." If this companion galaxy is at the same distance as I Zw 18 (assumed to be 10 Mpc, for which 1″ = 48 pc in the plane of the sky), then it could be as close as only a few kpc to the brighter starbursting main body of I Zw 18.

Prior to the *HST* studies, there has been some optical evidence that this companion galaxy and I Zw 18 are connected by emission in the red continuum (DKF89) and in Hα (DH90). In addition, VLA 21 cm maps presented by Viallefond, Lequeux, & Compte (1987, hereafter VLC87) showed that I Zw 18 is surrounded by an extended (60″ × 30″) H I for which the companion galaxy was located at a "depression in the H I surface density." VLC87 also presented a map of the H I velocity field, which they interpreted as indicating an "overall fairly regular radial velocity gradient" over the main H I cloud, with the velocities in the northwest dropping 30–40 km s^{-1} compared to the center of I Zw 18. Since the spatial resolution of VLC87 H I velocity maps was relatively poor (5″–8″), and it is further unclear if any of the H I is physically associated with the companion (although the ionized gas might be), we have obtained deep long-slit spectra in order to measure accurate radial velocities of emission-line gas in both I Zw 18 and the companion. The results are the subject of this Letter.

2. OBSERVATIONS AND REDUCTIONS

The observations were made on 1996 February 20 at the Observatorio del Roque de los Muchachos (La Palma), using the 4.2 m William Herschel Telescope (WHT) with the ISIS spectrograph at the Cassegrain focus. Two Tektronix CCDs with a configuration of 1124 × 680 pixels of 24 μm each were used in the blue and red arms of the spectrograph. The slit was 4′ long and 1″ wide. The dichroic used to separate the blue and red beams was set at 5400 Å. Two gratings were used, a 600 groove mm^{-1} one in the blue arm and a 1200 groove mm^{-1} one in the red arm. These gratings gave reciprocal dispersions of 33 and 17 Å mm^{-1}, respectively, and effective resolutions of about 1.41 and 0.73 Å for the blue and red arms, respectively. The blue spectra cover from 4300 to 5100 Å, the red ones from 6450 to 6850 Å.

The average seeing was about 1."8 throughout the observations. The slit position angle (P.A.) was 129.°15—centered on the bright Hα knot in the northwestern H II region of I Zw 18 and chosen to extend to the Hα knot associated with the companion stellar system. The location of this slit is shown overlaid onto a deep *HST* image in Figure 1 (Plate L10). Altogether, six 30 minute exposures were taken and combined to produce the final blue and red spectra. Comparison lamp exposures were taken before and after each set of object spectra.

The data were reduced using the standard IRAF[1] TWODSPEC reduction package to perform bias corrections, flat-fielding, cosmic-ray rejection, etc. All six of the CCD frames were combined and then geometrically corrected, wavelength calibrated, and sky subtracted in two dimensions. Because high humidity forced early closure of the telescope the night of the observations, spectra of standard stars could not be obtained to enable an absolute flux calibration of our spectra.

Figure 2 (Plate L11) shows the Hα two-dimensional profile along the central part of the single slit position observed, with contours overlaid onto the summed images. The brightest part corresponds to the northwestern H II region of I Zw 18. The Hα knot in the companion can be seen as the patch of emission at the upper part of the spectrum located 26" (1.25 kpc) from the peak emission of I Zw 18. Inspection of this figure shows four important results: (*a*) there is continuous Hα emission between I Zw 18 and the Hα knot in the center of the companion, (*b*) the Hα knot in the companion shows a profile that is very broad and diffuse, (*c*) the northwestern H II region of I Zw 18 has an Hα line profile of a bright core with faint broad wings, and (*d*) the major axes of the outer contours of the emission along the main body of I Zw 18 are tilted toward shorter wavelengths in the northwest and longer wavelengths in the southwest.

In order to quantify the velocity structure of the ionized gas along the slit, we performed Gaussian fits of the emission-line profiles using the Starlink DIPSO software package (Howarth & Murray 1990). One-dimensional spectra were extracted every 5 pixels along the slit to maximize the spatial information, given the typical FWHM of the seeing (≈1."8). Multiple Gaussian fitting was performed for those zones where the line profiles were complex, while in the other zones single Gaussian fits were sufficient to reconstruct the observed line profiles. For each single or multiple Gaussian fit, the DIPSO software gives the statistical errors in the fit parameters (velocity centroid, Gaussian sigma, FWHM, etc.).

3. RESULTS AND DISCUSSION

3.1. *The Overall Velocity Field*

The variation of heliocentric radial velocities measured for the dominant narrow component of the Hα and Hβ lines across a 50" length of slit (≈2.4 kpc) is presented in Figure 3. The average radial velocity of the brightest part of the companion, +751 ± 5 km s^{-1}, is similar to the average observed for the northwestern H II region area of I Zw 18, +745 ± 3 km s^{-1} (where the uncertainties include the residuals of the Gaussian fits and the dispersion of the radial velocities obtained for the different bright emission lines). However, the most striking aspect of Figure 3 is the smooth double-sinusoidal variation in V_r observed along the slit, ranging from V_r ≈ +735 km s^{-1} several arcseconds northwest of the brightest Hα knot in the northwestern cluster in I Zw 18, to V_r ≈ +776 km s^{-1} about 10" toward the southeast (near the eastern edge of the southeastern star-forming complex in the main body). This is the first time such an extended velocity field structure has been observed in the *ionized gas* of I Zw 18. We believe that this is due to (*a*) our deeper spectra compared to previous ground-based studies, (*b*) our increased spatial resolution compared to the previous 21 cm H I observations, and (*c*) the fact that the ionized medium is more physically linked to the star formation, winds, and ambient UV radiation field than the neutral medium.

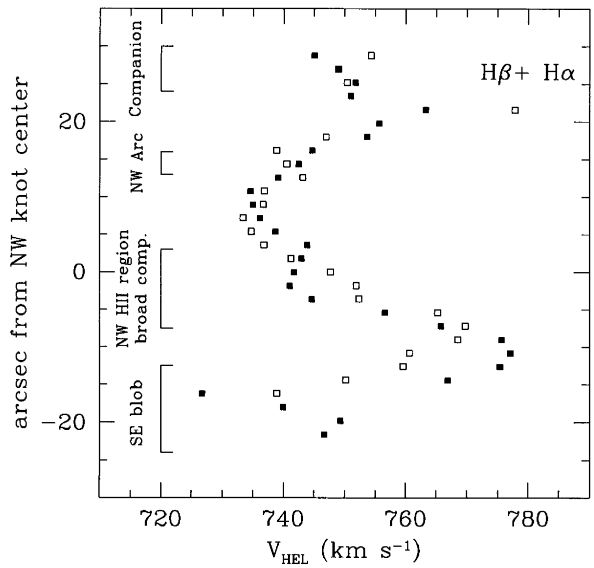

FIG. 3.—Position-velocity diagrams for the slit position observed. Filled and open squares correspond to the measurements obtained from the Hα and Hβ emission lines, respectively. Observational uncertainties are omitted for clarity; they are of the order of ±1–3 km s^{-1} in the brightest central ±10" for both lines and of the order of ±5–10 km s^{-1} in the external zones for Hα and ±7–15 km s^{-1} for Hβ.

Also in Figure 3, we have associated some morphological structures with several parts of the velocity distribution along the slit. The similarity of the radial velocities of the gas near the center of I Zw 18 and that of the emission knot in the companion is evident. But most significant is that the ionized gas between the two stellar systems shows a smooth trend in radial velocity—a trend that is *reversed* from the trend (or gradient) seen across the central part of I Zw 18 and one that kinematically links the ionized gas in the northwestern part of I Zw 18 to that in the companion galaxy. Therefore, we submit that these results indicate the high probability of a physical connection between the two stellar systems. The presence of extended faint Hα emission connecting the main body of I Zw 18 and the companion was previously noted from deep Hα imagery by DH90—who, in fact, first suggested a possible

[1] IRAF is distributed by NOAO, which is operated by AURA, Inc., under cooperative agreement with NSF.

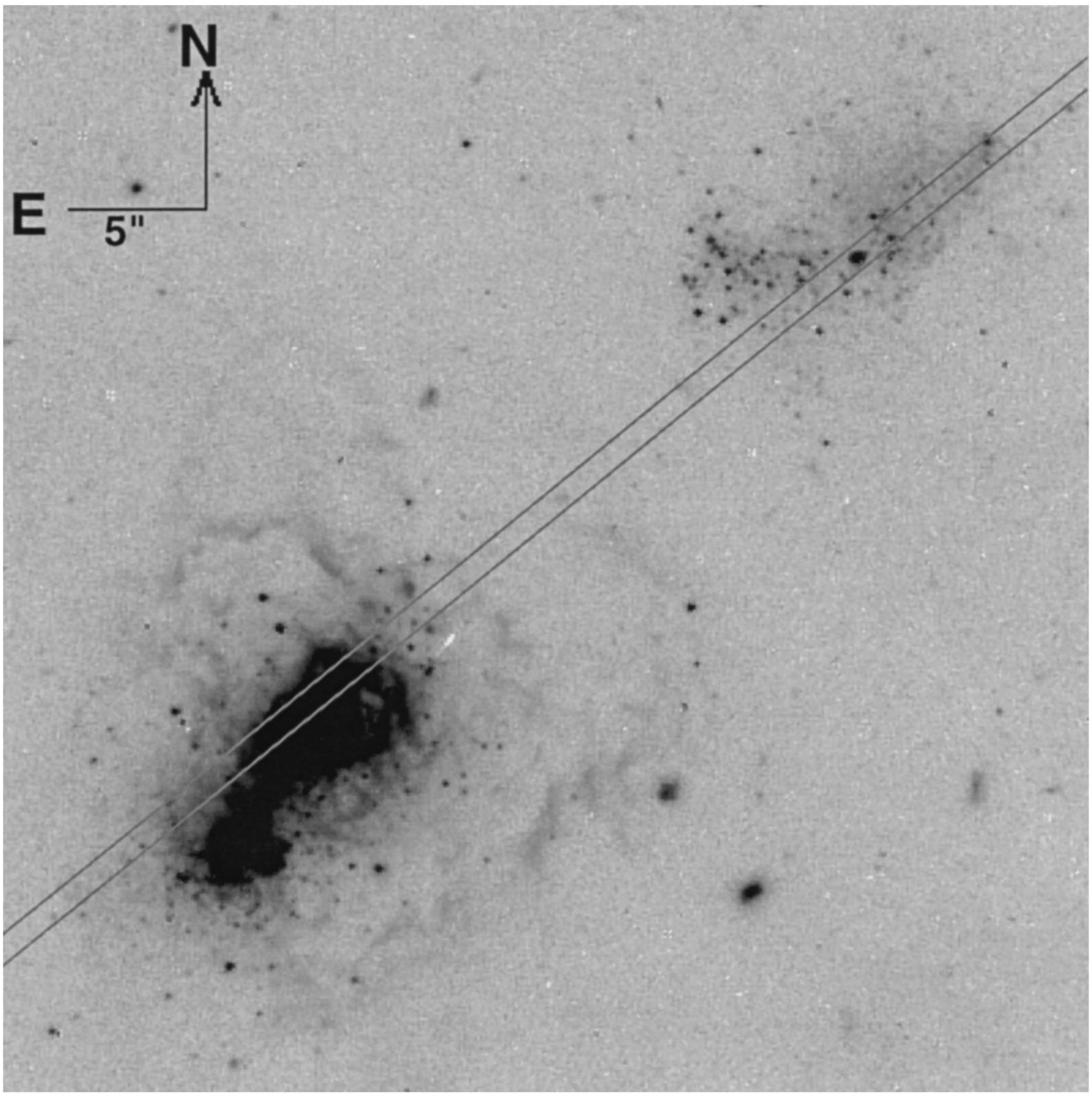

FIG. 1.—*HST* WFPC2 image of I Zw 18 and the companion galaxy. The field is 40″ square with the WHT ISIS slit position overlaid. Paired exposures taken through F450W, F555W, and F675W were summed in this image, for which the two galaxies were in the WF3 chip.

DUFOUR, ESTEBAN, & CASTAÑEDA (see 471, L88)

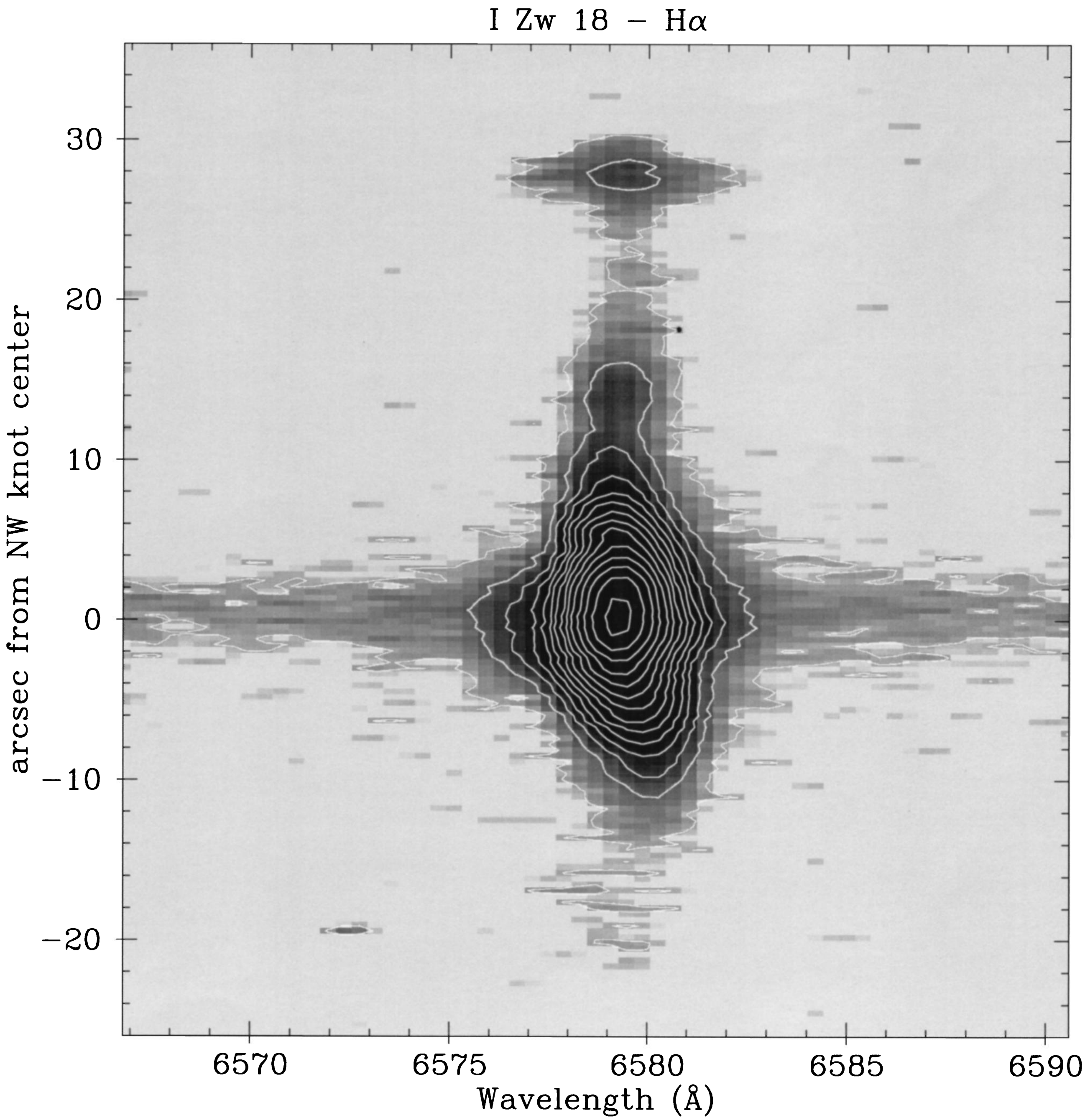

FIG. 2.—Two-dimensional profile of Hα along the central part of the slit observed. Each pixel corresponds to 0".36 in the spatial direction.

DUFOUR, ESTEBAN, & CASTAÑEDA (see 471, L88) physical connection. Here we show that the kinematics of this ionized gas between I Zw 18 and the companion galaxy is consistent with a physical connection.

Another interesting feature is the low-intensity Hα emission "tail" observed in the southeastern edge of the line emission distribution (labeled as "SE blob" in Fig. 3). This gas presents roughly the same heliocentric velocity ($\approx +740 \pm 10$ km s^{-1}) as the other features commented on above, and its position coincides with a detached H I cloud noted by VLC87 southeast of the main body of I Zw 18. However, on the H I velocity map of VLC87, the radial velocities in this southeastern region are $\sim +800$ km s^{-1}, significantly larger than what we find for the coincident H II gas. This, and the faint, diffuse appearance of the emission on both the *HST* images (in Hα, no continuum emission or stars are seen) and those by DH90, lead us to conclude that this "SE blob" emission is unlikely to be associated with the southeastern H I cloud seen by VLC87.

3.2. *The Central Velocity Field*

The velocity gradient observed between the two main clusters in I Zw 18 (noting that our slit passes a few arcseconds northeast of their centers) is $\approx +7$ km s^{-1} arcsec^{-1} going from the northwest to the southeast (across a 6″ ~ 300 pc distance). The linear velocity distribution that we find for the inner 20″ (~1000 pc) across the optical center of I Zw 18 is very similar to that obtained from optical long-slit spectroscopy by Martin (1996, hereafter M96) in her slit position 2, the one that goes through the major optical axis of I Zw 18 and the closest one to the position angle that we use in our observations. In addition, the (much lower spatial resolution) H I 21 cm velocity map presented by VLC87 showed a fairly regular velocity gradient across the two central H I clouds that lie near the optical center of I Zw 18 (noting that a recent reanalysis of the VLA data by Skillman et al. 1996 indicates almost perfect coincidence between the two central H I clouds and the two optical clusters in the center of I Zw 18). We also note previous Fabry-Perot observations: Castañeda & Fuentes-Masip (1995) indicate that, at small scales, the overall velocity field of I Zw 18 does not seem to be chaotic, for they generally see coherence in the isolines of velocity, running almost perpendicular to the velocity gradient.

Based on the assumption that this smooth central velocity gradient is due to rotation, VLC87 derived a virial mass of I Zw 18 that was over 1 order of magnitude higher than the H I mass. However, two recent studies (M96 & SK93) cautioned against interpreting this central axis velocity gradient as simply being due to pure virial motion. Martin's (M96) apprehension is based on the fact that she found clear kinematic signatures of two expanding supergiant shells in the central regions of I Zw 18, the most prominent located southwest of the northwestern starbursting cluster in I Zw 18, and a second, less prominent one located just north of the northwestern cluster. The model she favors to explain the kinematics of the ionized gas near the optical center of I Zw 18 is that of a bipolar superbubble with a polar axis inclined about 10° to our line of sight. The question that arises is whether this superbubble model can account for the double-sinusoidal velocity distribution that we observe. The answer is yes if we postulate that our slit crosses a superbubble between the northwestern cluster of I Zw 18 such that we are observing the receding component of a Doppler ellipse which produces the velocity reversal that we observe in the northwest, and that the velocity reversal that we observe in the southeast is just part of the dominant approaching component of the southeast superbubble. However, comparison of our slit location (Fig. 1) with those of M96 (her Fig. 1, where the Hα knot of the companion galaxy is clearly visible in the top right corner of the field) indicates that our slit crosses the lower part of the northern superbubble and does *not* cross the larger southeastern superbubble (both marked as "shell" on her figure). Moreover, we do not see evidence of a Doppler ellipse (or ellipses) in our (deeper) spectrum.

Another scenario is that the velocity distribution is the result of colliding clouds. SK93 reported some velocity results based on Multiple Mirror Telescope long-slit echellette spectra with a 2″ wide slit placed across the optical axis of I Zw 18 (P.A. = 321°). They found that the radial velocity was nearly constant throughout the northwestern stellar component, while noting a gradient near the southeastern component of ~10 km s^{-1} arcsec^{-1}, with most of the gradient occurring between the two components. This is similar to our results, noting that our slit is shifted a few arcseconds east of that used in SK93 and does not overlap the major stellar axis of I Zw 18. The picture that SK93 favor for the dynamics of the two star-forming regions of I Zw 18 is a merger of two (or more) clouds, as first suggested by Lequeux & Viallefond (1980). This, coupled with the smooth reversal of velocities that we observe in the ionized gas outside the main body of I Zw 18, leads us to favor the interpretation that the large-scale velocity results for the bulk of the ionized gas in I Zw 18 are more consistent with the scenario of I Zw 18 being a starburst resulting from the merger of two H I clouds.

However, we do observe the presence of *low-intensity*, high-velocity gas in the northwestern H II region, confirming previous observations of DKF89 and M96. The spatial extension of this asymmetrical high-velocity emission is about 9″ (≈430 pc), presents a FWZI of about 360 km s^{-1}, and extends over the two central star-forming knots. M96 did not find any evidence of a Doppler ellipse in her data for this feature. She suggests that champagne flows from the young H II regions could provide an appropriate description of its peculiar kinematics. Previous studies show also a peculiar kinematic behavior in the northwest knot. The echelle spectroscopy of DKF89 shows a splitting in the emission line, separated by 3″.5, and similar radial velocities of 740 km s^{-1}. Moreover, several recent studies, such as Izotov et al. (1996), have found low-intensity broad wings in several star-forming H II galaxies, showing very similar linear sizes and FWZI.

The points located at +15″ (northwest) from the center in Figure 3 correspond to the northern extreme of the supergiant shell(?) that surrounds the western part of I Zw 18 (M96), and they present the same heliocentric velocity as the main body of the galaxy, without any evidence of expansion. Indeed, nowhere along our slit in the northwest do the line profiles show evidence of splitting or Doppler ellipses that would indicate the dominant emission coming from expanding shells. This result supports the suggestion by DH90 that the western shell represents a radiation-bounded ionization front.

3.3. *High-Velocity Structure in the Hα knot of the Companion*

The Hα emission profile of the core of the companion system shows a contribution of broad emission that accounts for a significant fraction of the intensity in this line (about $\frac{1}{3}$). We have tried various possible multiple Gaussian fittings of the Hα profile of the companion. The simplest one includes two Gaussians, the narrow one has a FWHM of 32 km s^{-1}, and the broad one a FWHM of 182 km s^{-1}. A better fit can be

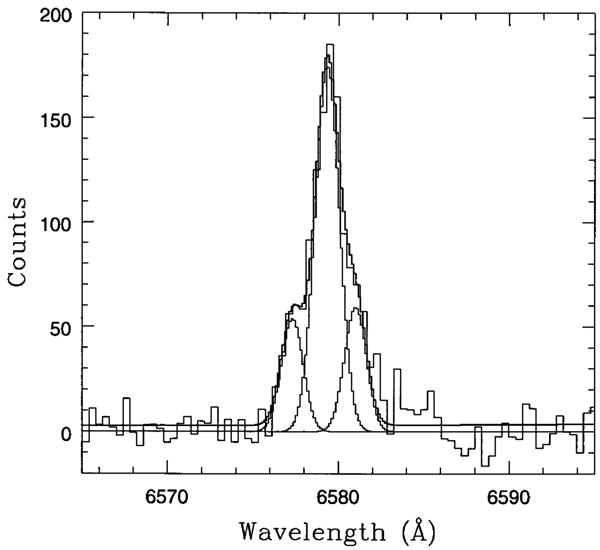

FIG. 4.—Examples of multiple Gaussian fits to the Hα line profile of the Hα knot in the companion system.

achieved using three Gaussians of similar width, as is shown in Figure 4. We interpret this situation as an expanding bubble inside a static H II region. The maximum expansion velocity of this bubble is about 85 km s^{-1}. A close inspection of the two-dimensional Hα profile shown in Figure 2 indicates that the broad component seems to extend along all the visible size of the patch of Hα emission. The total extension is about 4″.5, corresponding to a linear size of about 215 pc.

Taking into account these physical parameters and assuming the energy-conserving solution for the dynamics of stellar wind bubbles (Castor, McCray, & Weaver 1975), we derive a dynamical age of 0.75 Myr and a kinetic energy of $E_k = 5.9 \times 10^{52}\ n_0$ ergs, where n_0 is the ambient number density of particles. These numbers suggest this expanding feature could correspond to a superbubble powered by the mechanical effect of stellar winds and/or supernova explosions inside the companion stellar system. However, a puzzling characteristic of this emission knot evident on our spectra is that we do not see it in the nebular lines of [O III]. Deeper spectra covering a longer wavelength range are required to ascertain the true nature of this emission-line object.

4. CONCLUSIONS

These new spectra show that, outside the area of the two star-forming regions of I Zw 18, the velocity gradient *reverses* in both directions. Such a behavior is clearly unexpected if the ionized gas was in simple rotation about a center of mass in the main body. However, such behavior is possible by gas streaming from two colliding clouds, large extended superbubbles, or the tidal affects of a nearby comparably massive galaxy. In order to distinguish between these possibilities, complete spatial mapping of the velocity field of the extended ionized gas in I Zw 18 will be required.

The H I distribution, coupled with the fact that the northwestern H II region of I Zw 18 containing the most massive star cluster, the companion galaxy, and the southeastern H II gas are all moving roughly at the same velocity—the systemic velocity (~740 km s^{-1})—leads us to favor the scenario that the I Zw 18 "system" consists of a complex of dynamically associated clouds. The northeasternmost cloud is now seen as an evolved stellar system containing stars at least several hundred Myr old (Dufour et al. 1996a, 1996b), the two central clouds are undergoing a starburst with the northwestern one containing the older cluster (Hunter & Thronson 1995), while the southeasternmost cloud has yet to show any star formation. Therefore, these new results are consistent with the speculation by DH90 that a sequence of star formation is occurring in the various H I clouds progressing from the northwest to the southeast.

A remaining important question is whether the nucleosynthesis products of prior generations of stars in the older Im companion galaxy have "polluted" one or both of the H I clouds now comprising the starbursting I Zw 18 system. If the supernova (and/or wind-driven) ejecta of massive stars in the companion has dispersed over 4π steradians and it has been several kiloparsecs distant in the past, the answer is probably no. However, if the gas surrounding the companion has been tidally pulled into mixing with the pristine material of the two central H I clouds, the possibility for "pollution" is significant. Such a scenario *now* merits additional study, both observational and theoretical.

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