INTRODUCTION

The internal kinematics of galaxies has been one of the central elements that led to initially establishing the dark matter hypothesis in astrophysics (Rubin et al. 1978; Bosma 1978). In particular, the non-Keplerian behavior of disk galaxy rotation curves has been naturally incorporated into the current cosmological paradigm, the LCDM model, through dark matter halos surrounding galaxies, and even the halo mass assembly is accurately predicted by the model (e.g., Frenk et al. 1988). The halos surrounding galaxies, and even the halo mass assembly is critical in order to compare cosmological predictions with observations, the presence of non-circular motions is a common result; almost every new study reports galaxies whose rotation curves are consistent with cores, but also a minority that are consistent with cusps (Simon et al. 2005), in some cases “cuspier” than cosmological predictions, suggesting some systematic effect. However, still there is not a unanimous agreement about the interpretation of these observational results, in particular for the detected non-circular motions, for example, some valuable methods assume the epicyclic approximation,

distinguishing between different galaxy formation scenarios makes it important and interesting to quantitatively evaluate possible deviations from the rotational support assumption, the so-called non-circular motions. They have been largely discussed as being motivated by either the observed structures of some galaxies, like bars, spirals, and lopsidedness (Rhee et al. 2004; Spekkens & Sellwood 2007; Sellwood & Sánchez 2010), or by the possibility of elliptical galaxy disks triggered by triaxial dark matter halos but masked by projection effects (Hayashi & Navarro 2006). The pursuit of adopting methods free from the non-circular motion complications has triggered a revision of both theoretical (Bailin et al. 2007) and observational analysis techniques (Kuzio de Naray et al. 2012; Kuzio de Naray & Kaufmann 2011; Spekkens & Sellwood 2007). Currently, in observations, the presence of non-circular motions is a common result; almost every new study reports galaxies whose rotation curves are consistent with cores, but also a minority that are consistent with cusps (Simon et al. 2005), in some cases “cuspier” than cosmological predictions, suggesting some systematic effect. However, still there is not a unanimous agreement about the interpretation of these observational results, in particular for the detected non-circular motions, for example, some valuable methods assume the epicyclic approximation,
which may be problematic for strong perturbation like bars or considerably elliptical disks (Franx et al. 1994; Schoenmakers et al. 1997), and others do not adopt these hypotheses (Spekkens & Sellwood 2007; Sellwood & Sánchez 2010; Kuzio de Naray et al. 2012). Some other methods assume a subdominant and random nature in non-circular motions (Oh et al. 2011).

Recently, it has been shown that bar instabilities are present in some dwarf LSB galaxies used to study the central dark matter distribution using their rotation curve (NGC 3109, NGC 6822; Valenzuela et al. 2007). The bar dynamical effects are arguably enough to explain the discrepancy with cosmological predictions, at least when they act together with pressure support (Valenzuela et al. 2007). For one dwarf galaxy (NGC 6822), the bar has been clearly revealed in H i kinematics residuals after rotation subtraction (see Figure 2 in Rhee 2009; G. Rhee et al., in preparation), questioning whether or not the rotation curve fully constrains the mass distribution for this galaxy. It is, however, necessary to analyze more dwarf galaxy cases before arguing that this is a general result. On the contrary, NGC 2976 belongs to a sample of galaxies that has been argued to present a pure disk, with no bar, spiral arms, or bulge. The clear detection of non-circular motions raised the possibility of witnessing an elliptical disk triggered by the dark halo triaxiality (Simon et al. 2003, 2005). Later, Spekkens & Sellwood (2007) reported evidence favoring a kinematic bisymmetric distortion over an inflow/outflow, leaving open the question of whether the kinematic perturber is a stellar bar or a prolate dark matter halo. More recently, Adams et al. (2012) found stellar kinematic evidence for non-circular motions possibly consistent with a disk inside a cuspy halo. Although recent analysis of Two Micron All Sky Survey images of NGC 2976 (Menéndez-Delmestre et al. 2007) marginally suggested the presence of a stellar bar candidate, more recent theoretical studies conclude that based on the photometrically estimated disk mass, the triaxiality must have been preserved after the disk formation (Kazantzidis et al. 2010), making the triaxial halo presence scenario appealing. It is then important to quantitatively assess the bar presence/absence, together with measurements of its strength. A possible bar may represent evidence of secular evolution in dwarf irregular galaxies, whose importance is currently uncertain in evolution models. In this paper, we used techniques commonly used in giant high surface brightness galaxies in order to confirm the bar presence and also with the aim of measuring the strength of the perturbation with enough signal to noise. The paper is structured as follows. Section 2 describes the observations used in this study. Section 3 describes the different diagnostics performed in NGC 2976 in order to detect and measure the bar/arm properties. Section 4.1 presents a discussion about the nature of non-circular motions and their relationship with a bar or non-spherical halo. Section 4.2 briefly discusses the consequences for the detected bar and arms for satellite galaxy transformation models in groups like tidal stirring. Finally, in Section 5 we present our conclusions.

2. OBSERVATIONS

Daigle et al. (2006) describes NGC 2976 as a peculiar dwarf ($M_B = 16.90$) late-type (SAd pec) galaxy with a nearly linear rotation curve, no spiral arm visible, and two strong HII regions located on each side of the galaxy. They report a photometric/kinematical position angle and inclinations of $323/323.5$ and $63/70$, respectively. Stil & Israel (2002) observed that in H I, the rotation curve seems to flatten near the edge of the H I disk. According to Bronkalla et al. (1992), the outer parts of NGC 2976 have been undisturbed for a long time and are very old (5 Gyr, probably up to 15 Gyr). This last conclusion seems to be at odds with the recent results in Walter et al. (2002) and Chynoweth et al. (2008), who observed the M81/M82 group, finding that M81, M82, NGC 3077, and NGC 2976 show the remnants of strong interactions as well as over 40 dwarf galaxies in their close neighborhood. Chynoweth et al. (2008) studied the H I emission of the group covering an area $3° \times 3°$ centered on M81 to include NGC 2976 and the extended emission associated with the group, finding an H I cloud located 27 kpc to the northeast of NGC 2976 and calculating a mass of $2.67 \pm 0.65 \times 10^{10} M_\odot$, which may be contributing to the observed perturbation in NGC 2976.

NGC 2976 is part of the Spitzer Infrared Nearby Galaxies Survey sample and our photometric analyses take advantage of the already available 3.6 $\mu$m IRAC images with a scale of 1.22 arcsec pixel$^{-1}$. We combined these data with observations at visible wavelengths, mainly the $B_J$-band images of the photometric system by Gullixson et al. (1995) as observed by Frei et al. (1996) with a scale of 1.35 arcsec pixel$^{-1}$. We also use Hz monochromatic maps from the Fabry–Perot of New Technology for the Observatorio du mont Megantic with a scale of 1.61 arcsec pixel$^{-1}$ that are described in Daigle et al. (2006). After matching the images to the same resolution, we built a $(B – 3.6)$ color index map to get new insights on the structural properties of NGC 2976. For some of the analysis we tried to deproject the image assuming a circular disk and a disk thickness consistent with galaxies with similar rotation curve amplitude; we avoided the deprojection in some cases because the possible non-axisymmetric structure and inclination may complicate the traditional strategy (García-Gómez et al. 2004; Hernández-López et al. 2009).

3. DIAGNOSTICS FOR THE BAR PRESENCE

3.1. Morphological Evidence: Dust Lanes and CO Intensity Maps

It is well established in galaxy dynamics that a galaxy bar produces interstellar medium shocks which can be traced by dust lanes (Athanassoula 1992; Prendergast 1983). In order to search for the presence of shocks we constructed a $B – 3.6$ $\mu$m color image presented in the upper panel of Figure 1. The dark structures are the most dust-obscured regions. Particularly notable are the pair of curved dust lanes in the central region of NGC 2976, similar to the ones presented by Athanassoula (1992) in the case of weak or slow bars. In the upper right region of the color map image there is a spiral-arm-like disk structure. This finding supports the existence of a disk bar and spiral arms; however, it can still be argued that a random star formation pattern may produce the structures, therefore we will study other diagnostics like the kinematic response traced by H I in the bar region in the following sections. As support for the bar interpretation, we present in the lower panel of Figure 1 the CO integrated intensity contours in NGC 2976, taken from the HERACLES survey (Leroy et al. 2009) and the STING survey (A. Bolatto et al., in preparation) on top of the 3.6 $\mu$m image, and together with the color map contours. An elongated CO structure with a different position angle compared with the average stellar component is outstanding; the structure twists on both sides, developing narrow arcs similar to tightly wound spiral arms. The spiral-arm-like features are coincident with the dust map structures. The two symmetric bright spots suggest the beginning of spiral arms.
Figure 1. Morphological bar evidence. The upper panel contains a color map of $B - 3.5 \mu m$. The curved dust lanes in the central region are characteristic of a weak/slow bar. The upper right region suggests the geometry of spiral arms. The lower panel shows the $3.6 \mu m$ image tracking the stellar component with little dust extinction, combined with dust map contours (thick black lines) and CO intensity contours (thin blue lines). The central region presents a box-like structure resembling a weak stellar bar and is spatially coincident with the curved dust lanes. The contours are for integrated intensity CO $J = 0 \rightarrow 1$, CO $J = 2 \rightarrow 1$, along each line of sight considering regions with $I_{CO} > 2\sigma$ (taken from A. D. Bolatto et al., in preparation, and Leroy et al. 2009). Notice the change in position angle and the coincidence with boxy stellar structure as well with the dust lanes.

(A color version of this figure is available in the online journal.)

### 3.2. Radial Fourier Modes

A bisymmetric structure like a galactic bar or a spiral arm pair can be well represented by even Fourier components. A first diagnostic to the presence of such structures is the amplitude of the second Fourier mode and the behavior of its phase. Figure 2 shows the first two Fourier modes for the average stellar component and the CO gas emission (solid and dashed lines, respectively). The first Fourier mode shows a very small amplitude in the stellar component (less than 0.05), while for the CO tracer the behavior is noisier but with a larger amplitude. The phase is consistent for both tracers. It is not straightforward to disentangle if this amplitude is the result of the clumpy distribution of molecular gas or a truly global lopsidedness. The second Fourier mode barely has a non-zero amplitude inside 70 arcsec in $3.6 \mu m$ where the isophotes show a boxy shape; however, its amplitude in CO indicates that 20% of the surface brightness is in the $m = 2$ mode, consistent with the more elongated CO distribution. The corresponding phase is consistent in both tracers, showing a big jump at 50−70 arcsec, suggesting the transition from bar to the spiral arms. The azimuthal average and projection effects may have a non-trivial influence on one-dimensional Fourier analysis, not to mention the flocculent structure; therefore, we will apply other diagnostics.

### 3.3. Two-dimensional Fourier Analysis

In order to keep azimuthal information, we performed a two-dimensional Fourier analysis of the $3.6 \mu m$ image. We split the image in two: one image built with all of the even modes and another one built with the odd modes. If there is a bar or bisymmetric arms it must be shown in the even mode. Figure 3 shows at the top the deprojected $3.6 \mu m$ image next to a deprojection of the color map, and at the bottom both even and odd images (left and right, respectively). The even image clearly shows a boxy structure at the position of the CO bar and the beginning of bisymmetric spiral arms. Although
The Astronomical Journal, 147:27 (8pp), 2014 February

Figure 2. Azimuthally averaged first and second Fourier modes. Top panel: mean surface brightness profile in the stellar component (solid line) and molecular gas CO (dotted line). Middle left: A1 Fourier mode (lopsidedness). Middle right: A1 phase profile in radians. Lower left: A2 Fourier mode (bisymmetric distortion) amplitude. Note the A2 mode amplitude in CO is large while in 3.6 μm it is negligible, suggesting gaseous richness in the bar. The A2 mode phase shows a big jump close to 50 arcsec (0.5 kpc), coincident with the beginning of the spiral arms. (A color version of this figure is available in the online journal.)

encouraging, complications associated with the deprojection have to be carefully handled (García-Gómez et al. 2004); it is, however, remarkable that the bar and spiral arm structures are so well defined despite the fact that the radial Fourier mode in the stellar component is not large, supporting the interpretation that both bar and arms are gas rich, but they have a stellar counterpart.

3.4. Kinematic Signatures of Bar-induced Shocks

Shocks across dust lanes are readily identified as steep velocity gradients (Athanassoula 1992; Weiner et al. 2001). We used the Hα velocity field kindly previously discussed by Daigle et al. (2006). The data points in the right panel of Figure 4 show the observed velocities along a pseudo-slit crossing the velocity field placed with an orientation perpendicular to the curved dust lanes shown in the left panel. The pseudo-slit reveals a projected velocity gradient of almost 30 km s^{-1} that is coincident with the prominent dust lane. A similar configuration and signature is discussed in Záñmar Sánchez et al. (2008). We conclude that regardless of projection effects, the gas-rich bar has a dynamical effect on NGC 2976 internal kinematics.

3.5. Two-dimensional Force Map

Once we are confident about the presence of a bar in the stellar component of NGC 2976, it is natural to ask for the bisymmetric perturbation strength. Buta & Block (2001) and Buta (2003) introduced the ratio of tangential to radial force Q_b as a diagnostic of the bar/arm strength. After solving the Poisson equation on the deprojected stellar component image, the potential is differentiated in order to calculate radial and tangential forces point by point. Afterward, we built a two-dimensional map of the ratio as shown in Figure 5. The characteristic bar/arm signature is the alternating sign of this ratio as we move through quadrants, verifying the bar/arm interpretation in our previous diagnostics. The central region shows a slightly asymmetric central pattern, and the large-scale diagram illustrates the spiral arm force as discussed by Block et al. (2004). The ratio of the maximum tangential force to the average radial axisymmetric amplitude has been shown as an amplitude measurement (Combes & Sanders 1981). For NGC 2976, the value in the bar region is around 0.4; therefore, the bisymmetric perturbation is a strong one, regardless of its nature. At the arms region the tangential perturbation is even larger, reaching values of 80% of the radial force.

4. DARK MATTER DISTRIBUTION

NGC 2976 dark matter distribution has been discussed by several studies; most of them favored a cored halo distribution based on interpretation of the rotation curve (Simon et al. 2003; Spekkens & Sellwood 2007; de Blok et al. 2008). However, recently Adams et al. (2012) concluded that stellar kinematics and anisotropic Jeans modeling combined with information about its star formation history favored a cuspy dark matter distribution. A critical difference between these studies is the interpretation of non-circular motions. These non-circular motions are detected in both the gas and stellar components. In the next sections we will discuss their possible nature.
4.1. Non-circular Motions: Triaxial Halo/Bar and Arms?

NGC 2976 has been proposed as a system that provides kinematic evidence for a triaxial halo. This is important because the existence of non-spherical dark matter halos is a ubiquitous prediction of hierarchical structure formation models. Galaxy disks that are expected to react to the triaxial halo potential become elliptical and even develop instabilities triggered by the halo perturbation. The halo triaxiality is also modified by the process, making non-trivial the predictions about the central density structure (Bailin et al. 2007). However, a positive detection of halo triaxiality in disk galaxies has been hampered partly because of the degeneracy between true disk ellipticity and projection effects. A promising avenue to verify this prediction is a kinematic detection of disk ellipticity in the absence of bars and spiral arms. Simon et al. (2003) pointed out that NGC 2976 shows considerable non-circular motions but the galaxy lacks of an obvious non-axisymmetric internal baryonic perturber, raising the possibility that we are witnessing an elliptical disk triggered by a triaxial halo. Spekkens & Sellwood (2007) showed that a bisymmetric model is preferred by the data over a radial flow. Furthermore, recently Kazantzidis et al. (2010) showed that constraints on the disk mass suggest that adiabatic disk formation would not have been able to erase halo triaxiality. Although our results do not question the theoretical calculations, we positively detect a bar and spiral arms. It is fair to mention that the bar and arms system is unusual; the bar is clearly shown in the CO intensity map, but in H\textsc{i} the bar is rather uncertain while the arms are detectable. In 3.6 \( \mu \text{m} \) the bar appears only as a box-like structure, and the arms are noticeable mainly through the symmetric bright spots. The situation in normal galaxies is the opposite: a clear stellar bar and a gaseous response to the dynamical perturbation are observed, hinting at a bar. If NGC 2976’s gaseous disks are dominant over stars, it is possible to explain its morphology. However, the reported stellar mass is \( 5 \times 10^9 \, M_\odot \) and the gaseous mass is at most 30% of that of stars (1.5 \( \times 10^8 \, M_\odot \); Del Popolo 2012). Although there is evidence of gas tidal stripping, and
Figure 4. Dynamical effect of the bar. The left panel presents the color map showing dust lanes across the whole galaxy. The vertical lines show cuts along the velocity field crossing the dust lanes. Specifically, the vertical line labeled (298, 311) crosses the curved dust lane at these pixel coordinates. The right panel shows how the velocity profile presents a jump of about 30 km s$^{-1}$ going from pixel 330 to 311, in other words crossing the dust lane.

(A color version of this figure is available in the online journal.)

Figure 5. Torque map based on the 3.6μm image and solving the Poisson equation. Red (blue) colors correspond to a negative (positive) sign. The alternating sign is the distinctive signature of a bar/arm quadrupole.

(A color version of this figure is available in the online journal.)

therefore the galaxy may have been even richer in gas, there is not an obvious reason for the bar to be more visible in gas. Williams et al. (2010) and others have discussed the presence of a stellar spheroid or halo of intermediate-age stars; this structure may be observed in projection as a boxy bulge. One possible alternative interpretation is that indeed we are witnessing the gas/star response to an elongated dark matter halo. In such a case, stars reacted to the triaxial halo orbital structure developing the boxy bulge. Indeed, disk non-axisymmetric structures and triaxiality are not necessarily mutually exclusive. It is well known that an elongated halo is able to trigger spiral arms (Bekki & Freeman 2002). Some recent studies simulated the interaction of bars and disks inside triaxial live halos, concluding that disk bar formation is possible but it can also erase halo triaxiality in the central region (Berentzen et al. 2006; Athanassoula et al. 2013). However, the models were tuned to high surface brightness galaxies unlike NGC 2976; therefore, because of its low baryonic fraction, we cannot rule out the possibility that considerable triaxiality has survived in the central region of NGC 2976 regardless of the bar/arm presence. We conclude that non-circular motions in the central 80 arcsec are likely triggered by the detected bar/arms, and it is not obvious how to disentangle the importance of bar/arms against halo triaxiality inside 50 arcsec. Nevertheless, triaxiality may survive at the galaxy outskirts. In order to test this interpretation, we used controlled smoothed particle hydrodynamics (SPH) simulations of gaseous disks in triaxial halo potentials. The simulations will be described in detail in another paper (B. Pichardo et al., in preparation); here we present only the basic information. The halo has a logarithmic potential with a very small core radius, mimicking a cusp-like halo model. A Kuzmin gaseous disk with an isothermal equation of state is initially set in equilibrium inside a spherical halo, and later during 20 dynamical times at twice the initial disk radius (adiabatically), the halo model axis ratios are gradually modified; recently, a similar study was described in the literature (Khoperskov et al. 2012). The disk responds by developing ellipticity and spiral arms, and the gas inflow triggers a bar-like central structure whose reality is uncertain because of the idealized simulation set-up. An interesting finding is that for disk plane ellipticity of 0.3–0.4 or larger, the gas at turn around piles up and, in the more eccentric cases, develops two symmetric shocks. NGC 2976 shows two symmetric bright spots in the stellar photometry and Hα, suggesting that either the spiral arms are stronger than expected or the disk ellipticity at that radius is near 0.3–0.4 or greater (see Figure 6).
4.2. Environment Triggered Evolution of Satellite Dwarf Galaxies

Once we have confirmed the presence of a gas-rich non-axisymmetric structure in the disk of NGC 2976, the most natural explanation is that the tidal interaction with the environment triggered a mass redistribution, making the galaxy unstable regardless of the low baryonic mass fraction. Specifically, the NGC 2976 environment is the M81 group, and an extended H\textsc{i} tidal tail suggests that the galaxy has indeed suffered an interaction with the M81–M82 system. The whole M81 group mass is close to $10^{12} M_\odot$ (Karachentsev & Kashibadze 2006) and the projected distance to NGC 2976 is close to 190 kpc; therefore, a crude estimation for the crossing time is 1 Gyr. Chynoweth et al. (2008) estimates 0.2–0.3 Gyr for the age of the neutral gas bridge connecting M81–M82, which, based on the bridge projected extension, is younger than the one connecting M81 and NGC 2976, and therefore a 1 Gyr estimate for their interaction age is conservative and also in agreement with Williams et al. (2010). In comparison, at the last measured optical rotation curve point (2 kpc), the NGC 2976 rotation amplitude is 80 km s$^{-1}$, and therefore the rotation period is approximately 0.024 Gyr, suggesting that enough time has passed since the interaction that the NGC 2976 disk should be relaxed by now. We conclude that disk self-gravity is important in NGC 2976 and as a consequence the bar and spiral arms are unlikely transient structures. Recently, a low-luminosity active galactic nucleus (AGN) has been revealed in NGC 2976 through X-ray and near-IR observations (Grier et al. 2011). This probably reveals the presence of gas inflows triggered by the non-axisymmetric structure and also of energy injection into the central galaxy interstellar medium. Both processes may have effect on the dark matter halo structure.

4.3. Generality

A critical question to ask is, how common is NGC 2976 between satellite dwarf galaxies? There are two ways to address such a question: through statistical analysis of the satellite galaxy population or using theoretical predictions. There are not many systematic studies searching for bars in satellite galaxies around normal galaxies. Statistical analysis of more massive galaxy groups shows that AGNs potentially triggered by secular evolution are more common in satellites than in central galaxies (Allevato et al. 2012); however, there are not many similar studies in less massive groups like M81. It is natural to ask if the whole evolution, including disk instability and nuclear activity, is triggered by the environment and if a similar situation may be common to other satellite dwarf galaxies located in low-density groups like M81 or the Local Group. Recently, Grier et al. (2011) found AGN candidates in a sample of THINGS galaxies where NGC 2976 is included; however, more work is required. From the theoretical side, the scenario is a low-redshift incarnation of the so-called tidal stirring one (Mayer et al. 2001). Kazantzidis et al. (2011) recently characterized the evolutionary tracks of satellite dwarf galaxies, finding that bar instabilities developed before a global mass redistribution happened, and the evolutionary stage seems quite insensitive to orbit details and more dependent on the cumulative tidal force (Lokas et al. 2011), and then is more sensitive to the satellite accretion time. However, more recent calculations, including supernova feedback of gas-rich dwarf galaxies, seem to show that no bar instabilities developed before a global mass redistribution happened, and the evolutionary stage seems quite insensitive to orbit details and more dependent on the cumulative tidal force (Lokas et al. 2011), and then is more sensitive to the satellite accretion time. However, more recent calculations, including supernova feedback of gas-rich dwarf galaxies, seem to show that no bar instabilities developed in galaxies similar to NGC 2976, likely because gas inflow may inhibit bar growth (Mayer 2011). Finding a bar and spiral arms in NGC 2976 is a good constraint to this model. Based on NGC 2976, we can speculate that the energy injection triggered by the low-luminosity AGN/nuclear...
starburst may constrain the gas inflow, allowing bar growth. Further insight into this matter may be obtained by analyzing more satellite galaxies in M81 and other nearby low-density groups (Hernandez-Toledo et al., in preparation), and some hints suggesting environmental transformation of satellite galaxies in low-mass groups may be already reported in the M101 group (Mihos et al. 2012). Another consequence of this scenario is that the transformation process triggered by the environment may bias comparisons with theoretical predictions for isolated galaxies, including expected mass–$V_{\text{max}}$–concentration relationships, triaxiality, star formation rate (Colín et al. 2010; Rodríguez-Puebla et al. 2012), and some hints satellite galaxies in M81 and other nearby low-density groups.