

Corrugations in the Disk of the Edge-On Spiral Galaxy IC 2233

L. D. Matthews¹ & Juan M. Uson²

ABSTRACT

We recently reported the discovery of a regular corrugation pattern in the H I disk of the isolated, edge-on spiral galaxy IC 2233. Here we present measurements of the vertical structure of this galaxy at several additional wavelengths, ranging from the far ultraviolet to the far infrared. We find that undular patterns with amplitude $\lesssim 5''$ ($\lesssim 250$ pc) are visible in a variety of Population I tracers in IC 2233, including the young-to-intermediate age stars, the H II regions, and the dust. However, the vertical excursions become less pronounced in the older stellar populations traced by the mid-infrared light. This suggests that the process leading to the vertical displacements may be linked with the regulation of star formation in the galaxy. We have also identified a relationship between the locations of the density corrugations and small-amplitude ($\lesssim 5$ km s⁻¹) velocity undulations in the H I rotation curve. We are able to exclude several possible mechanisms for the origin of the observed corrugations, including tidal interaction from a companion, Parker instabilities, or a galactic bore. Global gravitational instabilities appear to be the most likely explanation, although local perturbations may also be important.

Subject headings: galaxies: spiral – galaxies: Individual (IC 2233) – galaxies: structure – ISM: structure – instabilities

1. Introduction

It is well known that the disks of late-type galaxies are not completely flat. Warping of the outer gas disk into an “integral sign” shape is a nearly ubiquitous feature of spiral galaxies, even those that appear to be quite isolated (García-Ruiz et al. 2002). A significant fraction of galaxies also have warped stellar disks (Sánchez-Saavedra et al. 1990; Reshetnikov & Combes 1998). For several decades it has been recognized that the H I disk and

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, USA 02138

²National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA USA 22903

other Population I components of the Milky Way exhibit an additional type of vertical structure in the form of systematic displacements from the mean plane known as “corrugations” (e.g., Gum et al. 1960; Quiroga 1974,1977; Lockman 1977; Sanders et al. 1984). These corrugations are present along both radial and azimuthal directions and have scales ranging from ~ 50 to 350 pc in amplitude and from one to several kiloparsecs in wavelength (Spicker & Feitzinger 1986).

Despite predictions that corrugations may be a common phenomenon in disk galaxies, systematic searches for these features have been limited, and consequently, little has been known about their true frequency of occurrence in external galaxies. To date, evidence of corrugations has been reported for only a handful of cases outside the Milky Way: in the emission nebulae of M31 (Arp 1964), in the stellar (optical) light of three edge-on, late-type galaxies (Florido et al. 1991,1992), and in the velocity structure of the face-on spiral NGC 5427 (Alfaro et al. 2001).

The origin of disk corrugations is a matter of longstanding debate given the small number of galaxies in which they have so far been detected (see the reviews by Alfaro & Efremov 1996 and Alfaro 2003). Suggestions have included: gravitational instabilities (e.g., Nelson 1976); tidal interactions (Edelsohn & Elmegreen 1997), collisions of high-velocity clouds with the disk (Franco et al. 1988; Santillán et al. 1999); interaction of spiral waves with the gaseous disk (Alfaro et al. 2001); and the undular mode of the Parker instability (Franco et al. 2002). Depending on their origin, the presence or absence of corrugations can provide important clues into the role of magnetic fields on galaxy disk structure (e.g., Spicker & Feitzinger 1986; Santillán et al. 2000; Franco et al. 2002), the formation of molecular clouds (e.g., Nelson & Matsuda 1980), the degree of self-gravity of galaxy disks (e.g., Revaz & Pfenniger 2004), or the timescales of recent interactions (e.g., Edelsohn & Elmegreen 1997). Moreover, current evidence suggests that whatever the physical process(es) responsible for corrugations, they are closely linked to the mechanisms responsible for the formation of the dense gas condensations and therefore with the regulation of star formation (e.g., Nelson & Matsuda 1980; Alfaro et al. 1992; Alfaro & Efremov 1996; Alfaro 2003).

In a recent paper (Matthews & Uson 2008; hereafter MU08), we presented optical and HI imaging observations of the nearby, edge-on spiral galaxy IC 2233. There we reported the discovery of a corrugated pattern in the HI disk of this galaxy—i.e., we found that the HI layer of IC 2233 exhibits a remarkably regular pattern of positive and negative vertical displacements from the kinematically-defined midplane. This pattern has a wavelength of $\sim 150''$ (7 kpc) and an amplitude that increases with distance from the center of the galaxy,

reaching a maximum of $\sim 3''$ (~ 150 pc).³ [For comparison, the FWHM thickness of the HI layer ranges from $\sim 10''.4$ near the disk center to $\sim 20''.3$ toward the outer disk (MU08)]. Subsequently, we have explored the vertical structure of IC 2233 using a variety of additional tracers of the stellar and interstellar components of its disk. We have also examined the relationship between the peaks of the vertical HI excursions with both HI density enhancements along the disk and with velocity perturbations in the disk rotation curve. Here we report the discovery of undular patterns in several additional Population I tracers in IC 2233. In contrast, we find the vertical displacements are minimal in the old stars. We also report the discovery of a link between the locations of the peak excursions from the midplane in HI with features in the HI rotation curve. In § 4 we discuss the implications of these findings for understanding the origin of the disk corrugations seen in IC 2233 and other galaxies.

2. A Multiwavelength Analysis of the Vertical Structure of IC 2233

IC 2233 is a bulgeless Sd galaxy located at a distance of ~ 10 Mpc. It has a moderately low surface brightness, “superthin” disk structure (Goad & Roberts 1981) and a low current star formation rate ($\lesssim 0.05 M_{\odot} \text{ yr}^{-1}$; MU08). The transparency and structural simplicity of IC 2233 make it well-suited to a detailed vertical structure analysis. IC 2233 also appears to be a very isolated system (MU08), implying that its disk structure should be minimally affected by external perturbations.

2.1. The Data

To investigate the vertical structure of the HI disk of IC 2233, MU08 extracted a series of HI intensity profiles perpendicular to the disk, spaced at regular intervals. These profiles were derived from an HI total intensity image with a spatial resolution of $\sim 16''$. The position angle for the galaxy was taken to be 172° , and the adopted center of the galaxy, $(x, z) = (0, 0)$, was the kinematic center established by MU08: $\alpha_{J2000} = 08^h 13^m 58.9^s$, $\delta_{J2000} = +45^{\circ} 44' 27''.0$. (Here x is the distance along the galaxy major axis, with values increasing toward the north, and z is taken as the distance above the midplane, with positive values to the east.) MU08 fitted a single Gaussian to each intensity slice and plotted the displacement of the computed centroid from the midplane ($z=0$) as a function of distance along the major axis. The resulting “corrugation curve” for the HI data is reproduced in the upper left panel of Figure 1.

³Throughout this paper we assume a distance to IC 2233 of 10 Mpc (see MU08).

The arrows on the upper left panel of Figure 1 indicate the extent of the stellar disk of IC 2233, as determined from the 25 magnitude arcsec^{-2} B -band isophote. It can be seen that near the edge of the stellar disk, the H I layer twists to form an “integral sign” warp. On the side of the disk where the H I layer is more extended, the layer bends back toward the midplane at larger radii. However, at small and intermediate projected radii, regular undulations are clearly visible across the disk of the galaxy. Furthermore, it can be seen that a portion of the galaxy near $x = 0$ is displaced from the kinematically-defined center-of-mass. One possible explanation is that this is linked with the presence of an inner bar.

To insure that our derived H I corrugation curve is not significantly impacted by optical depth effects, we have compared H I intensity profiles extracted from channel images with 16'' resolution (presented in MU08) with the corresponding ones made with more uniform weighting of the raw visibilities (i.e., with a robustness parameter $\mathcal{R} = -1$), which leads to images with 12'' resolution, albeit with rms noise about 40% higher. We find that the respective profiles and centroids agree to within the errors, although the higher resolution images resolve out some of the more diffuse H I component. The peak H I brightness temperatures are ~ 130 K for the 12'' images and ~ 108 K for the 16'' images, respectively, near the position of the kinematic center of IC 2233 and at the systemic velocity. Examination of the profiles shows that the H I is optically thin with $\tau \lesssim 0.02$. This is consistent with the generally excellent agreement between the H I and H α rotation curves (see Figure 13 of MU08).

To better constrain the nature and origin of the corrugations in IC 2233, we have now extended our analysis of its vertical disk structure using a number of additional data sets, spanning far-ultraviolet (FUV) to far-infrared (FIR) wavelengths (Table 1). For each wavelength, we have computed a corrugation curve in a manner analogous to that used for the H I data. The results are presented in electronic form in Table 2. We have compared the positions of background radio sources and foreground stars with catalogued values from the NRAO VLA Sky Survey (Condon et al. 1998) and the Tycho Reference Catalogue (Høg et al. 2000), respectively. With the exception of the 70 μm and 160 μm images (where no foreground or background sources useful for registration were detected), we find that astrometric registration between images at different wavelengths is accurate to within a small fraction of a resolution element. Therefore, we assume that astrometric uncertainties do not impact our results unless explicitly noted.

Because of the low surface brightness nature of IC 2233, we have also assumed that optical depth effects have a minimal impact on our analysis at all available wavelengths. Above we noted that the H I optical depth of the galaxy is extremely low. At visible wavelengths the optical depth of IC 2233 also appears to be minimal. MU08 estimated the B -band extinction

toward the center of the galaxy to be ~ 0.7 magnitudes, but this is likely to be an upper limit, as fits to the radial surface brightness profiles of IC 2233 show that the light distribution is more strongly peaked than predicted by a simple exponential disk model, and both the WIYN images published by MU08 and the *Hubble Space Telescope* images published by Seth et al. (2005) reveal that there are very few optically thick dust clumps in this galaxy and no true dust lane. Because of this, optical depth effects are expected to be negligible in all of the *Spitzer* bands. The optical depth of IC 2233 at UV wavelengths is more uncertain. However, better characterization of this will require detailed radiative transfer modelling (see e.g., Matthews & Wood 2001) and is beyond the scope of the present paper.

Table 1. Data Sets used for Vertical Structure Analysis of IC 2233

Descriptor	Wavelength	Telescope	FWHM PSF (")	Reference	Dominant Components traced
NUV	1350-1750Å	<i>GALEX</i>	4.6	1	young-to-intermediate age stars; B-star photospheres
FUV	1750-3000Å	<i>GALEX</i>	4.6	1	young-to-intermediate age stars ($< 10^8$ yr); B-star photospheres
<i>R</i>	5631-7156Å	WIYN	0.6	2	young-to-intermediate age stars (up to $\sim 10^9$ yr)
H α ^a	6534-6606Å	WIYN	0.7	2	ionized gas associated with young ($< 10^7$ yr), massive stars
3.6 μ m	3.18-3.94 μ m	<i>Spitzer</i> (IRAC)	1.7	3	old stellar populations; M-star photospheres
4.5 μ m	4.02-5.02 μ m	<i>Spitzer</i> (IRAC)	1.7	3	old stellar populations; M-star photospheres
8.0 μ m ^b	6.44-9.38 μ m	<i>Spitzer</i> (IRAC)	2.0	3	PAHs (linked with spiral arms, molecular clouds)
24 μ m	18.0-32.2 μ m	<i>Spitzer</i> (MIPS)	6	3	hot dust near sites of high-mass star formation
70 μ m	50.0-111.0 μ m	<i>Spitzer</i> (MIPS)	18	3	warm dust linked with star formation
160 μ m	100.1-199.9 μ m	<i>Spitzer</i> (MIPS)	40	3	cool, extended dust; infrared cirrus
H I	21 cm	VLA	16	2	neutral, atomic gas

^aContinuum-subtracted; includes a modest ($< 10\%$) contribution from [N II].

^bData are uncorrected for the contribution from stellar photospheric emission.

References. — (1) Gil de Paz et al. 2007; (2) MU08; (3) L. D. Matthews & K. Wood, in prep.

2.2. Results: Multiwavelength Corrugation Curves

Figure 1 shows corrugation plots derived from the datasets summarized in Table 1. Alongside each curve, a representation of IC 2233 at the corresponding wavelength is shown. For reference, each of the panels shows overplotted a polynomial fit to the H I data points lying within the boundaries of the stellar disk (i.e., excluding the outer disk regions where warping dominates the vertical structure). Gaps in the corrugation plots near $x \approx 50'' - 70''$ at some wavelengths are due to contamination from a foreground star.

Figure 1 illustrates that excursions from the midplane of up to $\sim 5''$ ($\lesssim 250$ pc) are present in a variety of tracers in IC 2233. In the case of the mid-infrared ($3.6\mu\text{m}$ and $4.5\mu\text{m}$) continuum, these highest-amplitude excursions occur only at the edges of the disk and can be attributed to the disk warp; however, at all other wavelengths shown in Figure 1, undulations with amplitudes of up to $\sim 5''$ are present at low and intermediate projected radii along the disk. None of these vertical undulations are as regular as those observed in H I; nonetheless, some interesting relationships emerge between the patterns seen in various tracers.

In the southern portion of the galaxy (i.e., along negative x values), we see that tracers of young to intermediate-age stellar populations (NUV, FUV, H α , and R -band) bend away from the plane with the same sign and comparable amplitude to that observed in H I ($\Delta z \sim +5''$). For the NUV and FUV light, there is some hint of a slight phase lag with respect to the H I curve. This correlation is largely maintained in the northern portion of the galaxy, to roughly $x \lesssim 40''$. In contrast, further north ($x \gtrsim 70''$), the vertical structure of these tracers diverges sharply from what is seen in H I; here, excursions are observed toward positive z , while the H I layer bends toward negative z values. Only beyond $x \gtrsim 120''$ do the vertical centroids again converge to values similar to those observed in H I. Visual inspection of the UV, R -band, and H α images suggests that higher frequency undulations may also be present in these bands. These are difficult to quantitatively characterize, but may account for some of the scatter seen in these tracers.

Turning toward tracers of the dust component in IC 2233, vertical undulations are also clearly visible. The corrugation curve derived from the $8\mu\text{m}$ light (believed to be dominated by PAH emission) exhibits a pattern comparable in shape to the H I data, but with larger dispersion. Both the $24\mu\text{m}$ and the $70\mu\text{m}$ corrugation curves also show close agreement with the H I data over much of the disk. The exception is the region between $x \approx 40'' - 100''$ where the $24\mu\text{m}$ and $70\mu\text{m}$ emission diverge sharply from the H I. In other galaxies both the $8\mu\text{m}$ and $70\mu\text{m}$ emission have been found to have distributions similar to the H I gas (e.g., Helou et al. 2001; Walter et al. 2007), although the PAH emission tends to correlate more closely with the molecular gas and cold dust, while the $70\mu\text{m}$ tends to be most prominent in the highest H I column density regions.

The vertical structure of the cool dust traced by the $160\mu\text{m}$ light shows relatively little correlation with any other wavelength. Our sensitivity is too limited to detect the outer $\sim 20\%$ of the galaxy at this wavelength, and in addition, the low resolution of these data ($40''$) makes the uncertainty in the location of the zero point comparable to the amplitude of the vertical excursions. Nonetheless, the data are clearly inconsistent with a flat, planar distribution for the cool dust. On the northern side of the galaxy, the $160\mu\text{m}$ emission appears qualitatively similar to the $70\mu\text{m}$ emission, although the amplitude of the vertical excursions appears larger. On the southern side of the disk, the $160\mu\text{m}$ emission appears to be anticorrelated with the H I (and with all the other tracers). Convolution and resampling the $70\mu\text{m}$ image to match the resolution and pixel size of the $160\mu\text{m}$ data, we were unable to reproduce either of these trends from resolution effects alone.

The divergent behavior between several of the Population I tracers on the northern side of IC 2233 complicates the description of the galaxy as a simple undulating plane. While projection effects due to warping or to the different radial extents of various tracers may make some contribution to these differences, there is no *a priori* reason to expect that these effects should be more severe on the northern side of the galaxy. Therefore, the observed differences between the vertical displacements of different disk components should offer some clues on the origin of the corrugation patterns and their possible link to the regulation of star formation in the galaxy. For this reason, we now examine some of these differences in greater detail.

Visual inspection of the UV, R , and H α images between $x \approx 70''$ - $120''$ reveals that the vertical intensity profiles in these bands are dominated by the light associated with a smattering of compact H II regions located several arcseconds above the plane. The brightest of these (near $x \approx 80''$) has counterparts at $24\mu\text{m}$ and $70\mu\text{m}$. Interestingly, this position also corresponds to the location of the only major disparity between the H I and H α rotation curves for the IC 2233; here, the H α curve dips toward the systemic velocity by $\sim 35 \text{ km s}^{-1}$ (see Figure 13 of MU08). This difference between the H I and H α rotation curves suggests that either there is an absence of ionized gas at the tangent point along this line-of-sight, or else that the ionized material along this direction has been kinematically perturbed. The former scenario seems more likely given that we detect significant H I emission near $x = 80''$ at the same velocity as the H α emission (see Figure 11 of MU08). However, the second possibility cannot be ruled out (see also § 4.1).

In the H I total intensity image of IC 2233, we see a distinct H I clump near $x \approx 100''$ that is visibly displaced toward negative z values (Figure 1). Tracers of hot young stars (FUV, NUV, H α , R -band) all show a depressed surface brightness at the corresponding location, although we do detect counterparts to the H I clump at $8.0\mu\text{m}$, $24\mu\text{m}$, $70\mu\text{m}$, and

100 μm . This dearth of starlight coupled with the presence of FIR emission suggests that this sight-line may intersect a young star-forming region where the gas is still predominantly cold and dense. Recent studies show that PAH emission tends to be a good proxy for dense molecular gas in quiescent galaxies (e.g., Haas et al. 2002; Paladino et al. 2008), while emission at longer IR wavelengths can be a hallmark of hot young stellar objects that are still highly embedded. The disparity between the vertical structure of different Population I tracers near this location thus could be partly a consequence of this region being at an earlier evolutionary state compared with some of the other optically prominent star-forming regions in the galaxy.

3. A Search for Velocity Corrugations

Models for the origin of structural corrugations in disk galaxies also predict corrugations in the velocity field (see Alfaro et al. 2001 and references therein). The amplitude of the velocity corrugations and the relationship between velocity and structural corrugations can in principle be used to distinguish between various models for their origin. Unfortunately, with the exception of the Milky Way, it is difficult to measure both types of corrugations in the same galaxy.

To explore whether any systematic patterns are discernible in the velocity field of IC 2233, we have re-examined the observed HI rotation curve from MU08. We have parameterized the approaching and receding sides of the curve with a Brandt (1960) function of the form:

$$V(x) = V_{\text{sys}} + \left[V_{\text{max}} \left(\frac{x}{x_{\text{max}}} \right) \right] \left[\frac{1}{3} + \frac{2}{3} \left(\frac{x}{x_{\text{max}}} \right)^n \right]^{\frac{-3}{2n}} \quad (1)$$

where $V_{\text{sys}} = 554.7 \text{ km s}^{-1}$, $V_{\text{max}} = 85.0 \text{ km s}^{-1}$, $x_{\text{max}} = 281''.4$, and $n = 1.09$. A comparison with this type of smooth, idealized curve can help to highlight subtle, systematic excursions from the expected circular velocity at a given radius. In Figure 2 we plot the residual velocity difference between the observed rotation curve and the Brandt model as a function of distance along the major axis. The dashed sections of the curve designate the portions of the HI disk where warping dominates the vertical structure (see above).

The residual curve in Figure 2 reveals that the observed radial velocities along the IC 2233 disk exhibit systematic positive and negative excursions from the Brandt model, with amplitudes of $\lesssim \pm 5 \text{ km s}^{-1}$. This type of systematic “waviness” has been seen previously in the rotation curves of other disk galaxies, particularly those with spiral arms (e.g., de

Vaucouleurs & de Vaucouleurs 1963; Pişmiş 1965; Fridman et al. 1998; Alfaro et al 2001). However, what is particularly striking in the case of IC 2233 is that the locations of the local minima and maxima in the residual velocity curve correspond closely to the locations of the peak vertical structural excursions observed in the H I gas.

4. Discussion

As noted above, a number of mechanisms have been proposed to account for the observed corrugations in disk galaxies. We now discuss the suitability of several of these mechanisms for explaining the observed corrugations in IC 2233.

4.1. Tidal Interactions

Numerical modelling by Edelson & Elmegreen (1997) demonstrated that tidal interactions with a low-mass companion are one means of producing a corrugated disk structure. In this model, the companion generates a spiral-shaped wave that propagates inwards from the edge of the disk, resulting in perpendicular motions. Although the simulations of Edelson & Elmegreen were performed for a Milky Way-like galaxy and a perturber roughly 8% as massive, the results exhibit qualitative similarities to our observations of IC 2233. However, MU08 found that IC 2233 appears to be an extremely isolated galaxy, exhibiting no obvious signs of a recent interaction or minor merger. This casts significant doubt upon tidal effects as being the primary driver of the vertical disk structure of IC 2233. In addition, since tidally induced corrugations are excited from the outer regions of the disk (see Edelson & Elmegreen 1997), this does not provide a natural explanation for the “null” seen at the kinematic center of IC 2233 (see § 2.1 and Figure 1). Interestingly, at least one of the galaxies found by Florido et al. (1991) to have disk corrugations (NGC 4244), also appears to be quite isolated (Dahlem et al. 2005). A search for corrugations in additional isolated systems, coupled with deep searches for low-mass companions, could provide better statistical constraints on the likely role of companions in exciting corrugated patterns.

While an intrusion from a companion galaxy seems unlikely in the case of IC 2233, the influence of impacts from very low-mass perturbers ($\lesssim 10^6 M_{\odot}$), such as high-velocity clouds, cannot be entirely ruled out. Based on their energetics, high-velocity cloud impacts were the explanation favored by Alfaro et al. (1991) to account for vertical displacements of the midplane of the Milky Way and their associated star formation activity (see also Franco et al. 1988). Moreover, IC 2233 is known to have a vertically extended H I component

that is kinematically distinct from the main disk component (MU08), and whose presence suggests that the circulation of H I material between the plane and higher galactocentric latitudes is actively occurring (e.g., Fraternali & Binney 2008). While it would be difficult to explain how a *global* corrugation structure as regular as that seen in the H I disk of IC 2233 could be explained by a series of cloud impacts, such events may help to account for *local* vertical displacements and offsets between certain disk components. For example, such an event offers one possible explanation for the differences in the vertical structure of various disk tracers that is observed over a portion of the northern half of IC 2233 as well as the perturbation in the H α rotation curve observed near this position (see § 2.2).

4.2. Galactic Bores

The results presented in Figure 2 seem to exclude another class of model for explaining the vertical meanderings of the IC 2233 disk. In particular, our findings appear to be inconsistent with a scenario where corrugations result from gas being hydraulically “lifted” off the plane by a spiral arm as a result of interaction of the spiral density wave with a thick, magnetized, gas disk (Martos & Cox 1998). In this so-called “galactic bore” model, the lifting effect is expected to show an even symmetry about midplane (see Alfaro et al. 2001), resulting in some thickening of the plane and no net velocity excursions in an edge-on galaxy.

4.3. Parker Instabilities

In contrast to the galactic bore picture, the undular mode of the Parker (1966) instability in a thick, magnetized gas disk predicts a velocity pattern similar to that seen in Figure 2 (see Franco et al. 2002). However, an additional prediction of this model is that density enhancements should be present at the locations of maximum deviation from the mean plane (e.g., Hanawa 1995). Indeed, such a trend has been observed in the corrugated Carina-Sagittarius arm of the Galaxy (Franco et al. 2002). While IC 2233 does show a series of H I density enhancements along its disk (MU08), we find no clear correlation between the locations of these clumps and the maxima in the corrugated pattern in the H I disk. Because corrugations resulting from the undular mode of the Parker instability occur along the azimuthal direction, line-of-sight integration effects may make it more difficult to match the location of density enhancements and vertical displacements in an edge-on galaxy. However, for the case of IC 2233, the Parker instability model encounters an additional challenge in that magnetic fields in small spiral galaxies with rotational velocities comparable to IC 2233

are typically quite weak (e.g., Chyży et al. 2007).

4.4. Spontaneous Gravitational Instabilities

The observation that the corrugated structure of IC 2233 is more pronounced in the younger stellar components than in the old stars would seem to argue against a purely gravitational origin for the corrugations, since both gas and stars will be influenced by gravity. However, gas is in general more dynamically responsive than stars owing to its dissipative nature and its lower velocity dispersion (e.g., Kim & Ostriker 2007). In addition, gaseous distortions may be amplified by self-gravity and/or magnetic effects (e.g., Edelson & Elmegreen 1997). For these reasons, even if the corrugations have a purely gravitational origin, it is not entirely unexpected to find the largest amplitude corrugations in the gaseous components of the galaxy. In this picture, the youngest stars (which still reside near their birth locations) would be expected to exhibit a corrugated structure, while dynamical evolution and heating would slowly erode these signatures in the older stars.

To determine whether an origin for the corrugations in IC 2233 via gaseous instabilities is feasible, it is valuable to compare the ages of the stellar populations participating in the corrugations with relevant dynamical timescales in the disk. For example, using equation 6-85 from Binney and Tremaine (1987), we can estimate the oscillation period, P , for stars in the disk of IC 2233. Assuming a mass equal to the dynamical mass of the galaxy ($M_d = 1.55 \times 10^{10} M_\odot$), a disk radius of 9.2 kpc, and a maximum rotational velocity $V_{\max} = 85 \text{ km s}^{-1}$ (MU08), then at intermediate galactocentric radii (near $r=4.5$ kpc), we find $P \sim 5 \times 10^6$ years. This is comparable to the lifetime of an H II region, implying that the hot young stars giving rise to these ionized regions must be born near their present off-planar locations. If the corrugations arise initially in the gas, then the presence of corrugations in the NUV and FUV light (corresponding to stars with ages $< 10^8$ years) implies that the midplane deviations need to persist for only a few oscillation periods to be visible in these bands. The mix of stars dominating the R -band light in IC 2233 is more uncertain, although the very blue color of this galaxy ($B - R=0.67$; MU08) suggests that this band may too be weighted toward moderately young stars, with ages no more than a few oscillation periods.

As discussed by Fridman & Polyachenko (1984), vertical displacements in a galactic disk may arise from two types of internal gravitational mechanisms: spiral density waves and vertical bending oscillations (see also Fridman et al. 1998). Variations of both types of mechanisms could be linked with disk corrugations, even in galaxies with negligible magnetic fields. For example, Nelson (1976) suggested that corrugations could arise from the perturbations of a spiral potential on a differentially rotating gas layer (see also Nelson & Matsuda

1980), while Masset & Tagger (1997) postulated that their origin could be the result of a non-linear coupling between a spiral density wave and two so-called “warp waves”. In the model of Masset & Tagger, a transmitted wave results in an integral sign warp, while a reflected wave produces corrugations. Several arguments suggest that IC 2233 is likely to exhibit at least rudimentary spiral structure (see MU08), but unfortunately its edge-on orientation makes it impossible to discern the details of this spiral pattern and thus to examine any possible relationship to the observed corrugations.

Vertical bending oscillations in galaxy disks have been explored by various authors as a possible origin for galaxy warps (e.g., Sellwood 1996; Revaz & Pfenniger 2004), but to our knowledge, relatively little attention has been paid to these oscillations as a possible origin of disk corrugations (although see Sparke 1995; Fridman et al. 1998; Griv & Chiueh 1998). While the sophisticated numerical simulations needed to explore this phenomenon are beyond the scope of the present paper, we point to the results of some existing studies that suggest that such an exploration might be fruitful. For example, in certain galaxy disk models, Sellwood (1996) found higher order bending modes whose amplitude and wavelength are reminiscent of the corrugation pattern of IC 2233 (e.g., his Figure 1d), although it remains to be explored how these results would translate to a disk containing both gas and stars. More recently, Revaz & Pfenniger (2004) used multi-component disk models to show that bending instabilities can be long-lived (i.e., persisting through several rotations) provided that disks have sufficient self-gravity. In their models it is assumed that some portion of the galaxy’s dark matter resides in the disk rather than in a halo. Revaz & Pfenniger explored only the low-order ($m = 0$ and $m = 1$) bending modes relevant to producing galaxy warps; however, a search for higher-order modes, as well as an extension of their models to include the dissipational behavior of the gas would be of interest.

5. Summary

We have presented a multi-wavelength analysis of the vertical structure of the late-type, edge-on galaxy IC 2233. Systematic excursions from the mean plane with amplitude $\lesssim 5''$ (~ 250 pc) are observed in a variety of Population I tracers in this galaxy, including the neutral hydrogen gas, the young stars, the H II regions, and dust components of various temperatures. This corrugated pattern appears most regular in the H I gas, and is absent from the old stars traced by the mid-infrared light.

Over a significant fraction of IC 2233, the vertical deviations observed in a variety of Population I tracers show similar signs and amplitudes. A notable exception occurs along the disk region between $x \approx 70''$ - $120''$, thus complicating the interpretation of the corrugation

pattern in terms of a simple, global pattern. One contribution to the differences seen along this region could be variations in the filling factors for various disk tracers. Star-forming sites may also have different spectral energy distributions depending on their ages, with the youngest being dim at UV and optical wavelengths. A third possibility is that perturbations (such as impacts from infalling gas clouds) may locally influence the vertical structure of the disk. Despite these complexities, we find that the locations of maximum deviation from the plane in the H I gas correspond to perturbations in the H I rotation curve with amplitude $\lesssim 5 \text{ km s}^{-1}$.

A number of different scenarios have been suggested in the past literature to account for the corrugated structure in disk galaxies, and we have evaluated their applicability to the case of IC 2233. Models invoking tidal interactions with a companion, Parker instabilities, or a galactic bore all encounter significant challenges in explaining the radial, galaxy-wide structural and velocity corrugations of IC 2233. Models involving gravitational instabilities of the gas layer appear to be more promising. However, sophisticated numerical modelling will be needed to evaluate such models further. The presence of a corrugated structure in this rather low surface brightness galaxy implies that vigorous star formation is not a necessary condition for the appearance of complex vertical structure in the disks of galaxies. Indeed, the quiescent nature of IC 2233 coupled with its low star formation density is undoubtedly an important factor in allowing us to observe the correspondence between vertical structures at a variety of wavelengths despite our edge-on viewing angle.

We thank the referee for thoughtful comments that helped to improve this manuscript. A portion of this work was based on observations from the *Spitzer Space Telescope*, operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract 1407 with the National Aeronautics and Space Administration (NASA). Financial support for this work was provided to LDM through JPL Contract 1279242. The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The H I data presented here were obtained as part of the NRAO observing program AM649.

REFERENCES

- Alfaro, E. J. 2003, in *Highlights of Spanish Astrophysics III*, ed. J. Gallego, J. Zamorano, and N. Cardiel, (Kluwer: Dordrecht), 195
- Alfaro, E. J., Cabrera-Caño, J., & Delgado, A. J. 1991, *ApJ*, 378, 106
- Alfaro, E. J., Cabrera-Caño, J., & Delgado, A. J. 1992, *ApJ*, 399, 576

- Alfaro, E. J. & Efremov, Y. N. 1996, *Rev. Mex. Astron. Conf. Ser.*, 4, 1
- Alfaro, E. J., Pérez, E., González Delgado, R. M., Martos, M. A., & Franco, J. 2001, *ApJ*, 550, 253
- Arp, H. A. 1964, *ApJ*, 139, 1045
- Binney, J. & Tremaine, S. 1987, *Galactic Dynamics*, (Princeton: Princeton University Press)
- Brandt, J. C. 1960, *ApJ*, 131, 293
- Chyży, K. T., Bomans, D. J., Krause, M., Beck, R., Soida, M., & Urbanik, M. 2007, *A&A*, 462, 933
- Condon, J. J. Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, *AJ*, 115, 1693
- Dahlem, M., Ehle, M., Ryder, S. D., Vlahić, M., & Haynes, R. F. 2005, *A&A*, 432, 475
- de Vaucoleurs, G. & de Vaucoleurs, A. 1963, *ApJ*, 137, 363
- Edelsohn, D. J. & Elmegreen, B. G. 1997, *MNRAS*, 287, 947
- Florido, E., Battaner, E., Prieto, M., Mediavilla, E., & Sanchez-Saavedra, M. L. 1991, *MNRAS*, 251, 193
- Florido, E., Battaner, E., Gros, A., Prieto, M., & Mediavilla, E. 1992, *Ap&SS*, 190, 293
- Franco, J., Kim, J., Alfaro, E., & Hong, S. S. 2002, *ApJ*, 570, 647
- Franco, J., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, M., & Mirabel, I. F. 1988, *ApJ*, 333, 826
- Fraternali, F. & Binney, J. J. 2008, *MNRAS*, 386, 935
- Fridman, A. M., Koruzhii, O. V., Zasov, A. V., Sil'chenko, O. K., Moiseev, A. V., Burlak, A. N., Afanas'ev, V. L., Dodonov, S. N., & Knapen, J. 1998, *Aston. Lett.*, 24, 764
- Fridman, A. M. & Polyachenko, V. L. 1984, *Physics of Gravitating Systems*, (New York: Springer-Verlag)
- García-Ruiz, I., Sancisi, R., & Kuijken, K. 2002, *A&A*, 394, 769
- Gil de Paz, A. et al. 2007, *ApJS*, 173, 185
- Goad, J. W. & Roberts, M. S. 1981, *ApJ*, 250, 79
- Griv, E. & Chiueh, T. 1998, *ApJ*, 503, 186
- Gum, C. S., Kerr, F. J., & Westerhout, G. 1960, *MNRAS*, 121, 132
- Haas, M., Klaas, & Bianchi, S. 2002, *A&A*, 385, L23

- Hanawa, T. 1995, in *The Formation of the Milky Way*, ed. E. J. Alfaro and A. J. Delgado, (Cambridge: Cambridge University Press), 1
- Helou, G., Malhotra, S., Hollenbach, D. J., Dale, D. A., & Contursi, A. 2001, *ApJ*, 548, L73
- Høg, E., Fabricius, C., Makarov, V. V., Urban, S., Corbin, T., Wychoff, G., Bastian, U., Schwekendiek, P., & Wicenec, A. 2000, *A&A*, 355, L27
- Kim, W.-T. & Ostriker, E. C. 2007, *ApJ*, 660, 1232
- Lockman, F. J. 1977, *AJ*, 82, 408
- Martos, M. A. & Cox, D. P. 1998, *ApJ*, 509, 703
- Masset, F. & Tagger, M. 1997, *A&A*, 318, 747
- Matthews, L. D. & Uson, J. M. 2008, *AJ*, 135, 291 (MU08)
- Matthews, L. D. & Wood, K. 2001, *ApJ*, 593, 721
- Nelson, A. H. 1976, *MNRAS*, 177, 265
- Nelson, A. H. & Matsuda, T. 1980, *MNRAS*, 191, 221
- Paladino, R., Murgia, M., Tarchi, A., Moscadelli, L., & Comito, C. 2008, *A&A*, in press (astro-ph/0805.0250)
- Parker, E. N. 1966, *ApJ*, 145, 811
- Pişmiş, P. 1965, *BOTT*, 4, 8
- Quiroga, R. J. 1974, *Ap&SS*, 27, 323
- Quiroga, R. J. 1977, *Ap&SS*, 50, 281
- Reshetnikov, V. & Combes, F. 1998, *A&A*, 337, 9
- Revaz, Y. & Pfenniger, D. 2004, *A&A*, 425, 67
- Sánchez-Saavedra, M. L., Battaner, E., & Florido, E. 1990, *MNRAS*, 246, 458
- Sanders, D. B., Solomon, P. M., & Scoville, N. Z. 1984, *ApJ*, 276, 182
- Santillán, A., Franco, J., Martos, M., Kim, J. 1999, *ApJ*, 515, 657
- Santillán, A., Kim, J., Franco, J., Martos, M., Hong, S. S., & Ryu, D. 2000, *ApJ*, 545, 353
- Sellwood, J. A. 1996, *ApJ*, 473, 733
- Seth, A. C., Dalcanton, J. J., & de Jong, R. S. 2005, *AJ*, 129, 1331
- Sparke, L. S. 1995, *ApJ*, 439, 42
- Spicker J. & Feitzinger, J. V. 1986, *A&A*, 163, 43

Walter, F. et al. 2007, ApJ, 661, 102

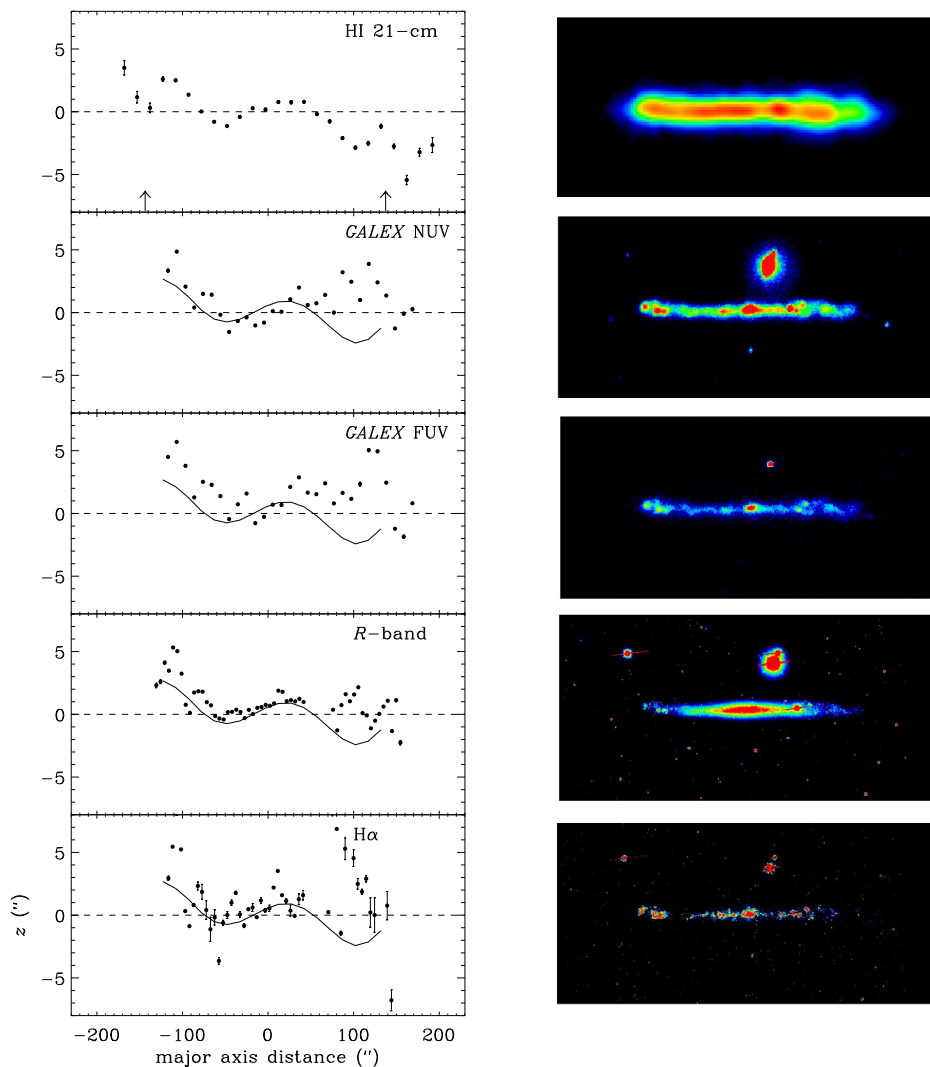


Fig. 1.— Corrugation plots for IC 2233 derived at various wavelengths, together with images of the galaxy in each band. The image panels are $210'' \times 450''$ across and are centered at $(x, z) = (0, 0)$. In the upper left panel, arrows denote the edges of the stellar disk defined by the 25 mag arcsec $^{-2}$ B -band isophote. In all other panels, the solid curve shows a polynomial fit to the HI data points interior to the arrows in the top left panel. At the distance of IC 2233, $1'' \approx 50$ pc.

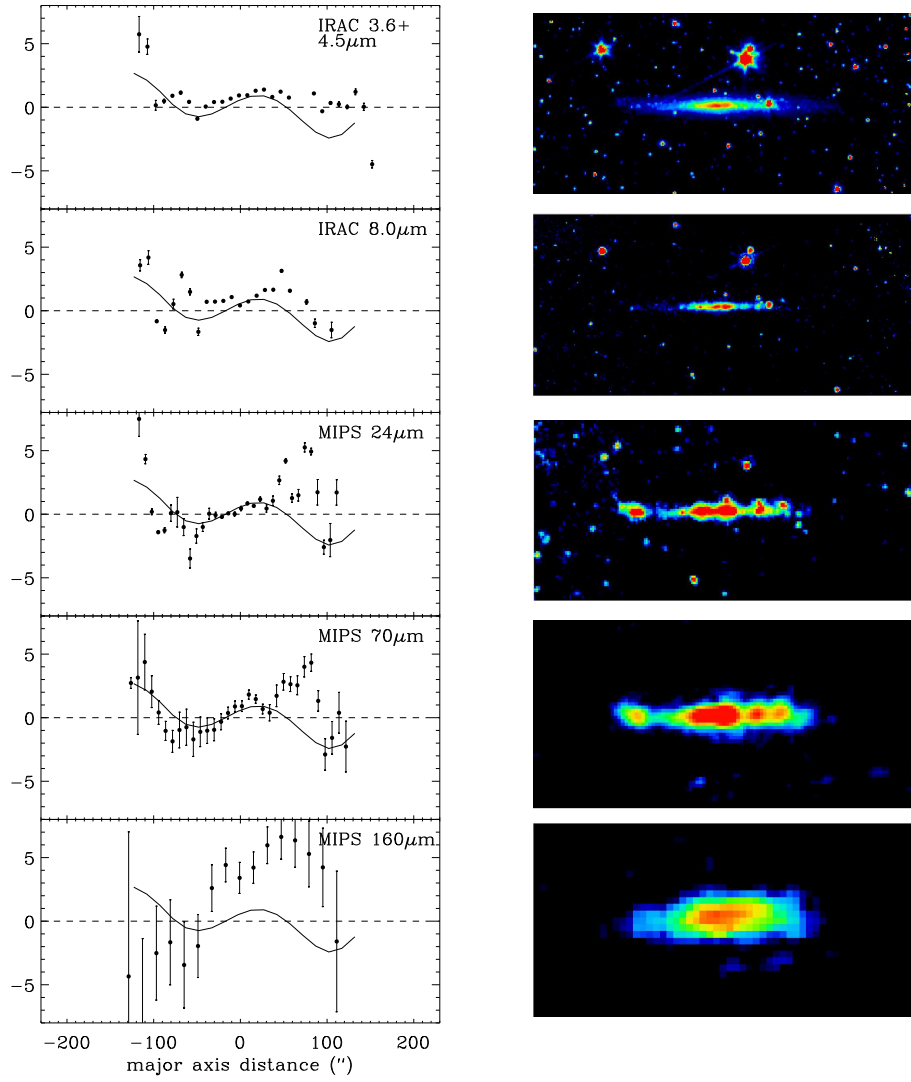


Fig. 1.— cont.

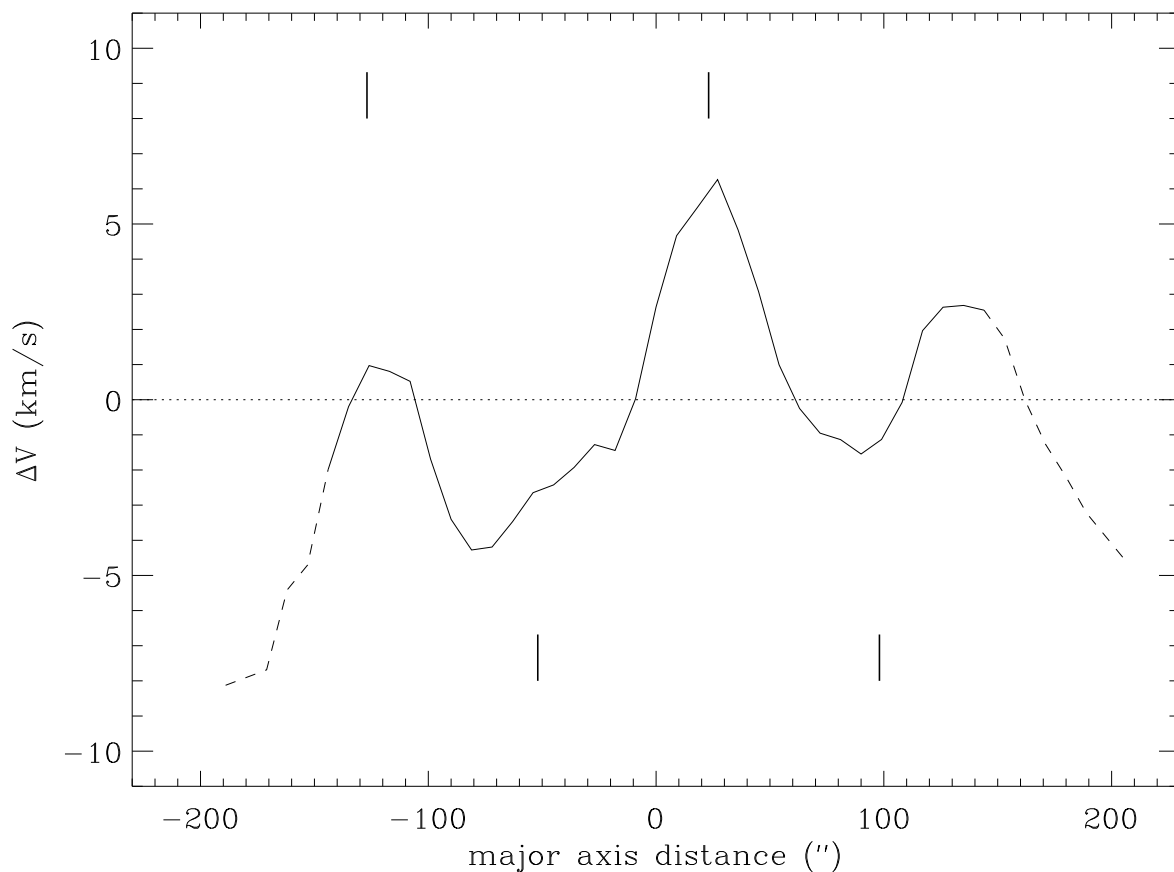


Fig. 2.— Velocity residuals after subtraction of a Brandt model rotation curve from the observed HI rotation curve of IC 2233. The residual curve has been smoothed to a resolution of $\sim 30''$ using a boxcar function. The dashed portions of the curve designate the regions of the HI disk where warping dominates the vertical structure (see upper left panel of Figure 1). The hash marks indicate the locations of the local minima and maxima of the vertical structural excursions of the HI layer as seen in Figure 1.

Table 2. IC 2233 Corrugation Curves

Band	Major axis distance (x) (arcsec)	Vertical displacement (z) (arcsec)	$\sigma(z)$ (arcsec)
(1)	(2)	(3)	(4)
NUV	-106.72	4.86	0.04
	-96.52	2.07	0.05
	-86.32	0.40	0.04
	-76.12	1.49	0.08
	-65.92	1.43	0.08
	-55.72	-0.17	0.06
	-45.52	-1.54	0.06
	-35.32	-0.67	0.07
	-25.12	-0.38	0.07
	-14.92	-1.02	0.06
	-4.72	-0.80	0.04
	5.48	0.11	0.06
	15.68	0.07	0.07
	25.88	1.06	0.03
	36.08	1.99	0.03
	46.28	0.60	0.06
	56.48	0.74	0.09
	66.68	1.41	0.08
	76.88	0.00	0.09
	87.08	3.21	0.03
	97.28	2.46	0.05
	107.48	1.00	0.09
	117.68	3.88	0.10
127.88	2.41	0.06	
138.08	1.36	0.06	
148.28	-1.26	0.08	
158.48	-0.09	0.11	
168.68	0.27	0.11	

Note. — Table 2 is available in its entirety in the electronic edition of the *Astrophysical Journal*. Explanation of columns: col. (1) wavelength of the observation (see Table 1 for further details); col. (2): displacement along the galaxy major axis in arcseconds, with respect to the kinematic center (see § 2.1); col. (3) displacement of the fitted centroid of the vertical intensity profile; (4) 1σ uncertainty in the position of the vertical centroid.