NGC 2915 – A Galaxy with a Dark or Faded Massive Disk?

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ABSTRACT

NGC 2915 is a remarkable blue compact dwarf galaxy which contains an inner H I bar and strong spiral structure in its H I disk extending well beyond its optical disk. We propose here that NGC 2915 has a dark or faint (not yet observed) massive disk component. By massive we mean of the same order as the H I gas mass which ranges from 0.5 – 10\(M_\odot/\text{pc}^2\). We present three different dynamical arguments:

1) The H I bar observed in the center is not massive enough to produce the observed non-circular velocities. A moderately massive additional component if it produced shocks in the neutral gas could cause the observed strong deviations from circular motion. This bar would then have mediated the starburst and be responsible for the H I bar which could then be similar to the twin peaks observed in CO in nuclear regions of other barred galaxies.

2) The H I gas disk by itself is stable to spiral density waves, in contradiction to the fact that there is spiral structure observed. For spiral density waves to exist a more massive disk is required.

3) Strong spiral structure observed in the outer parts of the galaxy probably requires forcing greater than can be caused by the neutral gas density alone.

The additional mass requirements from these three dynamical arguments depend upon the distance of the galaxy in the same way. If the galaxy were at a distance twice that estimated (10 Mpc instead of 5 Mpc), the additional mass required would be negligible. Virgocentric models show that if the galaxy were this distant its radial velocity would be 250-500 km/s below its local bulk flow value. Local flow models suggest that this is unlikely, however they also do not exclude it at high confidence levels.

We discuss two possible constituents for the conjectured additional matter, a molecular component and a stellar component. The possible molecular component should be easily detectable in CO emission. The possible stellar component also should be easily detectable with deeper red optical band imaging for moderate mass-to-light ratios (1-3 in \(R\) band). We favor a possible stellar component because late type galaxies commonly do not have large molecular gas fractions.

Detection of a quiescent or faint stellar disk population would be an exciting prospect since it would be strong evidence for a previous epoch of star formation in a

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previously low surface brightness galaxy. If this possibility were confirmed NGC 2915 would be an example of a galaxy which has faded and so could have been one of the faint blue galaxy population observed at moderate redshift.

\textit{Subject headings:} galaxies: structure — galaxies: spiral — galaxies: BCD

1. Introduction

NGC 2915 has optical properties of a weak Blue Compact Dwarf (BCD) (Meurer et al. 1994, hereafter MMC) whereas its H I morphology and global profiles (Meurer et al. 1996, hereafter MCBF) are those of an Sd-Sm disk galaxy (Roberts & Haynes 1994; Shostak 1978). Remarkably MCBF found that this galaxy contains an inner H I bar and strong spiral structure in its neutral gas disk which extends far beyond its optical disk – 5 times past its Holmberg radius (the radius, here \( r = 1.9' \), at which the \( B \) band surface brightness is 26.6 mag arcsec\(^{-2} \)). Recently Quillen & Pickering 1997 proposed that the presence of strong spiral structure in the neutral gas could be used to place limits on the disk mass of a low surface brightness galaxy. In particular they found that the stellar mass surface density in the two massive low surface brightness galaxies Malin 2 and UGC 6614 was of the same order as that in the atomic gas. In this paper we consider the disk mass in non-axisymmetric bar and spiral arm structures required to produce the strong spiral and bar structures observed in the H I gas distribution and velocity field in NGC 2915.

Various works have used perturbations from non-circular motion to place limits on the non-axisymmetric component of matter that is not directly visible. For example by modeling the velocity field of IC 2006 Franx et al. 1994 found that the halo of this galaxy was very close to axisymmetric in the plane of the galaxy. Models for the velocity field of the polar ring galaxy NGC 4650A, on the other hand, required a strongly flattened halo (Sackett et al. 1994). England et al. 1990 found that the bar mass of NGC 1073 was not sufficiently strong to produce the observed non-circular gas motions, and that an additional elliptical massive disk component was required. In this paper we consider the possibility of similar additional disk components in NGC 2915.

We consider three different approaches on placing limits on the disk mass in NGC 2915. In §2 we consider the mass in a bar-shaped disk component sufficiently massive to produce the observed non-circular motions and strong gas response in the central regions of the galaxy. We then (in §3) discuss the disk mass required for the disk to be unstable enough to support the observed spiral structure. This is intimately related to the result of MCBF that the galaxy did not obey the critical star formation threshold gas density commonly observed in spiral galaxies (Kennicutt 1989). Thirdly (§4) we consider the mass in a non-axisymmetric spiral component required to produce shocks in the H I consistent with the strong spiral structure observed in the H I gas distribution at large radii. This estimate is similar to that used in Quillen & Pickering 1997 to
derive lower limits for the disk mass-to-light ratio in the low surface brightness galaxies. The limits we place on the disk mass depend on the distance to NGC 2915 so wherever possible we have included a distance dependent correction factor. MMC estimated a distance of $D = 5.3 \pm 1.6$ Mpc, to which we scale all our relations.

In §2-4 we find that with our assumed distance a more massive disk than observed in HI is required to be consistent with the observations. Since a distance twice that assumed would make the additional mass required negligible, in §5 we the discuss the possibility that galaxy is more distant. We then consider two possible constituents for the conjectured additional massive disk component: a molecular component and a stellar component. Prospects for detection of both possible constituents are then explored. A summary and discussion follows.

2. The Mass of the Bar

In this section we consider the mass in a non-axisymmetric bar structure required to be consistent with the HI morphology and velocity field. In Figure 1 we show an $I$ band image and the HI column density map and velocity contours (from MCBF). It was noted in MCBF that within a diameter of 11 kpc or 7' the velocity field shows the characteristic twist of non-circular motion driven by a bar. Tilted ring fits were unable to account for the twist in the velocity field which contained residuals of $\sim 10$ km/s along the minor axis over the region $200'' < r < 450''$. For gas undergoing circular motion the zero velocity line of nodes is always perpendicular to the maximal velocity line of nodes in the velocity field. However these lines of nodes are not perpendicular for gas in non-circular or oval orbits. The failure of the tilted ring fits along the minor axis is strong evidence for non-circular motion. MCBF also observed that both the HI gas distribution and the optical isophotes are elongated in the central region. The HI gas distribution shows a prominent central bar about 2.5' (3.9 kpc) long and the optical isophotes, while only slightly elongated, do have major axes roughly aligned with the HI bar major axis.

The magnitude of the velocity deviations from circular motion within are significant (at least 10 km/s). This is in striking contrast to the contribution to the circular velocity predicted from the light (displayed in Fig. 16 of MCBF) which reaches a maximum of only 30 km/s at less than 1kpc and drops quickly, falling to 15km/s at a radius of $r = 5$ kpc or 190'', and the circular velocity contribution predicted from the neutral gas, which is flat at 15–18 km/s for $r = 1 - 15$ kpc (38''–580''). We ask here how can these two visible components be massive enough to cause the large observed deviations from circular motion?

2.1. The Strength of the HI Bar

MCBF found that that even in the bar region, the contribution to the circular motion from the stars (traced in optical images) and from the gas was small compared to the circular velocity.
As a result they found that the dark matter component required to fit the H I derived rotation curve dominated at all radii. Since the stars and gas contribute only negligibly to the circular velocity the magnitude of the oval non-axisymmetric (or bar) potential components resulting from the gas and stars must be small compared to the axisymmetric (presumably dark matter dominated) component. To confirm this we have computed the $m = 2$ Fourier component of the gravitational potential, $\Phi_2$, (displayed in Fig. 2) generated from the neutral gas distribution (corrected for He content from the hydrogen with a factor of 1.33) using the technique of Quillen et al. 1994 assuming an inclination of 58° and a position angle of $-70°$ (from the titled ring fit to the velocity field of MCBF outside the bar region).

We see that the $\Phi_2$ or $m = 2$ Fourier components of the gravitational potential are only a small fraction of the axisymmetric component derived from the observed rotation curve which is approximately flat at 80km/s past a radius of 200″ or 5.2 kpc. The magnitude of $\Phi_2$ is somewhat dependent on the inclination where a 5° lower assumed inclination results in a reduction in the $\Phi_2$ components of $\sim 10\%$. Using the $m = 2$ components of the potential and the rotation curve presented in MCBF, we estimate the velocity perturbations for gas in elliptical orbits in this potential. The resulting velocity perturbations (computed using Eqs. 6.30 from Binney & Tremaine 1987) are also shown in Figure 2. We have neglected the pressure from the gas in these equations which has the opposite sign of the potential terms and so tends to reduce the magnitude of the velocity residuals. We have also assumed a bar pattern speed which places the corotation radius at 300″ or 7.8kpc. This bar rotation rate places the H I bar at the Inner Lindblad Resonance (similar to the twin molecular peaks of Kenney et al. 1992) and the end of the bar at $\sim 250″$ where the $\Phi_2$ component begins to twist or vary in position angle indicating the onset of spiral structure outside the bar.

As expected (see Fig. 2d) the predicted velocity deviations from circular motion are small, much smaller than those observed except directly at resonances. Since the deviations from circular motion are detected over range of radius $200″ < r < 450″$ (and not confined to small regions that could be near resonances) these predicted velocity deviations are not sufficiently large to account for the observed non-circular motions. Varying the bar pattern speed since it only shifts the resonances does not allow stronger velocity deviations over the range of radius observed. In fact over much of the region where there is evidence for non-circular motion the predicted velocity deviations are also substantially smaller than the gas velocity dispersion of the outer disk (measured by MCBF $\sigma \sim 8 \text{ km/s}$). If the atomic gas were the only non-axisymmetric mass component, the gas response should therefore be smooth, and non shocked over a large range of radius. The gas would be in nearly circular orbits and so should not exhibit strong observed departures from circular motion. Consequently it is also improbable that the gas would be confined to the prominent H I bar observed. We therefore find that it is unlikely that the twists in the velocity field in the central region of the galaxy are caused solely by the mass in the H I bar itself. The optical component is only slightly elongated and only contributes significant (in mass) at small radii (within $\sim 100″$) and so is also not sufficiently massive or elongated to produce the
observed non-circular motions.

## 2.2. A Possible Additional Massive Bar Component

We now consider the possibility that non-circular motions are caused by a massive bar that has not been detected. If such a bar were to exist in NGC 2915 it would be a natural explanation for a variety of observations. The bar could have caused gas inflow which in turn produced the blue compact nucleus, which is actively forming stars and contains a relatively young stellar population (MMC; Marlowe et al. 1995). MCBF noted that with higher spatial resolution the H I bar is resolved into two clouds. This suggests that the H I bar might be similar to those observed in molecular gas in barred galaxies, like the “twin peaks” seen in CO of Kenney et al. 1992, which are suspected to be located at the bar’s Inner Lindblad Resonance. This would place the bar corotation radius roughly at 300″ which is roughly where the velocity twist reverses in direction as expected at the radius of corotation. The double peaked velocity profiles observed in the H I bar (MCBF) could then be interpreted in terms of a velocity jump across a shock region.

Strong non-circular motions in the gas can be caused by a modest non-axisymmetric or bar-like perturbation to the gravitational potential if the gas is undergoing shocks. This was stressed in early studies such as Roberts et al. 1979 who noted that only a 10% oval perturbation to the potential (which might result from a ∼ 30% perturbation in the density) was sufficiently strong in normal galaxies to cause strong non-circular motion in the gas response because shocks were produced in the gas.

We can make a rough estimate of the mass needed to produce shocks in the gas by considering the size of a Φ₂ component required to raise the velocity perturbations to the magnitude of gas velocity dispersion observed in the outer disk σ ∼ 8 km/s (MCBF). When the velocity perturbations are of this magnitude the gas flow can be supersonic and shocks can occur. This in turn allows large departures from circular motion as well as strong gas density contrasts. In Fig. 2d we show that for the H I mass distribution the velocity perturbations are ∼ 2 km/s (D/5.3 Mpc) over much of the bar region. For these velocity perturbations to be of the same order as the gas velocity dispersion a mass approximately four times the neutral gas density is required to produce shocks. The extended neutral gas surface density in the H I bar region ranges from 1.5 – 4M⊙/pc² for 2′ < r < 6′. We therefore estimate that the additional mass required is ∼ 6–16M⊙/pc² (5.3 Mpc /D) in the bar region. For an extended bar with major axis profile that is roughly of constant surface brightness (similar to those seen in barred galaxies and numerical simulations) a surface density of ∼ 6M⊙/pc² would be required.
3. Instability to Spiral Structure

It was noted by MCBF that the gas density is a factor of about 3 (range of 2-9) below the critical density, $\Sigma_{\text{crit}}$, for star formation (Kennicutt 1989), despite the star formation activity in the central regions. This critical density is defined in Kennicutt 1989 as

$$\Sigma_{\text{crit}} \equiv \frac{\alpha \kappa \sigma}{3.36G}$$

(1)

where $\alpha = 0.7$ was determined empirically. This critical density is intimately related to the Toomre stability parameter

$$Q \equiv \frac{\kappa \sigma}{3.36G\Sigma} = \frac{\Sigma_{\text{crit}}}{\Sigma \alpha}$$

(2)

(e.g. see Binney & Tremaine 1987) where $\kappa$ is the epicyclic frequency and $\Sigma$ is its mass surface density. We note that when $Q > 2$ amplification processes such as the swing amplifier are inefficient and the disk is unresponsive to tidal perturbations which could excite spiral density waves in a more unstable disk (see Binney & Tremaine 1987 and references therein). It is therefore unlikely for a disk with $Q > 2$ to show spiral structure. This implies that a disk with gas density below the critical gas density of Kennicutt 1989 is also unlikely to show spiral structure assuming there is no other disk mass component. (Note that $Q \sim 1.4$ for $\Sigma_{\text{crit}}/\Sigma = 1$.) Consequently if a gas disk is well below the critical gas density and yet shows spiral structure, a natural explanation is that there is another massive component in the disk (see Jog & Solomon 1984 for instability in a two fluid disk).

The ratio of $\Sigma_{\text{crit}}/\Sigma$ found by MCBF implies that the Toomre parameter $Q$ is on average 4.2 (range of 3 – 13) assuming a single fluid H I disk. (Multiply these values by a factor (5.3 Mpc /D) if a different distance to NGC 2915 is assumed). These large values for $Q$ would suggest that the gas disk should not show any spiral structure, in contradiction with the observations. The low gas densities of NGC 2915 coupled with its strong spiral structure are strong evidence for the existence of an additional massive disk component.

To estimate the mass of this additional massive disk component some assumption must be made about its velocity dispersion $\sigma_d$. For a stellar component of the same dispersion as the gas $\sigma \sim 8$ km/s for $Q < 2$ a disk mass of at least the mass surface density of the H I disk is required. If the additional mass component is molecular, then it could have a lower velocity dispersion and so a lower mass density would be required. For example a molecular component with a dispersion half that of the H I a disk surface density approximately half of that of the neutral gas would be required for the disk to be unstable enough to support the observed spiral structure. Using the neutral gas surface density measured from the H I observations, we estimate that the additional mass component should have mass surface density approximately $0.5 - 2M_\odot/pc^2 \left( \frac{5.3\text{Mpc}}{D} \right) \left( \frac{\sigma_d}{8\text{km/s}} \right)$ for $r > 300''$ outside the bar region.
4. Critical Spiral Forcing Required to Produce Shocks

The large density variations observed in outer spiral arms of NGC 2915 are evidence for shocks in the ISM induced by a spiral gravitational potential. Indeed the high arm/interarm density contrast of HI observed in galaxies such as M81 and M51 is one of the major predictions of the spiral density wave theory (e.g. Binney & Tremaine 1987 on the Lin-Shu hypothesis). In this section we consider how much mass is required in the form of spiral structure to drive shocks in the gas that would be consistent with the ∼2:1 arm/interarm density contrasts observed in the HI of NGC 2915.

A critical forcing parameter to produce shocks or large density contrasts in the ISM was explored by Roberts 1969 and Shu et al. 1973. These authors considered the role of $F$, the spiral gravitational force expressed as percentage of the axisymmetric force which can be written in terms of the density variation observed in the spiral structure (Quillen & Pickering 1997) as

$$ F = \frac{2\pi G \Sigma_2 r}{v_c^2} $$

(3)

using the WKB or tight winding and thin disk approximations. Here $v_c$ is the circular velocity. The forcing parameter depends on the size of the mass density variations in the spiral arms or on $\Sigma_2$, the magnitude of the $m = 2$ Fourier components of the density at a radius of $r$. $F \gtrsim 2\%$ is generally required for shocks to form (Roberts 1969, Shu et al. 1973, see also Toomre 1977). However this value was estimated in a Milky Way sized galaxy with rotational velocity of 200 km/s and gas velocity dispersion of ∼8 km/s. Since the forcing required to produce shocks is expected to depend on the ratio of the sound speed to the circular velocity, we expect that that forcing twice as large or $F \gtrsim 4\%$ could be required to produced shocks in NGC 2915 where the rotational velocity is less than half that of the Milky Way. For a short review of forcing requirements see Toomre 1977 or Quillen & Pickering 1997.

In Table 1 we have estimated the forcing parameter $F$ using the above equation and the neutral gas density variations (derived from the HI) for radii outside of the bar region. Table 1 shows that the forcing parameter $F$ is less than 2% in the outer parts of NGC 2915 and so is probably insufficiently strong to cause shocks in the ISM and the large neutral gas density contrasts observed. For a forcing of $F \gtrsim 2\%$ an additional disk mass component is required of approximately the same mass density as the neutral gas, if this additional mass component has the same density variations observed in HI. The mass of this component would then be

$$ M = 0.5 - 2M_\odot/pc^2 \left( \frac{5.3\text{Mpc}}{D} \right) \left( \frac{\Sigma_d}{\Sigma_{2,HI,\text{km/s}}} \right) $$

where the mass density required depends its azimuthal variations $\Sigma_d$ or on the magnitude of its $m = 2$ Fourier component.

5. A Summary of Additional Disk Mass Estimates

Here we summarize the excess disk mass requirements which we have estimated in the previous three sections.
1) Mass required in a bar component strong enough to cause shocks in the gas resulting in large scale non-circular velocities consistent with the observed velocities and the H I bar itself: $6 - 16M_\odot/\text{pc}^2 \ (5.3\text{Mpc}/D)$ for $r < 300''$. 

2) From the stability of the disk an excess surface density of the same order as the H I surface density: $0.5 - 2M_\odot/\text{pc}^2 \left(\frac{5.3\text{Mpc}}{D}\right) \left(\frac{\sigma_d}{8\text{km/s}}\right)$ for $r > 300''$ where the mass density depends upon its the velocity dispersion, $\sigma_d$. 

3) From the spiral forcing required in the outer disk an excess surface density of the same order as the H I surface density: $0.5 - 2M_\odot/\text{pc}^2 \left(\frac{5.3\text{Mpc}}{D}\right) \left(\frac{\Sigma_d}{\Sigma_{2.3\text{HI}\text{km/s}}}\right)$ for $r > 300''$ where the mass density depends on its azimuthal variations, $\Sigma_d$. 

We note that the mass surface densities we estimate from the above arguments are only approximate. Better estimates could be made with gas simulations such as those in Lowe et al. 1994 for spiral structure and in England et al. 1990 in barred galaxies.

### 5.1. Could NGC 2915 Be More Distant?

We note from the above summary that if the galaxy is twice as distant as 5.3 Mpc that the additional mass required would be negligible. How likely is this? Here we review distance estimates to the galaxy. MMC estimated the distance to NGC 2915 of $5.3 \pm 1.6$ Mpc, by scaling the properties of stars resolved in its compact core to those of the galaxy NGC 5253 which has a similar morphology. The distance of NGC 5253 has been accurately measured using Cepheid variables (Sandage et al. 1994). As in the compact nucleus of NGC 5253, MMC found that many of the resolved objects in NGC 2915 are most likely individual massive stars. For comparison, based on its radial velocity ($v_{\text{helioentric}} = 468 \pm 5$ km/s) and a linear virgo-centric inflow model, Schmidt & Boller 1992 estimate a distance of 4.1 Mpc to NGC 2915 consistent with the estimate of MMC (5.3 Mpc). Alternatively, the linear virgo-centric model adopted in Marlowe et al. 1995 gives a distance of 2.9 Mpc. Using the observed radial velocity (and no virgo-centric model) a Hubble constant of $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ gives a distance of 6.2 Mpc.

If NGC 2915 is actually at 10 Mpc then it would have a substantial peculiar velocity compared to the local bulk flow. Using a virgo-centric model with a distance to Virgo of 15.9 Mpc (based on $(H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$), and local inflow velocity of 220 km/s we estimate that if the true galaxy distance were 10 Mpc, its difference in radial velocity from the bulk flow would be $\sim 460$ km/s. This is large compared to the RMS variations in peculiar velocity from the bulk flow estimated by Aaronson et al. 1982 ($\sim 150$ km/s) for galaxies within the local supercluster and that ($\sim 100$ km/s, Sandage 1972, Faber & Burstein 1988) estimated for galaxies moving with the Local Group or with radial velocities less than 700 km/s. Using these standard deviations NGC 2915 would be 3-4 sigma away from the bulk flow. However for $H_0 = 56$ and using a virgo-centric model consistent with this value, NGC 2915’s difference in radial velocity would be only 260 km/s which is less than 2 sigma away from the local bulk flow. We also note that Faber & Burstein 1988 found that
the standard deviation in peculiar velocity from the bulk flow is substantially larger, \( \sim 300 \) km/s, for galaxies outside the Local Group flow, so if the galaxy is more distant a large deviation in peculiar velocity is not necessarily unlikely.

These estimates show that if NGC 2915 is at 10Mpc its radial velocity would be 250–500 km/s below its local bulk flow value. Local supercluster flow models suggest that this is unlikely, however they also do not exclude this distance with high confidence levels.

6. The Possible Constituents of the Additional Disk Component

There are two likely possibilities for our conjectured additional mass: a molecular component or a faint stellar component. Here we discuss both possibilities.

6.1. A Possible Molecular Component

A molecular component in the outer disk could have a low velocity dispersion and a large spiral arm density contrast, so that the mass required for such a component in the outer disk could be approximately half that of the neutral gas disk. However a high gas mass in the form of a central bar would still be required, (although then it would then be quite mysterious that such molecular component is not vigorously forming stars). With a molecular to atomic mass ratio of \( M(H_2)/M(HI) \sim 0.5 \), and a total neutral gas mass of \( \sim 10^9 M_\odot \) (MCBF), we estimate that the total molecular gas mass would be \( \sim 10^5 M_\odot \). Such a molecular gas mass should be easily detectable in emission in CO. We note that if the metallicity \( \lesssim 0.6 Z_\odot \), MCBF) is not extremely low, the CO to \( H_2 \) conversion factor should not be high compared to the Milky Way.

Late-type galaxies have lower molecular gas fractions than early-type spiral galaxies. For example, the Sd/Sm galaxies shown in [Young \\& Scoville 1991](Young & Knezek 1989, Thronson et al 1989) have a mean \( M(H_2)/M(HI) = 0.1 \) with scatter at the level of 0.2. This suggests that a massive molecular component is possible, though unlikely, particularly since the large concentrated gas masses required would be expected to be actively forming stars in the bar and outer disk (as in [Vogel et al. 1988](Vogel et al. 1988)). The survey of Blue Compact Dwarfs of [Sage et al. 1992](Sage et al. 1992) found that these galaxies typically had low molecular to atomic gas fractions. It is therefore unlikely that a significant percent of the disk mass in NGC 2915 is molecular gas.

6.2. A Possible Stellar Component

The conjectured stellar component must have surface brightness lower than that seen in the images presented in MMC and MCBF. The \( B \) band image of MMC detected the galaxy out to 27 mag/arcsec\(^2\) at \( r \sim 120'' \), whereas their \( R \) band image had a detection limit at 24.5 mag/arcsec\(^2\).
and only detected the galaxy at smaller radii presumably because of its red color (the outermost measured points have $B - R \sim 1.6$). The $I$ band image of MCBF is unfortunately uncalibrated but is similar to the $R$ band image in appearance and depth. The outer disk must therefore have have surface brightnesses greater than 27 and 24.5 mag/arcsec$^2$, in $B$ and $R$ bands respectively. For comparison a $B$ and $R$ band surface brightness of 27 and 26 mag/arcsec$^2$ with $M/L_B = 1$, $M/L_R = 1$ (in solar units) are both equivalent to a surface density of $1.0 M_\odot$/pc$^2$

For an extended bar with surface density of $\sim 6M_\odot$/pc$^2$ detected at a level fainter than the limiting surface brightnesses 27 and 24.5 mag/arcsec$^2$ in $B$ and $R$ bands, would have mass-to-light ratios $M/L \gtrsim 6$ and 1.5 in $B$ and $R$ bands respectively. For an outer disk with surface density of $\sim 1M_\odot$/pc$^2$ mass-to-light ratios $M/L \gtrsim 1$ and 0.25 are required in $B$ and $R$ bands respectively for a disk fainter than the above limits.

We now compare these mass-to-light ratio values with those predicted with population synthesis models and maximal disk fits to rotation curves. The reddest, and most abrupt exponential burst models of [Kennicutt et al. 1994] at 10 Gyr have $M/L_B = 4 - 8$ and $M/L_R = 3 - 5$. The single burst models of [Worthey 1994] have approximately the same mass-to-light ratios for a moderate metallicity stellar population of age 12 Gyr. This is to be compared to maximal disk models for normal spiral galaxies which have $M/L_R = 1 - 7$ ([Kent 1987a, Kent 1987b]), consistent with the hypothesis that the dark matter contribution is negligible in the central few scale lengths of these galaxies.

The above limits show that the conjectured stellar disk could have mass-to-light ratios of an old stellar population. In this case we expect expect $M/L_R \gtrsim 3$ otherwise the disk would have extremely red colors (the disk is faint at $B$ band). For an old stellar population (see above) with $M/L_B \sim 6$ and $M/L_R \sim 3 - 4$ and the reddish colors of $B - R \sim 1.5$, the disk should be detectable with deeper optical imaging in a red band ($R$ or $I$) particularly in the bar region. The mass-to-light ratios are required to be relatively high in the bar because of the large bar mass we estimate. The outer disk, however, would be difficult to detect unless it had lower mass-to-light ratios.

7. Summary and Discussion

We have presented three arguments that suggest there is a dark or faint massive disk in NGC 2915. By massive we mean with mass surface density of the same order as that in the HI gas, or a few $\sim M_\odot$/pc$^2$. The mass surface densities estimated are listed in the previous section.

1) The HI bar observed in the center is not massive enough to produce the observed non-circular velocities. A moderately massive additional component if it produced shocks in the neutral gas could cause the observed strong deviations from circular motion. This bar would then have mediated the starburst and be responsible for the HI bar which could then be similar to the twin peaks observed in CO in nuclear regions of other barred galaxies. Double peaked HI
velocity profiles detected at these H I peaks (MCBF) could then be naturally interpreted in terms of velocities on either side of a galactic shock.

2) The outer H I gas disk by itself is stable to spiral density waves, in contradiction to the fact that spiral structure is observed. For spiral density waves to exist a more massive disk is required.

3) Strong spiral structure observed in the outer parts of the galaxy probably requires spiral gravitational forcing greater than can be caused by the neutral gas density itself.

The additional mass requirements all depend upon the distance of the galaxy in the same way. If the galaxy were at a distance twice that assumed here (10 Mpc instead of 5 Mpc), the additional disk mass required would be negligible. Virgo-centric models show that if the galaxy were this distant its radial velocity would be 250-500 km/s below its local bulk flow value. Local flow models suggest that this is unlikely, however they also do not exclude it at high confidence levels. A more precise measurement of the distance to NGC 2915 is required to confirm the presence of a dark or faint additional disk component.

We discuss two possible constituents for the conjectured additional disk mass component, a molecular component and a stellar component. The possible molecular component should be easily detectable in CO emission. A possible stellar component could be an old stellar population, in which case it should be detectable with deeper R or I band optical imaging, particularly in the bar region for $M/L_R \sim 3 - 4$ which would give the galaxy red colors consistent with the limiting surface brightness observed in $B$ band and $M/L_B \gtrsim 6$ needed to give sufficient mass to the bar. We favor a possible stellar component because late-type galaxies usually have low molecular to atomic gas fractions, and it would be difficult to explain why such a molecular gas component is not actively forming stars, particularly in the bar. No visible evidence of star formation in the outer disk or bar.

We note that if further observations of the galaxy confirm its near solar metallicity ($\lesssim 0.6Z_\odot$) then this would imply that a significant fraction of its gas had undergone previous enrichment. This would be consistent with the proposed additional stellar disk component.

If the existence of an additional massive disk component is confirmed this would be evidence for a previous epoch of star formation in a galaxy which was until quite recently (before its present Blue Compact Dwarf phase) a low surface brightness galaxy. A population of red low surface brightness galaxies has been recently discovered ([O’Neil et al. 1997a, O’Neil et al. 1997b]) and NGC 2915 could similar to one of these galaxies, but with a newly formed blue compact core. NGC 2915 would then have a faded disk and could have been one of the faint blue galaxy population observed at moderate redshift ([Broadhurst et al. 1988, Efstathiou et al. 1991, Colless et al. 1990]).

Low surface brightness galaxies are natural sites for a search and study of previous epochs of star formation since the low levels of recent star formation facilitates observing an older dimmer stellar population. We note that only an undisturbed quiescent field galaxy could maintain a cold
stellar disk, without heating its stars and dispersing them into a thick disk or halo population which would then be unresponsive to spiral structure or bar formation.

If the disk in NGC 2915 contains an additional mass component then the halo mass required to fit the rotation curve could be much reduced. NGC 2915 would then be composed of populations with very different mass-to-light ratios and distributions. The resulting disk population would exhibit large variations in its mass-to-light ratio as a function of radius. This in turn would suggest that we reexamine rotation curve fits which predict halo parameters by assuming constant disk and bulge mass-to-light ratios in late-type, dwarf and low surface brightness galaxies.

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Fig. 1.— a) H I intensity (grayscale). Contours are shown with lowest contour at $2M_\odot/\text{pc}^2$ and a difference between contours equal to this value. At higher resolution the bar resolves into two peaks. The beamsize for the H I observations is shown on the lower left corner. Note that the surface density contrast is high with an arm/interarm contrast of $\sim2:1$. The high gas density contrast is a consequence of shocks in the ISM and one of the predictions of strong spiral density waves. These data are from MCBF. b) I band image of NGC 2915 shown as grayscale. These data are from MMC. The H I disk extends 5 times past its Holmberg radius (radius $r = 1.9'$ at which the $B$ band surface brightness is $26.6\text{mag arcsec}^{-2}$). c) H I velocity contours with a spacing of 10 km/s with the lowest contour on the lower left at 400 km/s. Note the twist in the velocity field probably caused by bar induced non-circular motions. These data are from MCBF.

Fig. 2.— a) Axisymmetric or azimuthally averaged component of the gravitational potential, $\Phi_0$, prediction from the H I or neutral gas distribution. b) Contribution to the circular velocity using $\Phi_0$ derived from the neutral gas density. The shape of this curve is somewhat different from that shown in MCBF because the azimuthal average was taken after the potential was calculated from the density instead of before. c) The $m = 2$ Fourier components of the gravitational potential. The solid and dotted lines represent the sine and cosine components for an angle of zero aligned with the H I bar. d) Velocity perturbations predicted from the $m = 2$ potential components presented in c) assuming the rotation curve derived in MCBF. The solid and dotted lines are the radial and tangential velocity components. For further information see §2. There are peaks in the velocity perturbations at the Inner Lindblad resonance ($\sim 80''$) and Outer Lindblad Resonance ($\sim 500''$). Note however that at most radii, the velocity perturbations are negligible ($\lt a2 \text{ km/s}$) and so are not large enough to produce the observed departures from circular motion over the range of radius observed. If a galaxy distance other than $D = 5.3 \text{ Mpc}$ is preferred $\Phi_0$, the $\Phi_2$ components and the velocity perturbations should be multiplied by $(D/5.3 \text{ Mpc})$ and the circular velocity, shown in b), should be multiplied by the square root of this factor.
Table 1. Spiral Forcing Strength$^a$

| $r$ arcsec | $v_e$ km/s | $\Sigma_{HI,0}$ $M_\odot/pc^2$ | $\Sigma_2/\Sigma_0$ | $F$ $^a$ |
|------------|------------|-----------------|----------------|--------|
| 300        | 82         | 1.5             | 0.29           | 1.4    |
| 424        | 82         | 1.0             | 0.22           | 1.1    |
| 502        | 82         | 0.8             | 0.20           | 1.0    |
| 557        | 88         | 0.5             | 0.25           | 0.7    |

$^a$The spiral forcing, $F$, is expressed as a percentage of the axisymmetric force, and is calculated with Eq. 3; see §4 for details. $F$ should be multiplied by the factor $(D/5.3$ Mpc) if a different distance to NGC 2915 is desired.

$^b$The rotation curve from MCBF.

$^c$The azimuthally averaged value of the neutral gas surface density.

$^d m = 2$ Fourier component of the HI column density expressed as a fraction of the azimuthally averaged value.
This figure "n2915fig1.gif" is available in "gif" format from:

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