

# EXPONENTIAL STELLAR DISKS IN LOW SURFACE BRIGHTNESS GALAXIES: A CRITICAL TEST OF VISCOUS EVOLUTION

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## ABSTRACT

Viscous redistribution of mass in Milky Way-type galactic disks is an appealing way of generating an exponential stellar profile over many scale lengths, almost independent of initial conditions, requiring only that the viscous timescale and star formation timescale are approximately equal. However, galaxies with solid-body rotation curves cannot undergo viscous evolution. Low surface brightness (LSB) galaxies have exponential surface brightness profiles, yet have slowly rising, nearly solid-body, rotation curves. Because of this, viscous evolution may be inefficient in LSB galaxies: the exponential profiles, instead would give important insight into initial conditions for galaxy disk formation.

Using star formation laws from the literature, and tuning the efficiency of viscous processes to reproduce an exponential stellar profile in Milky Way-type galaxies, I test the role of viscous evolution in LSB galaxies. Under the conservative and not unreasonable condition that LSB galaxies are gravitationally unstable for at least a part of their lives, I find that it is impossible to rule out a significant rôle for viscous evolution. This type of model still offers an attractive way of producing exponential disks, even in LSB galaxies with slowly-rising rotation curves.

*Subject headings:* galaxies: general — galaxies: evolution — galaxies: structure — galaxies: spiral

## 1. INTRODUCTION

An exponential stellar light profile over 4-6 disk scale lengths is an almost universal observational feature of disk galaxies (e.g., Freeman 1970; de Jong 1996). Yet, the production of a stellar exponential disk over more than 3 scale-lengths during the early stages of galaxy formation can prove highly challenging (e.g., Dalcanton, Spergel & Summers 1997; van den Bosch 2001; Ferguson & Clarke 2001, although see also Contardo, Steinmetz & Fritze-von Alvensleben 1998). Ever since their inception (Lin & Pringle 1987a), viscous evolution models have endured as an attractive way of producing exponential stellar disks over  $\gtrsim 4$  disk scale lengths, *almost independent of the initial density distribution*. In a differentially rotating gas disk, viscosity caused by non-circular gas motions and turbulence transports angular momentum outwards as mass flows inwards (Pringle 1981; Lin & Pringle 1987a). To prevent viscous evolution from reaching its logical endpoint (all the mass at the origin, all the angular momentum at infinity), the star formation (SF) timescale  $t_*$  should be within half an order of magnitude of the viscous timescale<sup>1</sup>  $t_\nu \sim r^2/\nu$  to ‘freeze in’ a nearly exponential stellar surface brightness profile over many disk scale-lengths (e.g., Lin & Pringle 1987a; Clarke 1989; Yoshii & Sommer-Larsen 1989; Olivier et al. 1991; Hellsten & Sommer-Larsen 1992; Firmani, Hernandez & Gallagher 1996; Ferguson & Clarke 2001; Slyz et al. 2002).

In 1D, the evolution of the gas density  $\Sigma_g$  at a given radius  $r$  is given by:

$$\frac{\partial \Sigma_g}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left\{ \frac{(\partial/\partial r)[\nu \Sigma_g r^3 d\Omega/dr]}{d/dr(r^2 \Omega)} \right\} - \psi_*, \quad (1)$$

where  $t$  is the time,  $\nu$  is the viscosity,  $\Omega$  is the angular velocity, and  $\psi_*$  is the SF rate (Lin & Pringle 1987a). A brief inspection of Eqn. 1 shows a well-known result: in a galaxy without shear (a solid-body rotation curve with  $d\Omega/dr = 0$ ) there can be *no viscous evolution*.

<sup>1</sup>This expression for  $t_\nu$  only applies in the case of a rotation curve which is *not* close to solid body.

Bearing this in mind, it is interesting to note that recently published high-resolution ( $\lesssim 2''$ ) H $\alpha$  rotation curves for low surface brightness (LSB) galaxies are slowly rising, and in a few cases are nearly solid-body, within the optical extent of the galaxy (e.g., de Blok et al. 2001; de Blok & Bosma 2002; Matthews & Gallagher 2002). Solid-body rotation curves have no shear, meaning that viscous evolution would not occur. Yet, many LSB galaxies have exponential surface brightness profiles over 4 or more disk scale lengths (e.g., McGaugh & Bothun 1994; de Blok, van der Hulst & Bothun 1995; Bell et al. 2000). This could argue against a significant role for viscous evolution in generating the exponential stellar disks of LSB galaxies, implying that the structure of (at least) LSB disks offers important insight into the initial conditions of galactic disk formation.

To understand if constraints on galaxy formation models can be gleaned from the structure of LSB galaxy disks, it is important to quantitatively explore this issue. The key questions are: *i)* how close to solid-body are the rotation curves of LSB galaxies? and *ii)* will the same kind of viscous evolution processes postulated to affect Milky Way-type galaxies be able to capitalize on any small departures from solid-body behavior, and be able to generate exponential stellar disks in LSB galaxies?

To address this problem, I set out in this paper to estimate the possible effect of viscous evolution in LSB galaxies with known, well-constrained surface brightness profiles and rotation curves. I make the central assumption that viscous processes in LSB galaxies and normal Milky Way-like galaxies have the same efficiency, and that any differences in viscous timescales are the *result of different rotation curves and gas densities only*. Comparing these viscous timescales for LSB galaxies with realistic SF timescales (e.g., Bell et al. 2000), one can say whether the same sources of viscosity that are applicable in normal galaxies could affect the evolution of LSB galaxies.

The plan of this paper is as follows. In §2, a brief description of the model is given. In §3, the model is calibrated to produce an exponential stellar light distribution for the Milky Way.

In §4, the Milky Way-calibrated model is applied to five LSB galaxies. I present my conclusions in §5. As an aside, I discuss viscosity from gas cloud collisions in Appendix A.

## 2. THE MODEL

To investigate the role of viscous evolution in LSB galaxies, I modify the model of Bell & Bower (2000) to include viscous evolution. Following Lin & Pringle (1987a), I adopt a smooth initial gas surface density distribution  $\Sigma_g(r)$ :

$$\Sigma_g(r) = \begin{cases} \Sigma_0[1 + \cos(\pi r/5h)] & 0 \leq r \leq 5h \\ 0 & r > 5h, \end{cases} \quad (2)$$

where  $r$  is the radius,  $h$  approximates the final exponential scale-length, and  $2\Sigma_0$  is the central surface density (the final exponential central surface density would be roughly  $5\Sigma_0$ ; see the dashed line in Fig. 1). The choice of this particular initial profile is arbitrary: Yoshii & Sommer-Larsen (1989) demonstrate that exponential disks are produced by viscous evolution from any smooth, centrally-concentrated initial profile. The evolution of gas density with time as a function of radius is followed using Eqn. 1.

SF is followed using either *i*) a gas density-dependent SF law (e.g., Schmidt 1959)  $\psi_* = k\Sigma_g^n$ , where  $k$  is the rate of SF at a gas surface density of  $1 \text{ M}_\odot \text{ pc}^{-2}$ , and  $n$  dictates how sensitively SF rate depends on gas surface density, or *ii*) a dynamical timescale-dependent SF law (e.g., Kennicutt 1998)  $\psi_* = K\Sigma_g/\tau_{\text{dyn}}$ , where  $K$  is the rate of SF at a gas surface density of  $1 \text{ M}_\odot \text{ pc}^{-2}$  and dynamical time of 1 Gyr, and  $\tau_{\text{dyn}} = 6.16r(\text{kpc})/V(\text{km s}^{-1}) \text{ Gyr}$  is the time taken to orbit the galaxy at a distance  $r$ . Both SF laws are reasonably consistent with the SF rates and histories of present-day spiral galaxies (e.g., Kennicutt 1998; Bell & Bower 2000). In the following, values of  $k$ ,  $n$ ,  $K$  and the chemical element yield are fixed at the values quoted in Table 1 of Bell & Bower (2000).

At present, sources of viscosity in galactic disks are not well-understood. In previous studies, the SF and viscous timescales,  $t_*$  and  $t_\nu$ , were directly related (where, again,  $t_\nu$  only applies where the rotation curve is *not* nearly solid body). The proportionality constant  $\beta = t_*/t_\nu$  was constrained to be within half an order of magnitude of unity in order to produce exponential stellar disks over 4–6 disk scale lengths (e.g., Lin & Pringle 1987a; Hellsten & Sommer-Larsen 1992; Ferguson & Clarke 2001). In this work, I wish to relax this constraint to a certain extent. In particular, one of the things that I wish to assess is if  $\beta \ll 1$  for LSB galaxies, as this would imply a minor role for viscous evolution in LSB galaxies.

In this paper, I explore viscosity due to gravitational instabilities. Since I find later that viscous evolution in Milky Way-type and LSB galaxies is efficient with this physically-motivated prescription, it is sufficient to adopt only one viscosity prescription for the purposes of this paper. Following, e.g., Olivier et al. (1991) I also explored viscosity due to collisions between gas clouds; however, I found that cloud-cloud collisions are incapable of driving significant viscous evolution in any spiral galaxies (see Appendix A for the derivation of this result). I therefore do not consider this prescription further. Large-scale gravitational instabilities give a viscosity (Lin & Pringle 1987b; Olivier et al. 1991):  $\nu = a_{\text{grav}}\pi^3 G^2 \Sigma_g^2 / \kappa^3$  where  $a_{\text{grav}}$  is a constant,  $G$  is the gravitational constant, and  $\Sigma_g$  is the gas density in  $\text{M}_\odot \text{ pc}^{-2}$ . The epicyclic frequency  $\kappa$  in  $\text{Gyr}^{-1}$  is given by  $\kappa = \{r d/dr(\Omega^2) + 4\Omega^2\}^{1/2}$ . I set the viscosity from gravitational instabilities to zero if the disk is gravitationally stable, i.e., if the

Toomre (1964)  $Q > 1$ , where  $Q = v_s \kappa / \pi G \Sigma_g$ . The gas velocity dispersion  $v_s$  is assumed to be  $6 \text{ km s}^{-1}$  (Kennicutt 1989; Binney & Tremaine 1987). The constant  $a_{\text{grav}}$  is set to produce an exponential stellar disk for the Milky Way (essentially,  $\beta$  for the cloud-collision and gravitational instability cases is set to be  $\sim 1$ : see §3). This value of  $a_{\text{grav}}$  is then left alone, and the LSB galaxy models are run to test if the difference in rotation curve shape and gas density significantly affects  $\beta$ . This is the central assumption of this analysis.

Stellar populations are modeled using the Bruzual & Charlot (in preparation) stellar population synthesis models (see, e.g., Liu, Charlot & Graham 2000) adopting a Salpeter IMF with a reduced number of low mass stars (following Bell & de Jong 2001). I adopt the instantaneous recycling approximation and the closed box approximation (Bell & Bower 2000). The detailed viscous flow of metals is not tracked in this model. These approximations do not affect the  $K$ -band surface brightness or  $B-R$  color significantly, and therefore will not affect the conclusions of this paper. It is worth noting that use of the  $B$ -band or stellar mass surface density profiles would also not affect the conclusions of this paper.

I solve these equations using a standard first order explicit scheme with 50 equally-spaced radius steps between  $0.2h$  and  $10h$ . Time steps are 4 Myr, for a galaxy age of 12 Gyr. There are two runs per galaxy model with the different SF laws. Following e.g., Lin & Pringle (1987a) and Ferguson & Clarke (2001), I allow mass to be lost from the center of the galaxy (i.e., total galaxy mass is not conserved); however, in practice less than 10% of the total mass is lost for even large amounts of viscous evolution. This does not significantly affect my conclusions, as the galaxies with large amounts of viscous evolution are typically quite luminous, and this ‘lost’ mass is easily accommodated within a bulge component.

## 3. REPRODUCING THE MILKY WAY

For the Milky Way, I adopt a flat rotation curve at all radii with  $V = 220 \text{ km s}^{-1}$  (adopting a more realistic rotation curve in the inner parts does not significantly change the results). I choose a value of  $h = 2.82 \text{ kpc}$ , and  $\Sigma_0 = 200 \text{ M}_\odot \text{ pc}^{-2}$ , resulting in disk central surface densities of  $\sim 1000 \text{ M}_\odot \text{ pc}^{-2}$  (see Table 1 for the modeling parameters of this and subsequent galaxy models). These values of  $V$ ,  $h$  and the disk central surface density are in reasonable accord with observations (e.g., Binney & Merrifield 1998). I assume that the gas disk was assembled instantaneously 12 Gyr ago (assuming more realistic infall histories for any of the models in this paper does not significantly change the results). A choice of  $a_{\text{grav}} = 0.02$  for the gravitational instability model results in a profile which is exponential to within 0.11 mag at  $r \leq 5h$  for the gas-density dependent SF law, and to within 0.14 mag for the dynamical time SF law. In both cases,  $B-R = 1.1 \pm 0.02$ , the gas fraction is  $23\% \pm 3\%$ , and the  $K$ -band central surface brightness is  $17.35 \pm 0.15 \text{ mag arcsec}^{-2}$ . These global parameters are typical of a galaxy of the Milky Way’s luminosity and size (e.g., Bell & de Jong 2000). Variations of  $a_{\text{grav}}$  by factors of 2–3 do not significantly affect the surface brightness profiles of the model Milky Way-type galaxies: they are still exponential to  $\lesssim 20\%$  within 4 disk scale lengths.

There are two interesting points which deserve further discussion. Firstly, my value of  $a_{\text{grav}}$  results in much slower viscous evolution than estimated by Olivier et al. (1991). Olivier et al. (1991) estimate short viscous timescales  $\lesssim 0.2 \text{ Gyr}$  for gas

TABLE 1  
PARAMETERS FOR GALAXY MODELS

Galaxy Name	$\Sigma_0$ ( $M_\odot \text{ pc}^{-2}$ )	$h$ (kpc)	$V$ ( $\text{km s}^{-1}$ )
Milky Way	200	2.82	220
ESO-LV 1870510	16	3.46	$52(1 - e^{-r[\text{kpc}]/2.8})$
UGC 11557	120	2.77	$110(1 - e^{-r[\text{kpc}]/5.1})$
F568-3 (solid-body)	40	2.96	$19.95 r[\text{kpc}]$
			$76.8 + 9.22(r[\text{kpc}] - 3.85)^{1/2}$
F568-3 ( $1\sigma$ curvature)	40	2.96	$19.95 r[\text{kpc}] + 6(1 - 0.27\{r[\text{kpc}] - 1.923\}^2)$
			$76.8 + 9.22(r[\text{kpc}] - 3.85)^{1/2}$
F583-1	20	1.71	$90(1 - e^{-r[\text{kpc}]/3.26})$
F583-4	16	2.14	$65(1 - e^{-r[\text{kpc}]/1.66})$

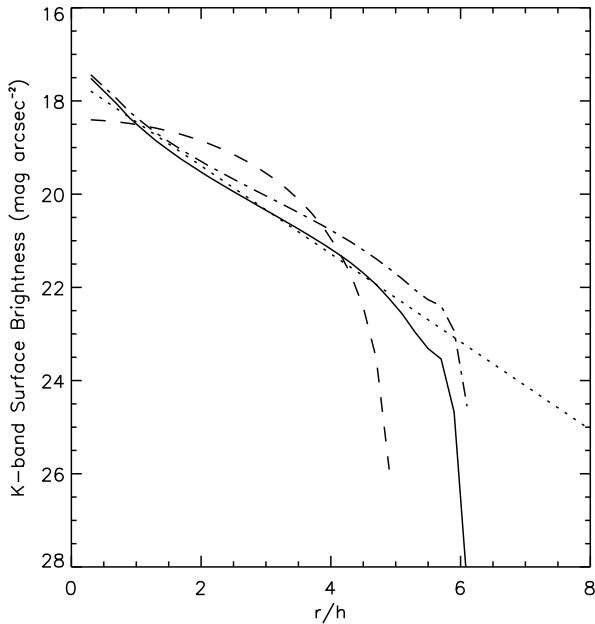


FIG. 1.—  $K$ -band surface brightness profile of a Milky Way model with a gas density-dependent SF law, which evolves subject to viscous evolution from gravitational instabilities. The solid line denotes the final  $K$ -band surface brightness profile, the dotted line denotes an exponential fit to the surface brightness profile for  $r \leq 6h$ , the dot-dashed line shows the star+gas surface density profile assuming a  $K$ -band stellar  $M/L$  of 1 in solar units, and the dashed line denotes the initial gas density profile, again assuming  $M/L_K = 1$ . The dynamical time SF law yields similar results.

at  $\sim 8$  kpc from the galactic center. In order to keep  $\beta \sim 1$ , it is necessary to have SF timescales  $\sim 0.2$  Gyr. These short timescales violate measured SF timescales in large spiral galaxies in general (e.g., Kennicutt 1998; Bell & de Jong 2000), and in the Milky Way in particular ( $\gtrsim 10$  Gyr in the solar cylinder; Rocha-Pinto et al. 2000). In addition, their viscous flows would have velocities  $\sim 5 \text{ km s}^{-1}$ , violating the  $\lesssim 1 \text{ km s}^{-1}$  constraint derived from radial metallicity distributions (Lacey & Fall 1985; Clarke 1989). In stark contrast, the ‘low’ viscous efficiencies that I adopt result in viscous and SF timescales of  $\sim 10$  Gyr at the solar cylinder, and gaseous flow velocities of  $\sim 0.1 \text{ km s}^{-1}$ : well within observational constraints. Secondly, the model surface brightness profile is exponential to  $\sim 10\%$  despite the ratio of the SF and viscous timescales,  $\beta = t_*/t_\nu$ , varying with radius by nearly an order of magnitude. This strengthens the conclusion of Hellsten & Sommer-Larsen (1992), who

stated that variations in  $\beta$  by a factor of two with radius resulted in an exponential profile: in fact, an order of magnitude variation in  $\beta$  with radius is acceptable in some situations.

#### 4. ARE LSB GALAXIES AFFECTED BY VISCOUS EVOLUTION?

The stage is now set to address the role of viscous evolution in LSB galaxies. All of the ingredients are in place: *i*) accurate observations of rotation curves for real LSB galaxies with well-constrained exponential profiles (required for Equation 1), *ii*) knowledge about SF timescales in LSB galaxies and plausible SF laws (Bell & Bower 2000), and *iii*) estimates of the efficiency of gravitational instability viscosity in Milky Way-type galaxies from §3. The central assumption of this comparison is that the efficiency of viscous processes in LSB galaxies is the same as for Milky Way-type galaxies (i.e.,  $a_{\text{grav}}$  is the same for all galaxies). With this assumption, I am postulating that the physical processes in LSB and Milky Way-type galaxies are identical, and differences in behavior result from differences in *rotation curve and gas density only*. I will present the analysis for one particular LSB galaxy, ESO-LV 1870510, before extending the analysis to a further four suitable LSB galaxies.

##### 4.1. ESO-LV 1870510

ESO-LV 1870510, at a distance of 29 Mpc (Bell et al. 2000), has a slowly-rising, almost solid-body,  $H\alpha$ -derived rotation curve from de Blok et al. (2001, see their Fig. 1 and the inset panel in Fig. 2). Bell et al. (2000) present optical and near-IR photometry (their Fig. 1), which demonstrates that the galaxy is exponential to within 0.1 mag over 4 disk scale lengths. ESO-LV 1870510 has an intrinsic  $B$ -band central surface brightness of  $23.75 \pm 0.2 \text{ mag arcsec}^{-2}$ , implying nearly a factor of 10 lower surface density than the canonical  $21.65 \text{ mag arcsec}^{-2}$  of Freeman (1970). For the model, I adopt the following smooth approximation to de Blok’s smoothed rotation curve:  $V = 52(1 - e^{-r[\text{kpc}]/2.8}) \text{ km s}^{-1}$  (see inset to Fig. 2), a value of  $\Sigma_0 = 16 M_\odot \text{ pc}^{-2}$  and  $h = 3.46 \text{ kpc}$  (see also Table 1).

Fig. 2 shows the resulting  $K$ -band surface brightness profiles of the density-dependent and dynamical time SF law LSB model galaxies. Clearly, the viscous redistribution and SF timescales turn out to be roughly equal, and exponential surface brightness profiles are produced. The stellar disks are exponential to within 0.07 mag (density-dependent SF law) or 0.13 mag (dynamical time SF law) within  $r < 4h$ . The model  $B-R$  colors match the observations to  $\lesssim 0.1$  mag, and the scale lengths, magnitudes and central surface brightnesses match the observa-

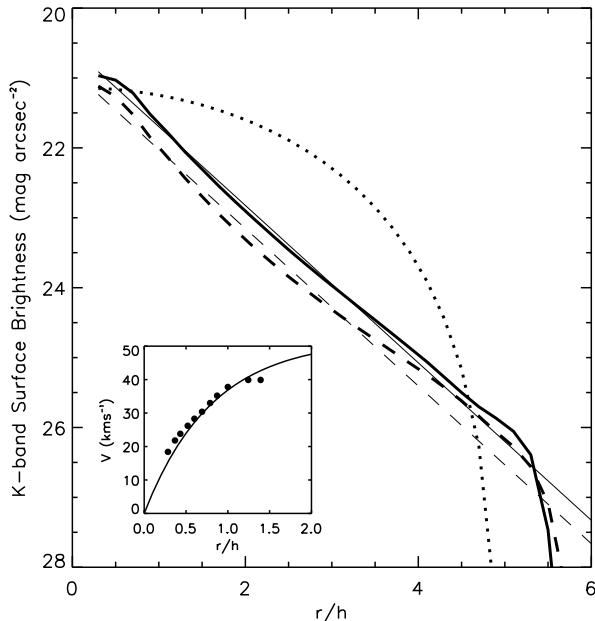


FIG. 2.— *K*-band surface brightness profiles of two ESO-LV 1870510 models which evolve subject to gravitational instability viscosity. The gas density-dependent SF law is shown as a thick solid line and the dynamical time SF law is shown by a thick dashed line. The exponential fits to both models are also shown (thin solid and dashed lines). The dotted line denotes the initial gas density profile, assuming  $M/L_K = 1$ . Inset is the smoothed rotation curve of de Blok et al. (2001) and my fit to the rotation curve (solid line).

tions to 20%. ESO-LV 1870510 lacks literature HI data, however, the model gas fraction of  $\sim 60\%$  is typical of LSB galaxies (e.g., Bell & de Jong 2000).

#### 4.1.1. Why Can Viscous Evolution Affect LSB Galaxies?

It is interesting to consider why viscous evolution can work with similar efficiency in LSB galaxies and Milky Way-type galaxies. After all, the rotation curves of LSB galaxies rise slowly (see, e.g., the inset panel in Fig. 2), implying that viscous evolution could be much less efficient. Using that  $t_\nu \sim r^2/\nu$ ,  $t_\nu \propto r^2\kappa^3/\Sigma_g^2$ . Fig. 3 of de Jong & Lacey (2000) shows that Milky Way-type and LSB galaxies have similar scale lengths, therefore characteristic values of  $r$  are similar for LSB and Milky Way-type galaxies (see also Table 1). The gas density  $\Sigma_g$  is a factor of  $\sim 10$  lower in LSB galaxies, which drives up  $t_\nu$ . However,  $\kappa \sim \Omega \propto V/r$  (Binney & Tremaine 1987) is substantially lower in LSB galaxies as  $r$  is similar but  $V$  is a factor of a few lower. Consequently  $\kappa^3/\Sigma_g^2$ , therefore  $t_\nu$ , are similar for Milky Way-type and LSB galaxies.

Considering the rest of Equation 1, we see that the top term in the equation is reduced for a LSB galaxy by a factor of 100: a factor of 10 from the  $\Sigma_g$  term and a factor of 10 from  $d\Omega/dr$ . The bottom term is reduced by a factor of  $\sim 5$ , simply due to the more solid-body rotation curve shape. Therefore the ratio, and the derivative of the ratio, is roughly a factor of 20 lower for a LSB galaxy. However, the gas densities are roughly a factor of 10 lower, so  $\{\partial\Sigma_g/\partial t\}/\Sigma_g$  is only reduced by a factor of 2 or so: viscous evolution from gravitational instability will be nearly as effective in LSB galaxies as it would be in large spiral galaxies! Coupled with the somewhat longer  $t_*$  in LSB galaxies, it is clear that  $\beta = t_*/t_\nu$  will remain of order unity, easily producing an exponential disk.

#### 4.1.2. Gravitational Instability and LSB Galaxies

I have demonstrated that viscous evolution through gravitational instability can be just as effective in LSB galaxies as in Milky Way-type galaxies. However, this seems to contradict at some level the argument that LSB galaxies are rather more likely to be gravitationally stable than their higher surface brightness counterparts. If LSB galaxies were gravitationally stable, no viscous evolution (at least through gravitational instabilities) would occur. van der Hulst et al. (1993) estimate the Toomre  $Q$  parameter, finding  $1 \lesssim Q \lesssim 3$ . This can be compared to  $0.5 \lesssim Q \lesssim 2$  for most luminous spiral galaxies in their inner parts (Kennicutt 1989). However, there are reasons to believe that van der Hulst et al. (1993) could significantly overestimate  $Q$ . Toomre's  $Q \propto 1/\Sigma_g$ , and poor resolution HI observations will tend to underestimate  $\Sigma_g$ . In addition, it is unclear how much molecular hydrogen there is in LSB galaxies, due primarily to the uncertainty in the CO to H<sub>2</sub> ratio  $X$  (see, e.g., Mihos, Spaans & McGaugh 1999; Boselli, Lequeux & Gavazzi 2002): a 50% increase in  $\Sigma_g$  caused by molecular hydrogen in the inner few scale lengths is not unreasonable given that  $X$  could be a factor of 10 higher than galactic, and given the level of current CO detections of LSB galaxies (Matthews & Gao 2001). Both of these effects would tend to drive down  $Q$ , making LSB galaxies less stable.

However, the model galaxy has gas densities which are somewhat larger than typical observed densities in LSB galaxies ( $10 \text{ M}_\odot \text{ pc}^{-2}$  at the model half-light radius, compared to  $\sim 5 \text{ M}_\odot \text{ pc}^{-2}$  for observed LSB galaxies). This problem can be alleviated by allowing the model galaxy to be built up by a lengthy gas infall. Assuming an ‘inside-out’ formation scenario with an  $e$ -folding timescale of 2.5 Gyr at the center, and 10 Gyr at  $\sim 4h$  (the infall case of Bell & Bower 2000), the gas density of the model galaxy is reduced by a factor of two, bringing it much closer to typical, observed gas densities in LSB galaxies. However, viscous evolution still occurs, producing a stellar exponential disk: the viscous evolution basically operates at a level which keeps the LSB galaxy on the edge of gravitational instability throughout its life. Given the considerable observational and modeling uncertainties, it is not unreasonable conservative to argue that LSB galaxies are at the edge of gravitational instability for most of their lives (note that Mihos, McGaugh & de Blok 1997, also argue for locally unstable LSB disks), and therefore could plausibly undergo significant viscous evolution.

#### 4.2. Other LSB galaxies

I have demonstrated that it is possible for the LSB galaxy ESO-LV 1870510 to undergo significant viscous evolution if it is gravitationally unstable for at least part of its life. In this subsection, I repeat the analysis with a further four galaxies with accurate, modelled rotation curves (de Blok et al. 2001) and exponential profiles to good accuracy over at least three disk scale lengths (de Blok, McGaugh & van der Hulst 1996; Swaters 1999; Bell et al. 2000): UGC 11557, F568-3, F583-1 and F583-4 (see Table 1 for modeling parameters and Fig. 3 for the results).

In all cases the gas disks can be unstable, and this leads to significant viscous evolution with either the gas density-dependent or dynamical time-dependent SF law. The cloud collision viscosity model gives very little viscous evolution. None of the rotation curves are solid body: most rise slowly out to  $\sim 2h$ , and turn over at larger radii. This is common amongst LSB galaxies (e.g., de Blok et al. 2001; Matthews & Gallagher 2002). The

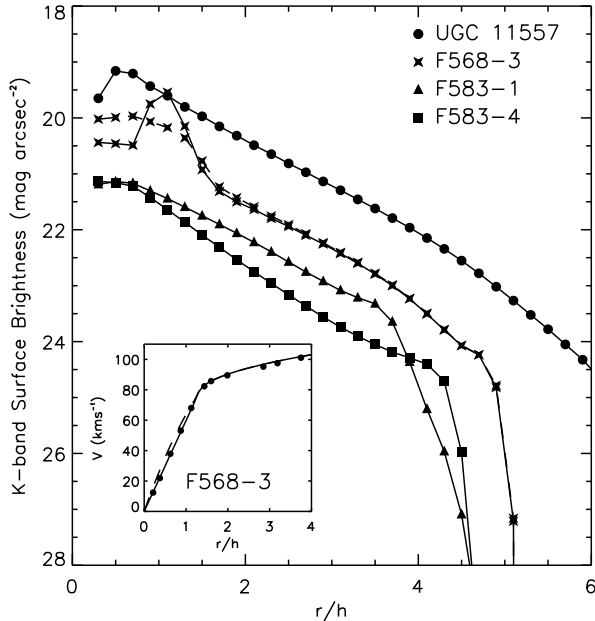


FIG. 3.— K-band surface brightness profiles of the models of four LSB galaxies from the sample of de Blok et al. (2001). The gas density-dependent models, which evolve due to viscosity from gravitational instabilities, are shown for all galaxies. F568-3 has two models shown: one with a solid-body inner rotation curve (solid line) and one with curvature which is consistent with the  $1\sigma$  errors in the rotation curve (dashed line). With the exception of the solid-body case of F568-3, all surface brightness profiles do not deviate from exponential by more than  $\sim 0.1$  mag. The use of the dynamical time SF law would not affect the results significantly.

only exception to this is F568-3, which has a rotation curve within  $\sim 1.2h$  which can be modelled as solid body. This leads to a ‘ring’ feature in the viscous model surface brightness profile, where material piles up at  $r \sim h$  (Fig. 3, solid line with stars). If the rotation curve is allowed to ‘curve’ slightly at the observational  $1\sigma$  level, the final surface brightness profile smooths considerably, and becomes exponential to within 0.1 mag RMS (Fig. 3, dashed line with stars).

This strengthens the conclusions considerably: it is impossible to rule out a significant role for viscous evolution during the life of five LSB galaxies with exponential surface brightness profiles for which accurate rotation curves are available from the literature.

## 5. CONCLUSIONS

Models of galaxy evolution which include viscosity due to non-circular and turbulent gas motions have, for the last 15 years, provided a relatively appealing way of producing accurately exponential stellar disks in large spiral galaxies almost independent of initial conditions. The primary assumption is that the viscous timescale and star formation timescale should be approximately equal. However, galaxies with solid-body rotation curves cannot undergo viscous evolution. Low surface brightness (LSB) galaxies have exponential surface brightness profiles, yet have slowly rising, nearly solid-body, rotation curves. Thus, it could be that LSB galaxies have had little redistribution of gas due to viscous evolution during their lifetimes. Their surface brightness profiles would give unique insight into the initial conditions of galaxy formation.

In this paper, I have constrained the importance of viscous evolution during the life of LSB galaxies. I have adopted star

formation laws from the literature, and have tuned the efficiency of viscous processes to reproduce an exponential stellar profile in Milky Way-type galaxies. Conservatively, I have assumed that the physics of turbulence are the same in LSB and Milky Way-type galaxies: any differences in the importance of viscous evolution in the two types of galaxy are the product of differences in rotation curve and gas density only. I then apply this model to LSB galaxies with observed rotation curves and surface brightness profiles. Under the conservative and not unreasonable condition that LSB galaxies are gravitationally unstable for at least part of their lives, I find that viscous evolution from gravitational instabilities is quite effective. Viscous evolution models still offer an attractive way of producing an exponential disk over four or more disk scale lengths, almost independent of initial density distribution, even for LSB galaxies with slowly-rising rotation curves.

Does this have implications for the power of surface brightness profiles to constrain galaxy formation theory? It is impossible at present to predict the degree of viscous evolution that *will* occur, as the physical mechanisms driving viscous evolution are so poorly constrained. However, this paper has shown that it *can* plausibly occur in both low and high surface density disk galaxies, and Yoshii & Sommer-Larsen (1989) have shown that it would modify most initial density profiles into an exponential disk. This reduces substantially the ability of observations to rule out models of galaxy formation based on surface brightness profiles. Indeed, the assembly of a disk with a reasonably centrally concentrated profile with roughly the right amount of angular momentum is all that is required of a galaxy formation model. However, it is impossible to reduce the central matter density of a galaxy through viscous processes; therefore, models which overpredict the central mass density of galaxy disks cannot escape the need for revision or modification (see, e.g., van den Bosch 2001).

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## APPENDIX

### A. EXPLORING CLOUD-CLOUD VISCOSITY

Here, I briefly discuss cloud-cloud collision viscosity. Despite its frequent use in the literature, it has not been comprehensively derived and so I will explore it here. Following, e.g., Silk & Norman (1981) and Olivier et al. (1991) I assume a cloud-cloud collision rate  $R \sim n_{\text{cloud}} v_s \pi r_{\text{cloud}}^2$ , where  $n_{\text{cloud}}$  is the number space density of clouds,  $v_s$  is the gas velocity dispersion, and  $r_{\text{cloud}}$  is the typical cloud radius. Assuming that the cloud properties and galaxy scale height are independent of gas surface density,  $n_{\text{cloud}} = \Sigma_g / (M_{\text{cloud}} h)$ , where  $\Sigma_g$  is the gas surface density,  $M_{\text{cloud}}$  is the typical gas cloud mass and  $h$  is the typical gas scale height. Adopting the cloud-collision parameters from Olivier et al. (1991),  $R \sim 0.032 v_s \Sigma_g \text{ Gyr}^{-1}$  where  $\Sigma_g$  is in  $\text{M}_{\odot} \text{ pc}^{-2}$  and  $v_s$  is in  $\text{km s}^{-1}$  (so far, this derivation does not significantly deviate from Olivier et al. 1991).

Following Pringle (1981), the kinematic viscosity takes the basic form  $\nu \sim v_s \lambda$ , where  $\lambda$  is the effective mean free path of clouds before they collide. In the limit that cloud collisions are much more frequent than once per orbit,  $\lambda$  is equal to the mean free path of the clouds which is  $v_s \tau_c$ , where  $\tau_c = 1/R$  is the cloud-collision timescale. This yields a viscosity  $\nu = 32.6 \eta_{\text{freq}} v_s / \Sigma_g \text{ kpc}^2 \text{ Gyr}^{-1}$ . In the limit of cloud collisions being much less frequent than once per orbit,  $\nu \sim v_s \lambda_r (\tau_c / \tau_{\kappa})^{-1}$  where  $\lambda_r \sim v_s \tau_{\kappa}$  is the radial excursion during one epicycle, and  $\tau_{\kappa} = 2\pi / \kappa$  is the epicycle timescale (Pringle 1981). In this case,  $\nu \sim v_s^2 \tau_{\kappa}^2 / \tau_c = 1.31 \eta_{\text{infreq}} v_s^3 \Sigma_g / \kappa^2 \text{ kpc}^2 \text{ Gyr}^{-1}$ , where  $v_s$  is in  $\text{km s}^{-1}$ ,  $\Sigma_g$  is in  $\text{M}_{\odot} \text{ pc}^{-2}$ , and  $\kappa$  is in  $\text{Gyr}^{-1}$ . Which limit is adopted depends on  $\Sigma_g$  (assuming that  $v_s$  is constant between different galaxy types). For gas densities  $\gtrsim 25 \text{ M}_{\odot} \text{ pc}^{-2}$ , the frequent collision case is more appropriate ( $\tau_c \lesssim 200 \text{ Myr}$ ), and for gas densities  $\lesssim 25 \text{ M}_{\odot} \text{ pc}^{-2}$  the infrequent case is more appropriate ( $\tau_c \gtrsim 200 \text{ Myr}$ ), for a constant  $v_s \sim 6 \text{ km s}^{-1}$ .

The crucial issue now is to estimate the efficiencies  $\eta_{\text{freq}}$  and  $\eta_{\text{infreq}}$  of the frequent and infrequent cloud-cloud collision cases. This is done by estimating the energy loss per cloud-cloud collision. The specific kinetic energy of a cloud is  $\sim v_{\text{rot}}^2$ , where  $v_{\text{rot}}$  is the rotation velocity. However, clouds collide with speeds much less than  $v_{\text{rot}}$  (because they are almost always in very similar, nearly circular orbits). In this case, the maximum possible specific energy loss is related to their relative speeds  $\sim v_{\text{relative}}^2$ . Therefore, the efficiency of energy loss per collision is  $\sim (v_{\text{relative}} / v_{\text{rot}})^2$ . The relative velocity  $v_{\text{relative}}$

can be approximated by the difference in velocity caused by the radial excursion of the cloud. Using that  $v_{\text{relative}} = v_{\text{rot}} \Delta r / r$ , where  $r$  is the radius, and substituting  $v_{\text{rot}} = r \Omega$  ( $\Omega$  is the angular frequency) and  $\Delta r \sim \lambda$ ,  $v_{\text{relative}} \sim \Omega \lambda$ . For the frequent collision case  $\lambda \sim \tau_c v_s$ , therefore  $v_{\text{relative}} \sim \Omega / 0.032 \Sigma_g$  (where  $\Omega$  is in  $\text{Gyr}^{-1}$  and  $\Sigma_g$  is in  $\text{M}_{\odot} \text{ pc}^{-2}$ ). Thus,  $\eta_{\text{freq}} \sim 977 / (r^2 \Sigma_g^2)$ , where  $r$  is in kpc. For the infrequent collisions case  $\lambda$  is the maximum epicyclic excursion, which is roughly  $v_s$  multiplied by the time for 1/4 epicycle  $\sim v_s / \kappa$ . Using that  $\kappa / \Omega \sim 1$ ,  $v_{\text{relative}} \sim v_s$  for the infrequent case, where  $v_s$  is in  $\text{km s}^{-1}$ . Therefore,  $\eta_{\text{infreq}} \sim v_s^2 / (r^2 \Omega^2)$ .

What are reasonable estimates of the timescales of viscous evolution in the frequent (Milky Way-type galaxy) and infrequent (LSB galaxy) cases? Using  $r = 7.5 \text{ kpc}$ ,  $v_{\text{rot}} = 220 \text{ km s}^{-1}$ ,  $v_s = 6 \text{ km s}^{-1}$ , and  $\Sigma_g = 50 \text{ M}_{\odot} \text{ pc}^{-2}$  for a Milky Way-type galaxy, I find that  $v_{\text{relative}} \sim 20 \text{ km s}^{-1}$  and  $t_{\nu} \sim r^2 / \nu \sim 2000 \text{ Gyr}$ . Similarly, adopting  $\Sigma_g = 10 \text{ M}_{\odot} \text{ pc}^{-2}$  and  $v_{\text{rot}} = 100 \text{ km s}^{-1}$  for the LSB galaxy infrequent case, I find  $t_{\nu} \sim 1000 \text{ Gyr}$ . Thus, it is fair to conclude that *viscosity from cloud-cloud collisions will be unimportant for all spiral galaxies*. This is because the low efficiency of energy loss in cloud-cloud collisions  $(v_{\text{relative}} / v_{\text{rot}})^2 \ll 0.01$ , which more than outweighs the fact that cloud collisions tend to happen  $\gtrsim 1$  time per orbit for most spiral galaxies. Of course, if some mechanism ‘whips up’ cloud collision velocities (such as a galaxy interaction), it may be possible to evolve significantly from cloud-cloud viscosity, but this mechanism should not play a significant rôle in the evolution of spiral galaxies in their normal, quiescent mode.