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Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

THE SURFACE BRIGHTNESS INDEPENDENCE OF THE TF RELATION

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RESUMEN

La pendiente y la dispersión en la correlación entre la luminosidad y el ancho de las líneas (relación "Tully-Fisher" o RTF) en galaxias soportadas por rotación contienen pistas importantes sobre los procesos relevantes a su formación. Discutimos los residuos Tully-Fisher (TF) en el contexto de la distribución relativa de la fracción de materia bariónica a materia oscura dentro del disco óptico. Los residuos en las relaciones ancho de línea-luminosidad y tamaño-luminosidad muestran una anticorrelación perfecta, y sugieren que la RTF es independiente del brillo superficial. La misma calibración TF describe galaxias espirales de alto y de bajo brillo superficial, con barra o sin ella. Podemos reproducir razonablemente las relaciones de escala observadas para galaxias brillantes, basándonos en las hipótesis físicas más sencillas, como el teorema virial para halos esféricos de materia oscura fría y el concepto de que la mayor parte del gas -o una fracción fija de él- forma estrellas en un disco tal que el tamaño del sistema estelar viene determinado por el momento angular.

ABSTRACT

The slope and scatter in the correlation of luminosity and line width (the "Tully-Fisher" relation [TFR]) of rotationally-supported galaxies hold important clues about the processes relevant to their formation. The Tully-Fisher (TF) residuals are discussed here in the context of the relative distribution of baryonic to dark matter fraction inside the optical disk. The residuals in the line width-luminosity and size-luminosity relations are perfectly anti-correlated and suggest that the TFR is independent of surface brightness. The same TF calibration describes spiral galaxies of low and high surface brightness, whether they are barred or not. We can reproduce the basic observed scaling relations for bright galaxies to a reasonable accuracy based on the simplest possible physical assumptions, such as the virial theorem for spherical cold-dark-matter halos and the notion that most of the gas, or a fixed fraction of it, makes stars in a disk such that the size of the stellar system is determined by angular momentum.

Key Words: **GALAXIES: BARS —GALAXIES: KINEMATICS —GALAXIES: PHOTOMETRY — GALAXIES: SPIRALS —GALAXIES: STRUCTURE—GALAXIES: KINEMATICS**

1. INTRODUCTION

Based on the flatness of galaxy rotation curves, it is now widely embraced that galactic disks are embedded in non-dissipative massive dark halos. However, the measurement of the relative fraction of luminous and dark mass in the light-dominated part of the galaxy is difficult owing to our inability to constrain the stellar mass-to-light ratio for any given disk. We use the definition that a disk is "maximal" if it contributes $85\% \pm 10\%$ of the total rotational support of the galaxy at $R_{disk} = 2.2h$, the radius of maximum disk circular speed, or $V_{2.2}/V_{total} \gtrsim 0.85$ Note that the inner 1-2kpc is likely dominated by baryons in most galactic systems, including early and late HSB barred and unbarred spirals (e.g. Broeils & Courteau 1997; Corsini et al. 1999), LSB galaxies (Swaters 1999; Swaters, Madore, & Trewhella 2000) and ellipticals (e.g. Brighenti & Mathews 1997).

Various lines of circumstantial evidence seem to favor relaxed dark matter halos that dominate the mass budget even within R_{disk}. Arguments based on the stellar kinematics of galactic disks (Bottema 1997), gas kinematics (Kranz et al. 2000), the stability of disks (Fuchs 2001) and the lack of correlated scatter in the Tully-Fisher relation for (non-barred) LSB and HSB galaxies (Courteau & Rix 1999, hereafter CR99) suggest that, *on average*, disks are not maximal. The two very different analyses by Bottema and CR99 both yield $V_{2.2}/V_{total} = 0.6 \pm 0.1$ or $M_{dark}/M_{total} = 0.6 \pm 0.1$ for HSB galaxies at R_{disk}. The geometry of gravitational lens systems, coupled with rotation curve measurements, can also be used to decompose the mass distribution of a lensing galaxy. This very promising technique has been applied to the galaxy-lens system 2237+0305 by Trott & Webster (2002). They find that $V_{disk}/V_{total} = 0.57 \pm 0.03$, in excellent agreement with the studies

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above.

A consistent picture of galaxy structure is emerging with a dominant halo with $M_{dark}/M_{total} \geq 0.6$ well into the optical disk at $2.2h$. Studies about our Milky Way, which is likely barred, do not reflect the same state of convergence; whether our Galaxy has a maximal disk (Gerhard 2002) or not (Dehnen & Binney 1998) is still a matter of debate. Crucial elements for local mass density estimates include the precise contribution of the massive central bar (e.g. Zhao, Spergel, & Rich 1995) or elongated bulge (Kuijken 1995), accurate measure of the disk scale length, and constraints from micro-lensing towards the bulge.

Few modern studies favor a dominant baryonic component at or beyond 1-2 disk scale lengths. The pattern speeds of bars have been used by Debattista & Sellwood (2000) to constrain models of bar evolution in "self-consistent" N-body simulations of stellar disks. Their simulations suggest that dynamical friction from a dense dark matter halo dramatically slows the rotation rate of bars in a few orbital periods. Because bars are observed to rotate fast, these authors propose that dark matter halos in high surface brightness disk galaxies must have a low central density; thus, their disk ought to be "maximal."

The TFR has been shown to be largely independent of surface brightness for both LSB and HSB galaxies (Sprayberry et al. 1995; Zwaan et al. 1995; CR99), but the case of strongly barred galaxies has not been addressed conclusively. Equipped with new 2-D integral velocity fields of late-type spirals, we have recently verified that the TF relation of barred and un-barred galaxies is the same provided kinematic inclinations are used to de-project the velocity field instead of photometric inclinations which are biased by the presence of m=2 perturbations (Courteau et al. 2003; see also Sakai et al. 2000).

1.1. *TF Residuals*

Figure 1 shows the plot of the residuals in the line width-luminosity ($\log V - \log M_I$) and size-luminosity ($\log R_{exp} - \log M_I$) relations for the Shellflow and SCII samples of late-type spirals (Courteau et al. 2000; Dale et al. 1999, resp.). These galaxies span the range $-24 \leq M_I \leq -18$ in redshift bins from 1000 to 9000 $\mathrm{km\,s^{-1}}$. Shellflow linewidths are extracted from Hα resolved rotation curves (RCs) and SCII uses both optical and radio line widths. The imaging is based on the I-band in both cases.

We find that $\partial \log V_{2.2} \,/\, \partial \log R_{exp} = 0.0$ with a great level of confidence for both data sets. In

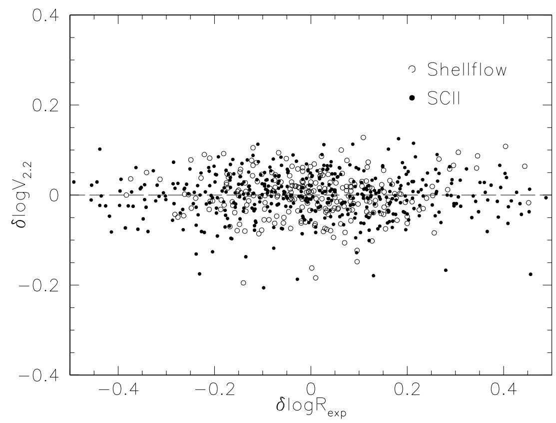

Fig. 1. Plot of linewidth-size residuals from the mean relation at fixed luminosity for the Shellflow and SCII samples.

other words, *the TF relation is completely independent of surface brightness.* Based on the model of CR99 (e.g. Fig. 8), this corresponds to a maximal contribution of the disk to the total potential at R_{disk} of $V_{disk}/V_{total} = 0.5$. Equivalently, $M_{dark}/M_{total} = 0.75$ at R_{disk}.

These, and other, basic observed scaling relations for bright galaxies can be reproduced to reasonable accuracy based on the simplest possible physical assumptions, such as the virial theorem for spherical cold-dark-matter halos and the notion that most of the gas, or a fixed fraction of it, makes stars in a disk such that the size of the stellar system is determined by angular momentum (Courteau et al. 2003). Firmani & Avila-Reese (2000) proposed that the correlation of line width- size residuals above should be weak (close to zero) because of a compensation effect produced by the star formation dependence on surface brightness. We have developed a simple toy model that demonstrates the origin of the slope of the TFR as well as its low scatter, in different terms than Firmani & Avila-Reese.

In summary, spiral galaxies appear to have submaximal disks at R_{disk}, disk galaxies (barred or unbarred) follow the same TFR independent of surface brightnesses, in agreement with basic models of galaxy structure.

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