THE MORPHOLOGICAL-DEPENDENT TULLY–FISHER RELATION OF SPIRAL GALAXIES

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ABSTRACT

The Tully–Fisher relation of spiral galaxies shows notable dependence on morphological types, with earlier type spirals having systematically lower luminosity at fixed maximum rotation velocity \( V_{\text{max}} \). This decrement of luminosity is more significant in shorter wavelengths. By modeling the rotation curve and stellar population of different morphological-type spiral galaxies in combination, we find that the \( V_{\text{max}} \) of spiral galaxies is weakly dependent on the morphological type, whereas the difference of the stellar population originating from the bulge–disk composition effect mainly account for the morphological type dependence of the Tully–Fisher relation.

Key words: galaxies: kinematics and dynamics – galaxies: spiral – galaxies: stellar content

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1. INTRODUCTION

The Tully–Fisher relation (Tully & Fisher 1977, hereafter TFR) is an empirical relation between the absolute magnitude \( M \) and the maximum rotation velocity \( V_{\text{max}} \) of spiral galaxies, which is typically expressed as

\[
M = \alpha \log \left( \frac{V_{\text{max}}}{200 \, \text{km s}^{-1}} \right) + \beta,
\]

where the values of slope \( \alpha \) and zero-point \( \beta \) are dependent on the photometric band of the \( M \) being measured.

It has long been known that the TFR has a morphological type dependence, with earlier type spirals having systematically lower luminosity at fixed \( V_{\text{max}} \) (Roberts 1978; Rubin et al. 1980). This luminosity difference is also wave band-dependent, with larger offsets in shorter wavelengths. For example, in the I band, Giovanelli et al. (1997) found a 0.32 mag lower zero point of the TFR for Sa/Sab galaxies and 0.10 mag lower for Sb galaxies than the Sbc and later type spirals. In the B band, Russell (2004) found that Sb galaxies have a zero point of 0.57 mag lower than Sc galaxies. In a recent study, Russell (2009) compared the TFR-derived distances of nearby groups and clusters and found a mean difference of 0.19 mag in the H band between the Sb and Sc spiral galaxies. Moreover, using a large sample of spiral galaxies, Masters et al. (2006, 2008) found that the morphological dependence of the TFR is not only a shift of the zero point, but even dependent on the luminosity in the way that the differences are more pronounced for more luminous galaxies.

The morphological dependence of the TFR originates from the differences of the stellar population (\( M \)) or the disk dynamics (\( V_{\text{max}} \)) or both.

On the one hand, it is well known that the colors of earlier type spirals are redder. Devereux & Young (1991) interpreted this color difference as originating from the bulge disk composition effect. The stellar population of bulges are typically older and more metal rich than that of the disks. A larger fraction of the bulge component in earlier type spirals naturally results in a redder color on average for the whole galaxy. However, with a bulge–disk decomposed sample, Kennicutt et al. (1994) studied and compared the star formation histories of only the disk component of different type spirals and found that the stellar population of the disks of later type spiral is also on average younger.

On the other hand, although the rotation curves of spiral galaxies are proposed to follow a universal shape (Persic & Salucci 1991; Persic et al. 1996), there is evidence showing that the rotation curves of early-type spirals rise more rapidly in the inner region than that of late types (Corradi & Capaccioli 1990; Noordermeer et al. 2007). Noordermeer & Verheijen (2007) show that the massive Sa galaxies lie better in the well-defined TFR when using the asymptotic rotation velocity \( V_{\text{asymp}} \) instead of \( V_{\text{max}} \), implying a dependence of \( V_{\text{max}} \) on the morphological type.

On the theoretical side, the zero point, slope, and scatter of the observed TFR can all be well accommodated by the current disk formation model in the framework of the cold dark matter hierarchical cosmogonies (Dalcanton et al. 1997; Mo et al. 1998; Mo & Mao 2000; Pizagno et al. 2005; Dutton et al. 2007; Gnedin et al. 2007). However, the morphological dependence of the TFRs has not been probed in these studies because the bulge component in these models is typically neglected. Another limitation of these models is that the stellar populations have not been tackled with a physical prescription, but with predetermined mass-to-light ratios.

In this study, we aimed to model the dynamics and stellar population of different type spiral galaxies in combination and try to find out which factor is the main contributor to the morphological dependence of the TFR. In specific, we will follow the dynamical model of Mo et al. (1998), hereafter MMW and extend it to include a bulge component. For the stellar population, we will parameterize the star formation histories of the disks and bulges separately and then derive their mass-to-light ratios in different bands using the stellar population synthesis code (Bruzual & Charlot 2003).

This paper is organized as follows. In Section 2, we describe our dynamical model of the spiral galaxies, including the disk, bulge, and dark halo components, respectively. In Section 3, we study the stellar properties of the disks and bulges with
parameterized star formation histories. We compare our model predictions with the observational data in Section 4. We make discussions on the uncertainties of our results in Section 5 and finally give a brief summary in Section 6.

2. DYNAMICAL MODEL OF SPIRAL GALAXIES

Our modeling of the dynamics of spiral galaxies follows and simplifies the disk formation model of MMW, but with more attention on the bulge contribution. The interested reader is referred to MMW for detail. Here, we repeat the essentials related to our study. In this model, initially, the gas and dark matter are uniformly mixed in a virialized halo. As a result of dissipative and radiative cooling, the gas gradually cools down and settles into a disc structure due to the conservation of angular momentum.

We define that the stellar mass of the galaxy finally formed is \( M_s \) and the fraction of this mass to the initial halo mass \( M_h \) is \( m_s \equiv M_s/M_h \). We express the bulge fraction of the formed galaxy being \( f_b \), so that the masses of the bulge and disk are \( M_b = f_b M_s \) and \( M_d = (1 - f_b) M_s \), respectively.

The rotation curve of a spiral galaxy is contributed by three dynamical components: halo, bulge and disk. We show and discuss our assumptions on each term below.

2.1. Halo

The N-body simulations show that the collapsed and virialized dark halos follow a universal density NFW profile (Navarro et al. 1996),

\[
\rho(r) = \frac{c}{4\pi Gr^2 \left[ \ln(1+c) - c/(1+c) \right]} \frac{r}{r_s + 1}, \tag{2}
\]

where \( r_s \) is a scale radius, \( G \) is the gravitational constant, \( V_h \) is the circular velocity, and \( c \) is the concentration parameter. The concentration \( c \) is defined as \( c \equiv r_{200}/r_s \), where \( r_{200} \) is the virial radius\(^4 \) of the halo. For a given cosmology, the virial radius \( r_{200} \), halo mass \( M_h \) and circular velocity \( V_h \) are related by

\[
r_{200} = \frac{V_h}{10H(z)}, \quad M_h = \frac{V_h^3}{10GH(z)}. \tag{3}
\]

where \( H(z) \) is the Hubble constant at redshift \( z \).

In this study, we use the concordance ΛCDM cosmology model, with \( H_0 = 70 \) km s\(^{-1}\) kpc\(^{-1}\), \( \Omega_0 = 0.3 \), \( \Omega_\Lambda = 0.7 \) and baryon mass density \( \Omega_B = 0.04 \).

With the assembling of the baryons into disk and bulge, the gravitational effect from the bulge and disk changes the initial halo mass distribution through contraction. We follow MMW and use the adiabatic contraction assumption to analysis this effect (see MMW for detail).

For a halo with given circular velocity \( V_h \), the concentration \( c \) is the only parameter to be quantified. At given redshift \( z \), the concentration parameter \( c \) is mainly correlated with the mass of the halos (Navarro et al. 1996; Bullock et al. 2001). We adopt a simple parametrization of the concentration \( c \) at redshift zero as that in Shen et al. (2002):

\[
c = 8.5 \left( \frac{V_h}{100 \text{ km s}^{-1}} \right)^{-1/3}. \tag{4}
\]

\(^4\) Here, \( r_{200} \) is the radius within which the mean mass density is 200 times the cosmic critical density \( \rho_{\text{crit}} \).

2.2. Bulge

We assume that the bulge component of spiral galaxies has a spherical mass distribution and the mass density profile \( \rho_b(r) \) follows a Hernquist (Hernquist 1990), whose projection approximates the classical \( R^{1/4} \) surface brightness profile of elliptical galaxies. The \( \rho_b(r) \) is expressed as

\[
\rho_b(r) = \frac{M_b}{2\pi r (r + a)^2}, \tag{5}
\]

where \( M_b \) is the total bulge mass, \( a \) is the bulge scale radius, which is correlated with the effective (half-light) radius \( R_e \) in the way \( R_e \approx 1.82a \) (Equation 38 of Hernquist 1990). To establish the dynamics of a bulge with mass \( M_b \), we need to know the scale radius \( a \) or effective radius \( R_e \). We assume that the bulges follow the observed size-mass \((R-M)\) relation of elliptical galaxies (Shen et al. 2003),

\[
R_e(\text{kpc}) = 3.47 \times 10^{-5} \left( \frac{M_b}{M_\odot} \right)^{0.56}. \tag{6}
\]

2.3. Disk

The surface brightness profile of spiral disks typically follow an exponential profile. Here, we assume the disk surface mass density profile is also exponential,

\[
\mu_d(r) = \mu_0 \exp(-r/R_d), \tag{7}
\]

where \( \mu_0 \) is the central surface mass density and \( R_d \) is the scale length. \( \mu_0 \) and \( R_d \) are related to the total mass of the disk \( M_d \) through \( M_d = 2\pi \mu_0 R_d^2 \).

Since the observed size of the disk in a spiral galaxy is affected by its central bulge, we do not take the observed \( R-M \) relation of spiral galaxies as that in the model. Following MMW, we assume that the disk size \( R_d \) is determined by its initial angular momentum \( J \), which can be parameterized by a spin parameter \( \lambda \),

\[
\lambda = J/E^{1/2}G^{-1}M^{-5/2}, \tag{8}
\]

where \( E \) is the total energy of the halo. With reasonable assumptions that the specific angular momentum per particle of the baryons is the same as the dark matter and there is no angular momentum transfer among different components, the angular momentum of the disk finally formed is therefore \( J_d = m_d J \). Here, \( m_d \) is the fraction of baryons settling into the disk and is equal to \( m_s(1 - f_b) \). The scale length of the disk \( R_d \) then equals

\[
R_d = \frac{1}{\sqrt{2}} \lambda r_{200} f_c^{-0.5} f_b(\lambda, c, m_d), \tag{9}
\]

where \( f_c \) is a factor coming from the halo density profile and only dependent on concentration \( c \) (see Equation (23) of MMW), \( f_b \) is a factor coming from both the halo density profile and the gravitational effects of disk and bulge (see Equation (29) of MMW). It is shown that the size of spiral galaxies predicted from \( \lambda \) is in excellent agreement with the observations (Syer et al. 1999; Shen et al. 2003).

Numerical simulations have found that the spin parameter \( \lambda \) of the dark matter halo follows a log-normal distribution with median \( \lambda \sim 0.04 \) and scatter \( \sigma_{\text{ln}\lambda} \sim 0.4 \) and this distribution is quite independent of the cosmology and halo properties (Bett et al. 2007). For the purpose of simplicity, we do not consider the scatter of the angular momentum distribution and take the median value \( \lambda = 0.04 \) for all disks (see more discussions in Section 5.1).
2.4. Rotation Curve

With the mass distribution of the bulge, halo, and disk components determined through the model parameters shown above, the rotation curve of a spiral galaxy can be determined by the sum in quadrature of contributions from these three terms:

\[ V^2(r) = \frac{GM_{DM}(r) + M_B(r)}{r} + V_d^2(r). \] (10)

During the calculation of the term \( V_d^2 \) contributed from the disk component, the flattened geometry needs to be taken into account (Binney & Tremaine 1987).

To fully determine the rotation curve of a given spiral galaxy with stellar mass \( M_\ast \), we still need to know the relative proportions of these three components (bulge, disk and dark halo). This could be done by settling the two other parameters, i.e., the baryon fraction \( m_b \) and the bulge–disk ratio \( B/D \).\(^5\) We set the baryon fraction \( m_b \) to be a function of the halo mass (in terms of circular velocity \( V_h \); Shen et al. 2003),

\[ m_b = \frac{0.13}{1+(V_h/150 \text{ km s}^{-1})^{-2}}. \] (11)

This assumption is based on the consideration that gas outflow process in low mass halo is efficient, due to their shallow potential well, and a large fraction of baryons is blown out of the dark halo, while the baryon fraction of high mass halos gradually approach the cosmic baryon fraction \( \Omega_b/\Omega_0 \approx 0.13 \) (White & Frenk 1991). The bulge–disk ratio \( B/D \) is taken to be 0.5/0.3/0.1 for model Sa/Sb/Sc galaxies, respectively (Simien & de Vaucouleurs 1986).

We show three examples of resulting rotation curves for three morphological types (Sa/Sb/Sc) in Figure 1. All three model galaxies are chosen to have the same circular velocity \( V_h = 120 \text{ km s}^{-1} \) and thus the same stellar mass \( M = 3 \times 10^{10} M_\odot \). For the earlier type spiral, as we can see from the figure, due to the larger bulge component, our model predicts a steeper increase of rotation velocity in the inner region, which brings to the larger bulge component, our model predicts a steeper increase of rotation velocity in the inner region, which brings about the larger bulge fraction of the spiral disks with a single stellar population with age of 10 Gyr.

However, the value of \( V_{\text{max}} \) only weakly correlates with the model type. The \( V_{\text{max}} \) of the Sa(Sb) spiral is only 1.3(1.0)% higher than the corresponding Sc spiral. This is because the relatively smaller bulge fraction of the later type spiral is always compensated by its larger disk fraction (see the components of rotation curves in Figure 1).

3. STELLAR POPULATIONS OF SPIRAL GALAXIES

Besides the different dynamics, the bulge and disk also show different stellar populations. The bulges are typically old and show little recent star formation, while the star formation timescales of the disks are long and there is still ongoing star formation throughout the disk at the present day.

In this study, we parameterize the stellar population of the bulge components with a single stellar population with age of 10 giga year (Gyr). For the disks, following the usual convention, we parameterize their star formation histories (SFH) with an exponential function

\[ \text{SFR}(t) \propto \exp(-t/\tau), \] (12)

where \( \tau \) is the timescale of the SFH. This simple analytical expression can parameterize different kinds of SFHs. For \( \tau \) approaching 0, Equation (12) represents a single stellar population. When \( \tau \) tends to infinity, the star formation rate is a constant along the history. The age of the disks is also set to 10 Gyr.

Kennicutt et al. (1994, hereafter K94) parameterized the SFH of the spiral disks with a \( b \) parameter, which is defined as

\[ b \equiv \frac{\langle \text{SFR} \rangle}{\langle \text{SFR} \rangle}. \] (13)

where \( \langle \text{SFR} \rangle \) is the star formation rate today and \( \langle \text{SFR} \rangle \) is the average star formation rate in past. They estimated the \( b \) parameter from the \( UBV \) colors and \( H\alpha \) fluxes for different morphological type spirals and found that the Sa/Sb/Sc disks have typical \( b \approx 0.12/0.33/0.84 \) and variation of about 0.05/0.15/0.20, respectively.\(^6\) With the SFHs parameterized by Equation (12) as a prior, these \( b \) values correspond to the \( \tau \) with median 3/5/30 Gyr and 1σ range [2, 4]/[4, 7]/[10, 100] Gyr for Sa/Sb/Sc spirals, respectively.\(^7\)

Based on the SFHs assumed for disk and bulge components, we use the new version of the stellar population synthesis code of Bruzual & Charlot (2003), denoted as CB07, to calculate their mass-to-light ratios in different wave bands. The metallicity of the stellar population is set to be the solar value while the stellar

\[^5\] B/D \( \equiv f_b/(1-f_b). \)

\[^6\] The \( b \) values are taken from Table 4 of K94, where the sub-types include Sa/Sab/Sb/Sbc/Sc/Scd spirals. We average the \( b \) values of Sa and Sab sub-types as the Sa type. The \( b \) value of Sb type is kept. For Sc type, we average the \( b \) values of Shb and Sc/Scd sub-types. The variations of \( b \) are estimated from Figure 6 of K94.

\[^7\] Here, the 1σ range denotes the 32th to 68th percentiles of the \( \tau \) distribution and is calculated from the estimated variation of \( b \). For Sc spirals, during the calculation of the range of \( \tau \), we force the upper limit of \( b \) to be 1, corresponding to \( \tau \approx \infty \), which gives the youngest average stellar population as that can do by Equation (12).
initial mass function is taken from Chabrier (2003) with lower and upper mass limit being 0.1 \( M_\odot \) and 100 \( M_\odot \), respectively.

Finally, with the predetermined stellar mass \( m_i \) and \( B/D \) for each model galaxy, we calculate its absolute magnitudes in different optical wave bands.

4. MODEL PREDICTIONS

In this section, we show our model-predicted morphologically dependent TFRs and compare them with the observational results. For each morphological type, we build 11 model galaxies with halo circular velocity \( V_h \) in the range from 100 to 200 km s\(^{-1}\) with an interval of 10 km s\(^{-1}\). With the baryon fraction characterized by Equation (11), the range of the stellar mass of our model galaxies is thus from \( 1.4 \times 10^{10} \) to \( 2.3 \times 10^{11} \) \( M_\odot \).

In our model, there is only one free parameter, i.e., the disk star formation timescale \( \tau \) in Equation (12). We first set the \( \tau \) values of different type spirals to be these suggested by K94, i.e., the median \( \tau = 3/5/30 \) Gyr and its 1\( \sigma \) range being [2, 4]/[4,7]/[10,\infty] Gyr for Sa/Sb/Sc spirals, respectively. We refer to this model setting as K94 model below.

4.1. I-band TFRs

Lots of recent observational TFR studies are in the near-infrared I band (e.g., Giovanelli et al. 1997; Dale et al. 1999; Vogt et al. 2004), which takes the advantage of better detector photometry than the H band and less scatter in TFR than the blue B band. More recently, Springob et al. (2007) compiled and published a new generation of a homogeneous galaxy catalog, referred to as the SFI++, which contains \( \sim 5000 \) spirals suitable for TFR study in the I band. Based on the SFI++ catalog, the TFRs of Sa, Sb, and Sc type spirals have been presented by Masters et al. (2006). Here, we first show our model-predicted I band TFRs for different type galaxies and make comparisons with the results of M06.

The K94 model-predicted I band TFRs of Sc, Sb and Sa spirals are shown in the top left, top right and bottom left panels of Figure 2, respectively. The model galaxies are represented by the triangles (Sc), squares (Sb), and stars (Sa) while the fitted TFRs are shown as the solid lines in each panel. The observed I band TFRs of different type galaxies are shown as the dashed lines for comparison. The dotted lines in each panel show the ranges of model-predicted TFRs when the star formation timescale \( \tau \) varies in its 1\( \sigma \) range. Inside its range, a larger \( \tau \) results a larger zero-point of the TFR, i.e., galaxies will be brighter at given \( V_{\text{max}} \) for larger \( \tau \).

Sc-type spirals (include Sbc/Sc/Scd) are the dominant morphological type in TFR studies.8 Lots of the TFR studies use Sc spirals as the reference and make morphological type corrections on other types, e.g., Giovanelli et al. (1997), Dale et al. (1999), and Ziegler et al. (2002). For Sc spirals, as we can see, by setting the model parameters to be either the typical values from numerical simulations (e.g., \( \lambda \) and \( c \)) or being constrained from other observations(e.g., \( \tau \sim 30 \) Gyr) without any further fine-tuning, our model-predicted I band TFR is in excellent agreement with the observations.

However, with default settings of model parameters, our model-predicted TFRs of Sb and Sa spirals are not well consistent with the observations of M06. The predicted TFR of Sb spirals (\( \tau = 5 \) Gyr) have a systematically larger zero point than observations, i.e., the model-predicted luminosity is too bright. When \( \tau \) reaches its upper range 7 Gyr, the discrepancy becomes smaller, but still be far from consistent with observations. We will discuss this discrepancy in more detail in next section.

For Sa spirals, the slope of the observed TFR is significantly shallower than our model predictions. However, as that discussed in Giovanelli et al. (1997) and M06, the disagreement of the TFR slope of the Sa spirals should be interpreted in caution because the incompleteness of the Sa spirals is large, especially in the low luminosity end, which will artificially bias the slope to lower value. On the other hand, our modeling on the B/D of Sa spirals is a constant 0.5, which might be too simplified. In the study of M06, all the S0/SA/Sab galaxies are grouped as Sa type. Among three sub-types, the earlier type galaxies, e.g., S0, having systematically larger B/D, are also systematically brighter. Therefore, from low \( V_{\text{max}} \) to high \( V_{\text{max}} \) galaxies, there is actually a systematic change of B/D, which will also shallower the slope of TFR. By introducing a systematical change of B/D as a function of \( V_{\text{max}} \), we can in principle reproduce the slope of Sa spirals as observed. However, we prefer not to tune our model to reproduce this relation with a cost of introducing more uncertainties.

Comparing with the uncertainties in the modeling of the TFR slope, the zero point is quite robust. Moreover, many studies of the morphological dependence of the TFRs only report a global shift of the zero point, e.g., Giovanelli et al. (1997) and Russell (2004, 2009; see the next section). Therefore, in the following section, we parameterize the morphological dependence of the TFRs only with the shift of the zero-point \( \Delta M \).

4.2. Morphology-dependent TFRs in Different Bands

We choose the zero-point shift \( \Delta M \) of the TFRs at \( V_{\text{max}} = 200 \) km s\(^{-1}\), where the corresponding absolute magnitude is

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8 The later type spirals are more likely to be strong \( H_\alpha \) or \( H_\alpha \) emitters so that the measurement of the rotation width is easier.
roughly the $M_V$ of the luminosity function of spiral galaxies and where the number counts of galaxies in a flux-limited sample normally peaks. In this case, $\Delta M = \Delta \phi$ of Equation (1).

We show the $\Delta M$ between Sb and Sc spirals in the top panel of Figure 3, whereas the $\Delta M$ between Sa and Sc spirals is shown in the bottom panel. The model-predicted $\Delta M$ in different wave bands are connected as a function of their effective wavelengths with lines. The wave bands include $U,B,V,R,I,J,H,K$ and the wavelength ranges from 0.33 to 2.2 micron. The observed difference of $\Delta M$ at $V_{\text{max}} = 200 \text{ km s}^{-1}$ in different bands found in the literature are plotted against their effective wavelengths. Results from different authors are labeled with different symbol types. The references and details of these morphology dependent TFRs are listed in Table 1. A few other studies in the literature are not quoted in Table 1 and Figure 3, including Rubin et al. (1985), Giovanelli et al. (1997) and the TFR of Sb spirals of Sandage (2000). Rubin et al. (1985) found the magnitude differences $\Delta M$ between Sa and Sc spirals are as high as 2 mag in the $B$ band and 1 mag in the $H$ band, whose number of each type galaxies is limited ($< 20$) and without error estimation quoted for the parameters of TFRs. The $I$-band data of Giovanelli et al. (1997) has been expanded and re-analyzed by M06 and their results are generally consistent. The TFR of Sb spirals in Sandage (2000) is arbitrarily neglected, where its zero point is even lower than Sc spirals, i.e., $\Delta M(\text{Sb} - \text{Sc}) < 0$, contradictory to most of the other studies.

The solid lines in Figure 3 show predictions from the K94 model, i.e., the model with $\tau = 3.5$, 30 Gyr for Sa, Sb, Sc spirals, respectively. The shadowed regions show the ranges of model-predicted $\Delta M$ when $\tau$ varies in its 1$\sigma$ range. As we can see, the K94 model overpredicts the differences of the zero points significantly for both Sb/Sc and Sa/Sc pairs. The average observed zero-point differences in near-infrared bands are $\Delta M(\text{Sb} - \text{Sc}) \sim 0.15$ mag and $\Delta M(\text{Sa} - \text{Sc}) \sim 0.20$ mag, whereas the model prediction is as high as $\Delta M(\text{Sb} - \text{Sc}) \sim 0.45$ mag and $\Delta M(\text{Sa} - \text{Sc}) \sim 0.60$ mag. That means, if the differences of the stellar populations of the disks of different type spirals are as that suggested by K94, the shift of the zero point of the TFRs would be much larger than observed.

With the disk star formation timescale $\tau$ approaching its upper range (the lower boundary of the shadowed region), the discrepancy between the model-predicted $\Delta M$ and the observations becomes smaller. This result prompts us to consider an extreme case, $\tau = 30$ Gyr for both Sa and Sb disks. In this case, the stellar populations of the disks of different type spirals are the same, while the different global colors of different type spirals only originate from the bulge–disk composition effect. This scenario is consistent with the results of Devereux & Young (1991). To distinguish it from the K94 model, we refer to this scenario ($\tau = 30$ Gyr for all type disks) as the “composition” model below.

For the “composition” model, the model-predicted $\Delta M$ as a function of the effective wavelength is shown as the dotted lines in Figure 3. Surprisingly, the predicted $\Delta M$ from this model, especially in near-infrared bands, is generally consistent with observations, either for Sb/Sc or Sa/Sc pairs. The predicted $\Delta M$ in the $B$ band is smaller than that observed. A possible solution to this discrepancy is the dust extinction which has not been taken into account in our model. If the face-on dust extinction of earlier type spirals is more significant, the $\Delta M$ in blue band will be larger than now we predicted (see detailed discussions in Section 5.3).

Finally, it is worth mentioning that the $\Delta M$ between different spiral types is not contributed by the stellar population alone but composed by both the dynamics and stellar population. As we have shown in Section 2.4, for the galaxies with the same stellar mass $3 \times 10^{10} M_\odot$, the $V_{\text{max}}$ of a Sa(Sb) spiral is about 1.5(1.0)% higher than Sc spiral, which corresponds to the $\Delta M \sim 0.04(0.03)$ mag, independent of the wave bands. This contribution is shown as two dashed horizontal lines in the top and bottom panels of Figure 3. However, as we can see, the stellar population is still the dominant contributor to the morphological dependence of the TFR.

5. DISCUSSION

There are some uncertainties in our modeling of both dynamics and stellar population of the spiral galaxies, e.g., the scatters of model parameter, the diverse bulge properties, and the internal dust extinction, etc. We discuss these issues below.

5.1. Scatters of Model Parameter

In our modeling, we only take the typical values for each model parameter and do not consider their scatters except the key parameter $\tau$. However, all these model parameters show scatters as suggested by either numeric simulations or observations, e.g., Mo & Mao (2000), Jing (2000), and Shen et al. (2002). If the scatters of model parameters are independent variables and do not correlate with the morphological types (as suggested in our model), these scatters will only make contributions to the scatters of the predicted TFRs and will not affect any of our conclusions (Mo & Mao 2000; Shen et al. 2002).

However, the morphological type may correlate with the spin value of a galaxy. A smaller $\lambda$ may trigger a formation of larger bulge easier through disk instability (Shen et al. 2003), so that
when we considered the scatter of spirals would be biased to the galaxies with systematically lower λ. This is because the lower λ can be characterized by a S´ersic profile with S´ersic index n significantly smaller than 4. The classical bulges typically appear in earlier type spirals and their masses are high. The majority of the stellar mass of the bulges is in classical bulges (∼90%, Gadotti 2009).

If the bulges of late-type (e.g., Sc) spirals are pseudo-bulges, the difference of stellar population between early- and late-type spirals will be even larger because the pseudo-bulges are bluer than classical bulges. This will increase the predicted ΔM between the early- and late-type spirals and decrease the allowed differences between their disks again.

5.2. Pseudo and Classical Bulges

In this study, we have treated all the bulges as scaled elliptical, i.e., the classical bulges, for simplicity.

The current view on the bulges is quite complex. There are mainly two types of bulge, i.e., the classical bulge and the pseudo-bulge, which may be originated from different physical formation processes (Fisher & Drory 2008; Fisher et al. 2009; Gadotti 2009). The classical bulges are similar to scaled elliptical galaxies, with their surface brightness following classical R1/4 profile and colors being red. The pseudo-bulges tend to show younger stellar population and their density profiles can be characterized by a S´ersic profile with S´ersic index n significantly smaller than 4. The classical bulges typically appear in earlier type spirals and their masses are high. The majority of the stellar mass of the bulges is in classical bulges (∼90%, Gadotti 2009).

If the bulges of late-type (e.g., Sc) spirals are pseudo-bulges, the difference of stellar population between early- and late-type spirals will be even larger because the pseudo-bulges are bluer than classical bulges. This will increase the predicted ΔM between the early- and late-type spirals and decrease the allowed differences between their disks again.

5.3. Dust Extinction

In our modeling, we have not considered the effect of internal dust extinction, which might be different for different type spirals. Fortunately, the internal dust extinction has at least been partly corrected in most of the observational TFR studies, e.g., Giovanelli et al. (1997) and Masters et al. (2006, 2008). In these studies, they all made the corrections of the internal dust extinction using the parametrization of Giovanelli et al. (1994),

\[ A = \gamma \log(a/b), \]

where γ is a wave-band-dependent coefficient and a/b is the observed axis ratio indicating the inclination angle of the spiral disk. This parametrization of the dust extinction has accounted the extinction from the geometry effect, i.e., it has corrected all the spiral disk to face-on viewing and assumed zero dust extinction for face-on case (A ∼ 0 for a/b ∼ 1).

However, the internal dust extinction of face-on spirals may not be negligible (Shao et al. 2007; Driver et al. 2007). The inner parts of the spiral disks are very likely to be optical thick even when viewed in face-on (Giovanelli et al. 1994). The dependence of this face-on extinction on the morphological type is complicated. On the one hand, the late type spiral disks are gas richer and so that may contain more dust (Stevens et al. 2005). On the other hand, the early type spirals have larger bulge component and this component suffers more from the dust extinction because the dust layer is peaked in the central region (Tuffs et al. 2004; Driver et al. 2007). Countering these two effects, the global dust extinction may only be weakly dependent on the morphological types. A very recent study of Muñoz-Mateos et al. (2009) based on the multi-wavelength data shows that there is a weak global trend of the internal dust extinction, Sb>Sa>Sc.

If the face-on dust extinction of early-type spirals were more significant considering their more concentrated light, the smaller ΔM predicted by the "composition" model in the B band could be explained since the extinction in the B band is 5 times more larger than the K band given the typical extinction curve of normal spiral galaxies (Shao et al. 2007). Moreover, if we took the higher dust extinction for the early-type spirals into our model, the model-predicted ΔM would be larger, thus the stellar populations of different type disks even could not be very different as that suggested by K94.

6. SUMMARY

In this paper, we have studied the morphological-dependent TFRs by modeling the dynamics and stellar population of spiral
galaxies in combination. We model the dynamics of spiral galaxies by following the disk formation model of MMW and extending it to include a bulge component. We parameterize the SFHs of the bulge and disk separately and derive their mass-to-light ratios with population synthesis code of Bruzual & Charlot (2003). Our model reproduces the observed I band TFR of the Sc spirals very well without any free parameters. Our model shows that the morphological dependence of the TFRs is mainly contributed by the stellar population through bulge disk composition effect, although the effect from the dynamics is not negligible.

The effects of the dynamics and stellar population on the morphological dependence of the TFR are different. The shift of the $V_{\text{max}}$ (or luminosity), caused by dynamics, shows a characteristic that is independent of the wave bands. On the other hand, the shift of the zero point of TFR is a function of the wave bands, when the morphological dependence is caused by the stellar population. Therefore, the morphological dependence of the TFR in different bands is an effective way to constrain the dynamics and stellar populations of spiral galaxies. Our results show that the observed morphological-dependent TFRs are consistent with a scenario that the stellar population of different type spirals are only different in the bulge disk composition on average.

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