The Tully Fisher Relation and Dust Attenuation in Spiral Galaxies

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Approach

Measuring Cosmological Distances with Galaxies
-The Faber-Jackson relation
-The Fundamental Plane
-The Tully Fisher relation
-The Physics behind

Tully Fisher
-Calibration and distance modulus
-Sources of Error
-Observed Dust attenuation in Spiral Galaxies
+Attenuation in function of Inclination
+Attenuation in function of Luminosity

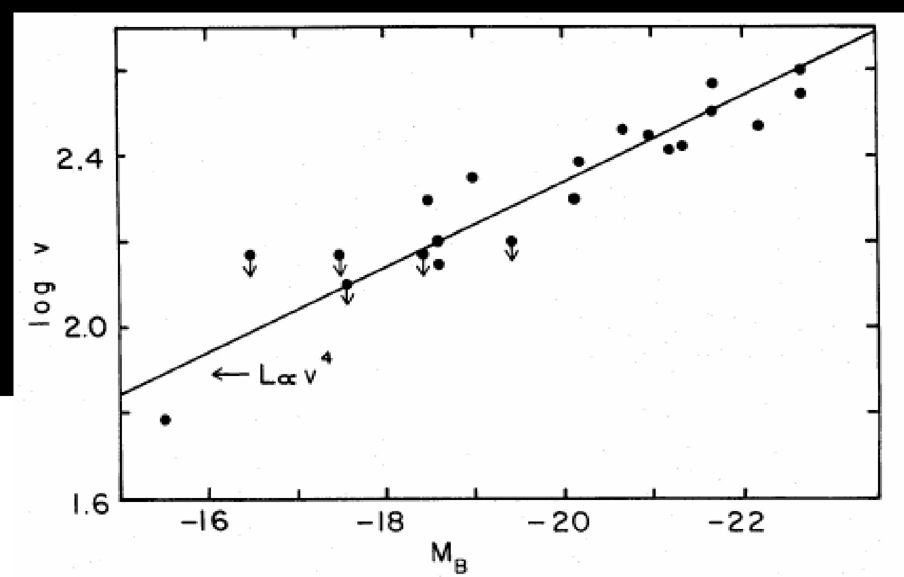
Simulations of Dust Attenuation in Spiral Galaxies
-Radiative Transfer Problem
-Sunrise
-Results
-Comparison of Results

The Faber-Jackson Relation

- Discovered in 1976 by Sandra Faber and graduate student Robert Jackson

- A simple relation between the central (inner few kiloparsecs) velocity dispersion, and the luminosity of elliptical galaxies.

$$L \propto \sigma_v^{\alpha}$$



Line of sight velocity dispersion versus absolute magnitude. Faber & Jackson (1976)

The Fundamental Plane

- Discovered independently and simultaneously by Djorgovski & Davis (1987) and Dressler et al. (1987b).
- Based on the Faber-Jackson relation but with one more observable parameter, I_o

$$L \propto I_o^x \sigma_v^y$$

with $(x,y) \cong (-0.7, 3)$ (Dressler et al. 1987; Djorgovsky & Davis 1987).

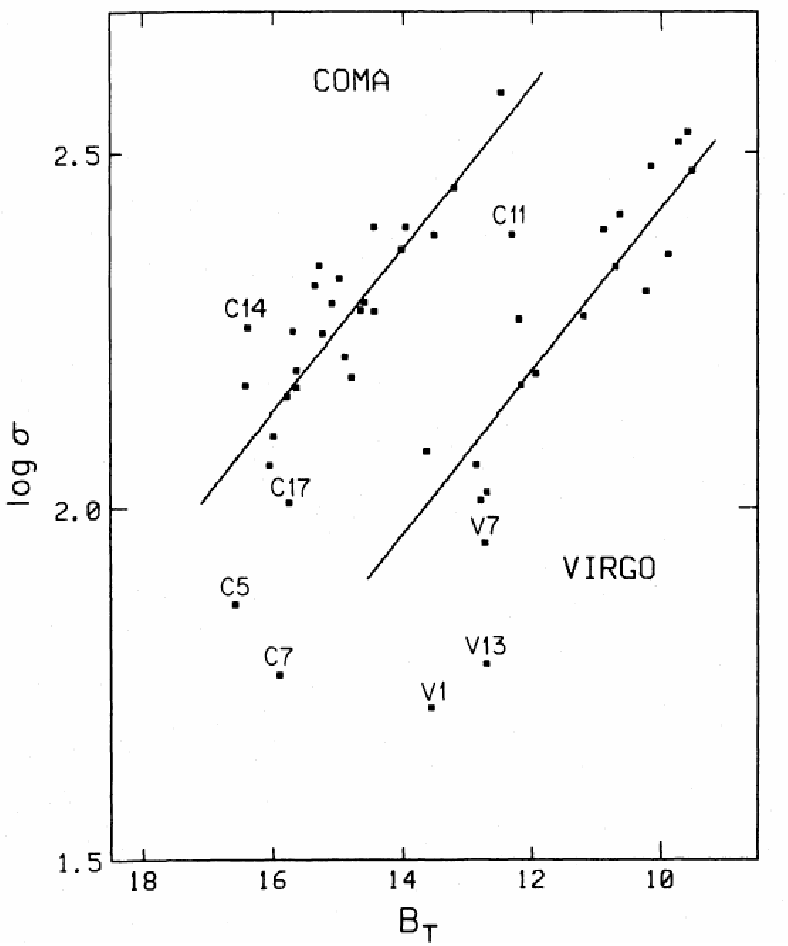
$(x,y) \cong (-0.75, 1.49)$ (Bernardi et al. 2003)

- Since $L \propto I_o r_o^2$ *it also* implicitly relates r_o, σ_v and L, or r_o, σ_v and I_o.

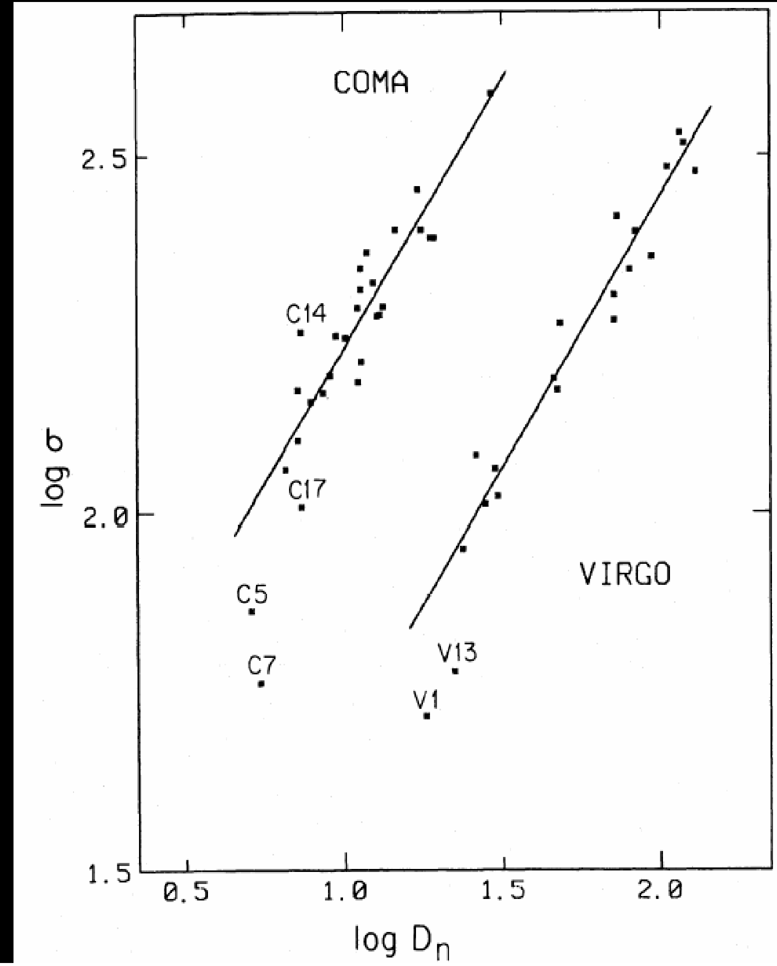
- Also known as $D_n - \sigma$ relation, where D_n is the diameter enclosing a mean surface brightness equal to some reference value. $D_n \propto I_o^a r_o^b$*, and if the reference value used is 20.75 mag arcsec*$^{-2}$ *(*Dressler et al. 1987) then,

$$\sigma_v \propto D_n^z$$

Faber-Jackson vs. D_n- σ



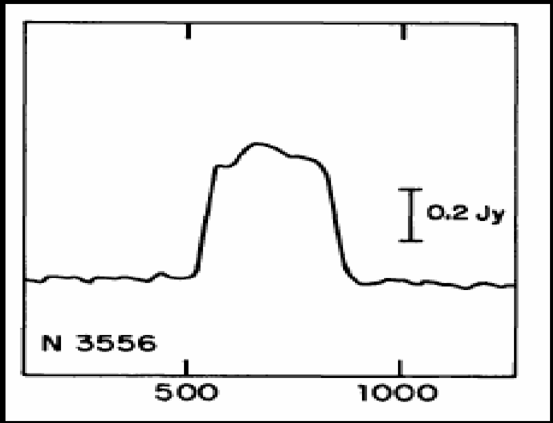
Total blue magnitude vs. central velocity dispersion for ellipticals in the Coma and Virgo clusters The lines log σ = -0.114B_T+C, where C=3.651 and C=3.960 for Coma, are the best median fits. The rms scatter in B_T from this lines are 0.57 mag for Virgo and 0.69 mag for Coma.



Log D_n vs. log σ for the same galaxies. The lines log σ = 0.750 log D_n is 0.059 for Virgo and 0.072 for coma, a factor of 2 smaller scatter than with the Faber-Jackson relation.

The Tully-Fisher relation

In 1977 Brent Tully and Richard Fisher discovered a similar relation between the rotational velocity of the disk and the luminosity of a spiral galaxy. The Tully-Fisher (TF) relation describes the empirical connection between neutral hydrogen (HI) 21-cm emission line profile widths and the absolute magnitudes of spiral galaxies.



H I emission spectra from N3556. Horizontal scale is in Km/s with respect to the sun. (Tully & Fisher 1977)

$$L \propto \Delta V_o^{\lambda}$$

Where $\lambda = 2.5$ (Tully & Fisher 1977)

$\lambda = 3.1$ (Tully et al. 1998)

The Physics Behind

In order to have a virialized system we require that the Ek = Ep/2, or

$$v^2 = \frac{GM}{R} .$$

Given that $\theta = \frac{R}{d}$ and $f = \frac{L}{4\pi d^2}$, we can express the surface brightness as

$$I = \frac{f}{\theta^2} = \frac{Lv^4}{4\pi G^2 M^2} ,$$

which rearranging gives

$$L = \frac{v^4}{I} \frac{1}{4\pi G^2 (M/L)^2}$$

Hence $L \propto v^4$, translating to
$L \propto \sigma^4$ for ellipticals
$L \propto V_{max}^4$ for spirals

The fact that this exponentials are observed to be different, tell us that M/L has a dependence on Luminosity

Calibrating and Finding Distances

1. Find appropriate candidates for calibration, galaxies with:

   -Well determined distances

   -Accurately known global hydrogen profile width

   -Inclinations of: $45^o < i < 85^o$. Sufficient inclination so that there is no appreciable error in correcting the hydrogen profile for projection, but no too much to avoid large extinction uncertainties in the observed magnitudes.

2. Apply corrections to calibrators

   -Correct hydrogen profile for projection

   $$\Delta V_o = \Delta V / \sin\theta$$

   -Correct for dust extinction

   ~~$A_\xi = 0^m.28\,(a/b - 1)$~~

   $$A_\lambda = \gamma_\lambda \log\left(\frac{a}{b}\right)$$

3. Find relation

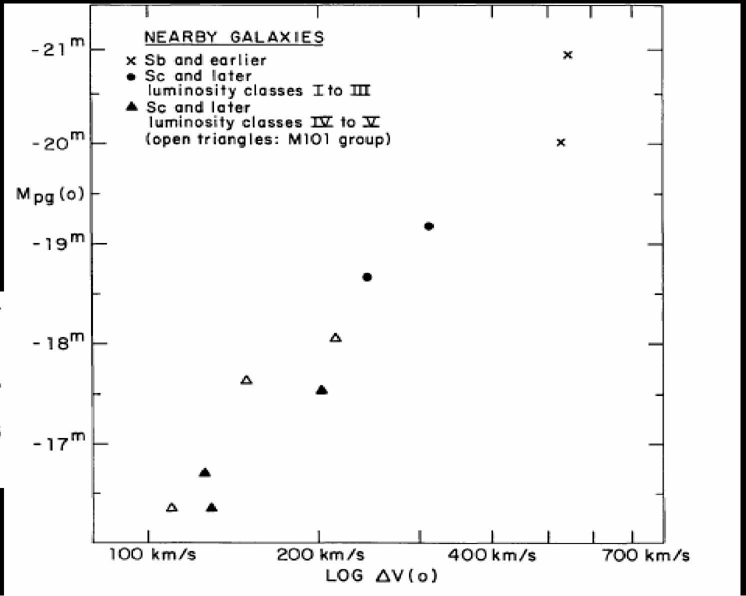
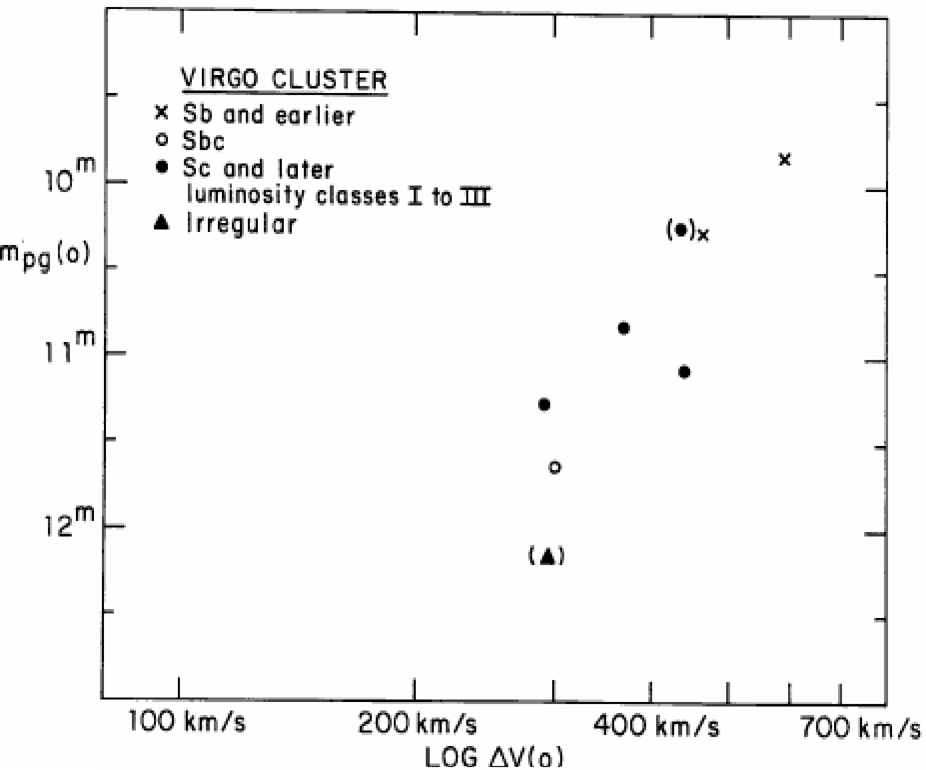


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller [illegible] in the M81 group and open triangles are smaller systems in the M101 group

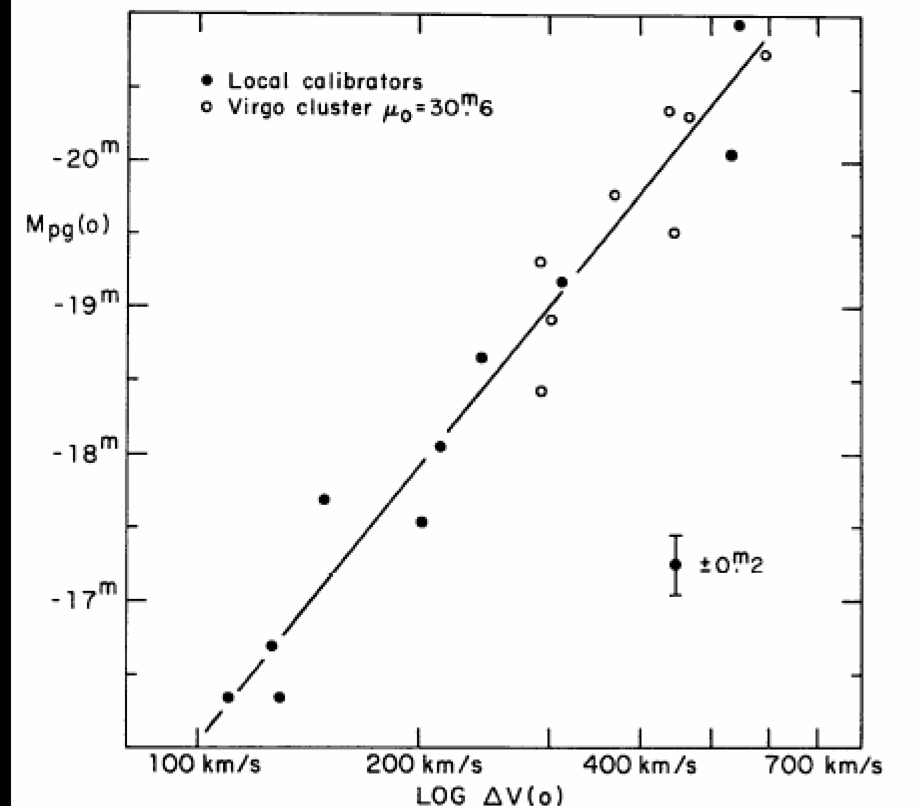
(Tully & Fisher 1977)

4. Repeat 1-3 for the sample used to find a distance



Apparent magnitude – global profile width relation for those members of the Virgo cluster observed by Holmberg (1958). Morphological types are distinguished. NGC 4535 is in brackets because with $\xi = 42°$ the inclination correction to the global profile width is substantial

5. Find distance modulus by requiring the sample to match the calibration.



Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m\!.6 \pm 0^m\!.2$

$$\mu_0 = 3.5 + 6.25 \log \Delta V(o) + m_{pg}(o)$$

$$r = 10 \wedge (\frac{\mu + 5}{5}) = 13.2 \pm 1 \text{ Mpc}$$

(Tully & Fisher 1977)

Sources of Error in The TF Relation

- Low signal-to-noise ratio in the profiles

- There have been many different methods to calculate the uncorrected HI line-profile width. For example, Giovanelli et al. (1997*a*) use *W*50, the width at 50% of the peak intensity as their definition of HI line-profile width, whereas conventionally *W*20 has been used in literature (e.g. Tully & Fisher (1977); Haynes et al. (1998)). Tully & Fouqué (1985) used a combination of *W*20 and *W*50 to calculate the HI line-profile width. No comprehensive model has been done to date to compare the differences between these methods.

- A standard and reliable inclination correction method has yet to be found. The most commonly used definition is:

$$\cos i = \sqrt{\frac{(\frac{b}{a})^2 - r_e^2}{1 - r_e^2}} \quad ,$$

with r_o being the axes ratio when edge-on, and *i* the inclination angle. However, Heidmann et al. (1971) suggest that r_o depends upon the morphological type *T* of a galaxy. Fouqué et al. (1990) use a similar variable r_o but their values are higher than the ones proposed by Heidmann et al. Giovanelli et al. (1997b) use r_o = 0.13 or 0.2.

- Improper corrections due to dust extinction effects, which depend not only on inclination but also on luminosity as demonstrated by Giovanelli et al. (1995)

Observations of Dust Attenuation in Spiral Galaxies

Extinction effects are normally detected as a decrease in flux along the line of sight. However, in certain configurations such as when the of disk galaxies are seen face on, a flux increase can be observed. This is because scattering can produce excess light along certain lines of sight. Extinction effects are quantified by defining attenuation as

$$A_\lambda = m_\lambda^o - m_\lambda = 2.5\mathrm{Log}(\frac{f_\lambda^o}{f_\lambda}) \quad ,$$

with m_0 and f_0 being the magnitude and the flux in the absence of dust respectively.

- Attenuation Dependence in Inclination

It has been found empirically (Tully et al. 1998; Giovanelly 1995) that the attenuation in Sipiral galaxies has a dependence on inclination that is linear in logarithmic space, adopting a function of the form

$$A_\lambda = \gamma_\lambda \log(\frac{a}{b}) \quad .$$

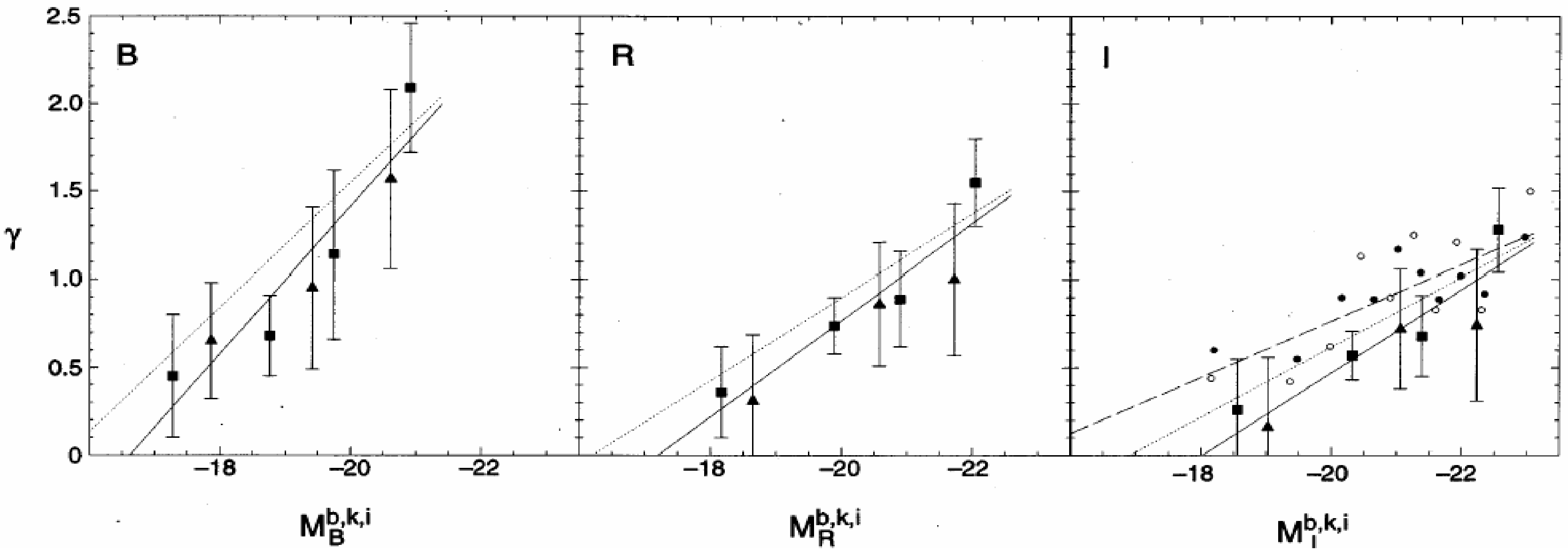
More recent studies (Masters et al. 2003) suggested that a simple value of γ, as defined in the above equation, wasn't adequate for describing the attenuation dependence on inclination for all values of log(a/b). Thus, Masters et al. (2003) adopted a bi-linear law fitting separately high and low inclinations systems as separated by log(a/b) = 0.5. Looking for less linear relations that
fitted their observation they also used quadratic expressions of the form

$$A_{\lambda\upsilon} = B_{\lambda\upsilon} + C_{\lambda\upsilon}\log(a/b) + D_{\lambda\nu}[\log(a/b)]^2$$

- Attenuation Dependence in Luminosity

It is expected that brighter galaxies will show more internal extinction at a given inclination than dimmer ones. This is due both to the increase in physical size (and thus optical path lengths) and to the increase in metallicity (and dust presumably dust content) in the more luminous galaxies.

Tully et al. 1998 found that γ increases linearly with luminosity, $\gamma \propto L$



Dependence of the extinction amplitude parameter γ on absolute magnitude. The Dashed line in the I panel is a least-squares fit to the Giovanelli et al. (1995) data. The solid lines in this and the other panels are least-squares fits to the data points of the present paper. The dotted line in the I panel gives equal weigh to the old and the new data. The dotted line in the B and R panels are offset from the solid lines by an amount corresponding to the offset of the dotted line from the solid line in the I panel. (Tully et al.1998)

Impact of Adopted Extinction Corrections on the TF Relation

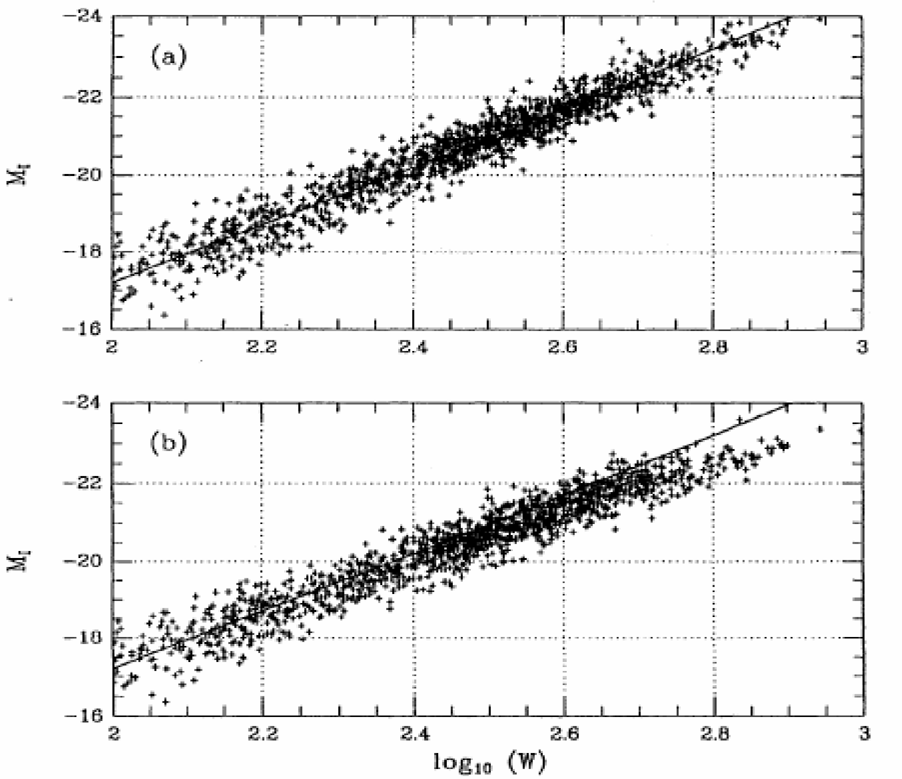


FIG. 9. Simulations of the TF relation, obtained following the prescriptions listed in Secs. 5.2 and 6.2. The sample was produced with an intrinsic TF relation which in each panel is represented by the solid straight line of slope −7.5. The scatter in the TF relation depends on log(W), as it usually does for real samples. The model sample is assumed to be well characterized by a luminosity dependent extinction relation as given by Eq. (8) and Fig. 7(c). Panel (a) displays the resulting TF relation when magnitudes have been corrected adequately via Eq. (8), with γ as given by Fig. 7(c); the slightly different slope between the simulated data and the input is due to a sample selection (Malmquist) bias. Panel (b) results from assuming an inadequate internal extinction relation: one with γ=0.4 for log(a/b)=0.75 and $m-m^0$=0.3 for log(a/b)>0.75. The latter produces a systematic underestimate of the total magnitude, especially severe at the bright end.

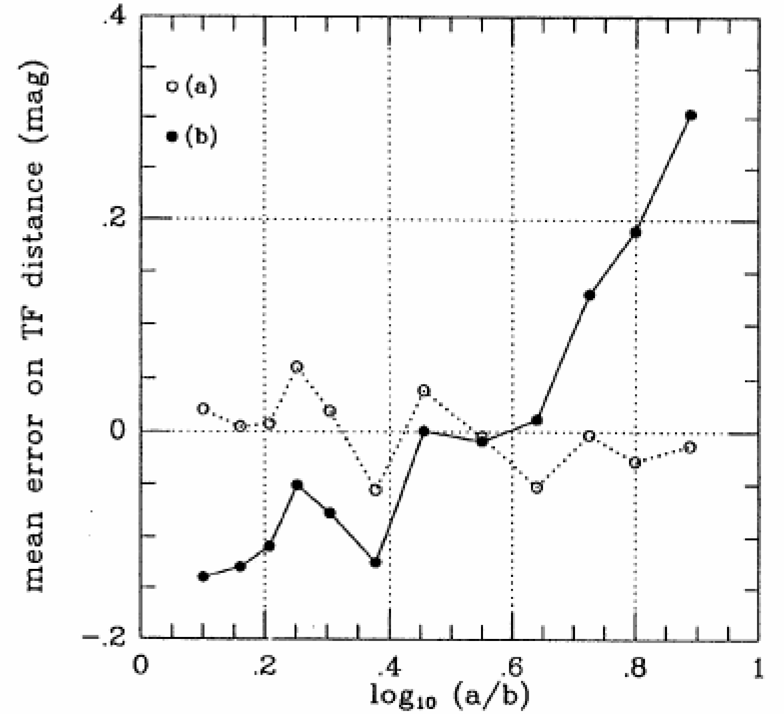


FIG. 10. The inclination dependence of the mean distances estimated using the TF relation, for the simulated sample displayed in Fig. 9, are shown. To each of the TF relations in Fig. 9, a linear law is fit; the residuals of those fits are then averaged in bins of increasing inclination. Unfilled circles refer to the predictions obtained from the relation in Fig. 9(a), while the filled symbols refer to predictions obtained from Fig. 9(b). The simulated sample contains no peculiar motions. An error of 0.3 mag is equivalent to 15% on the distance.

Giovanelli et al. (1995)

Simulations of Dust Attenuation in Spiral Galaxies

Understanding the behavior of dust extinction in spiral galaxies may not be an easy task.

That means that one may have to deal with a six-dimensional, sometimes nonlinear, integro-differential equations !!

$$\hat{\mathrm{k}} \cdot \Delta I_v = \epsilon_v - \rho \kappa_v I_v + \rho \kappa_v^{sca} \int \phi(\hat{\mathrm{k}}, \hat{\mathrm{k}}') I_v(\hat{\mathrm{k}}') d\Omega'$$

Where the dependent variable, $I_{v,}$, is the "specific intensity", defined by

$$dE = I_v(\hat{\mathrm{k}}, x, t)\hat{\mathrm{k}} \cdot d\mathrm{A}\, \mathrm{d}\Omega\, dt\, dv$$

Finding an Appropriate Metallicity Gradient

$g(r) = g^o e^{-\frac{r}{R_g}}$ and $s(r) = s^o e^{-\frac{r}{Rs}}$

$z(r) = z^o 10^{-G\,r}$ (Zaritsky et al. 1994)

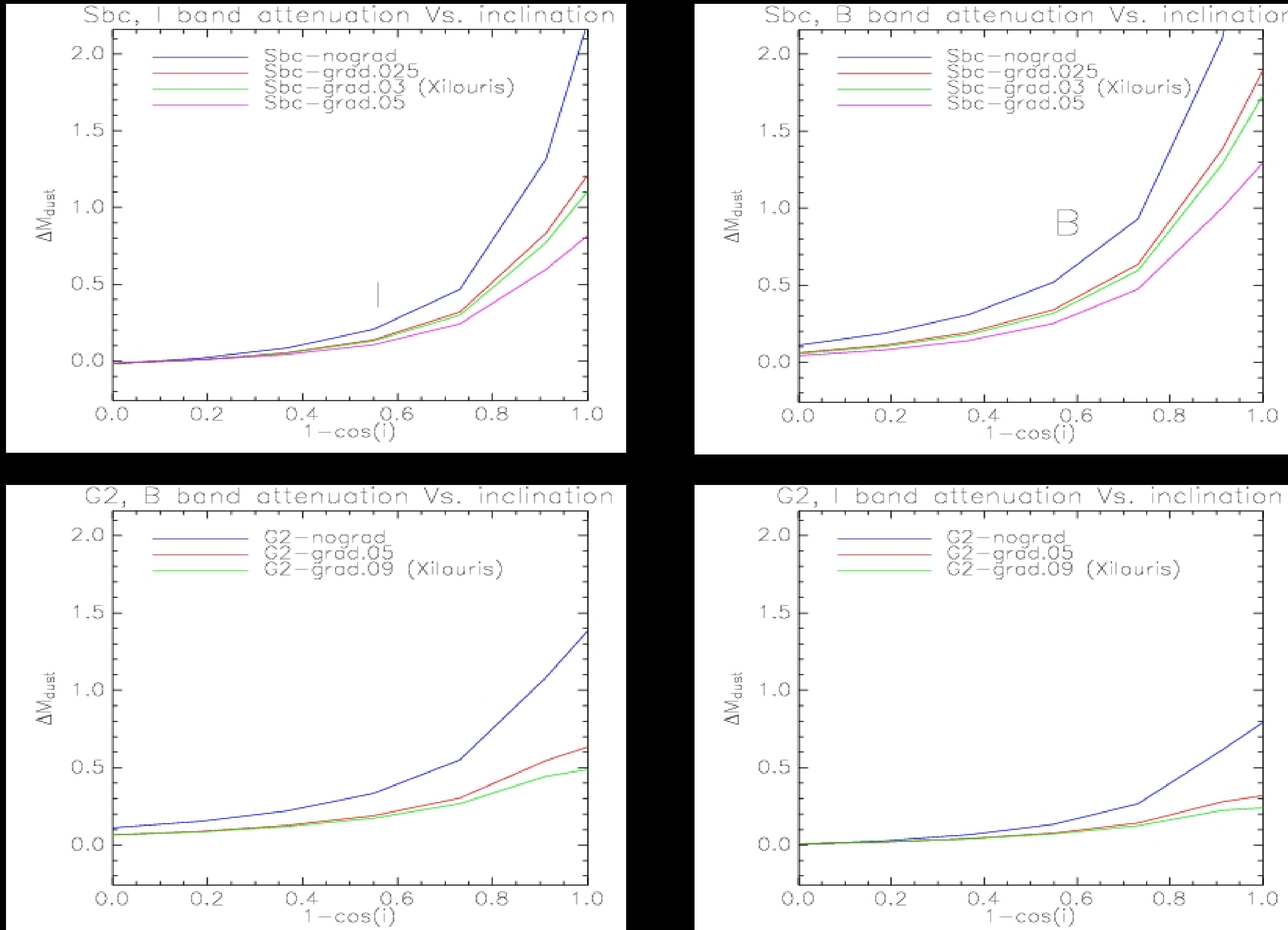
d $\cong$ 0.4 z (Dwek et al. 1998)

$$d(r) \propto g(r) z(r) \propto e^{-\frac{r}{R_g}} 10^{-G\,r} = e^{-\frac{r}{R_d}}$$

Rd=1.4 Rs (Xilouris et al. 1999)

Rg = constant Rs

G= 0.03 kpc^{-1} for the Sbc model

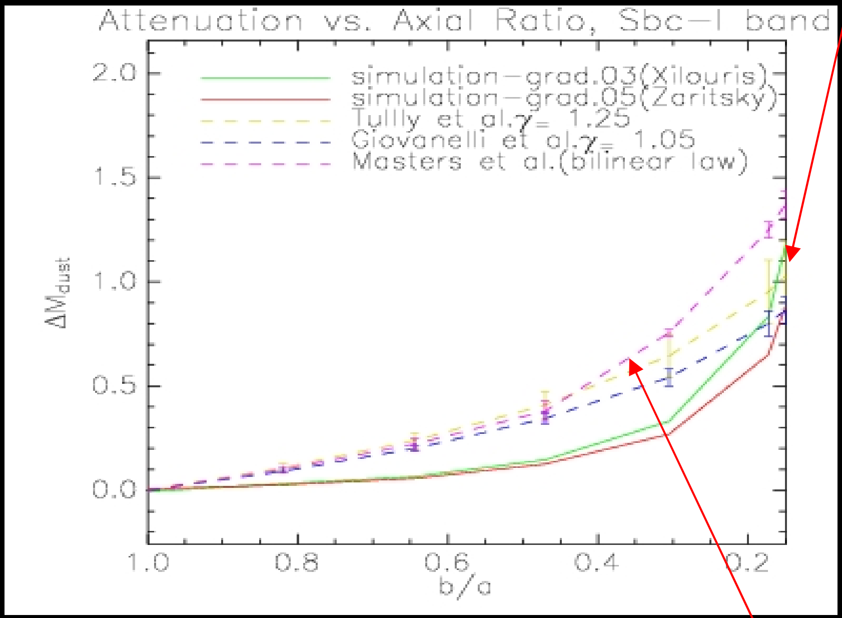


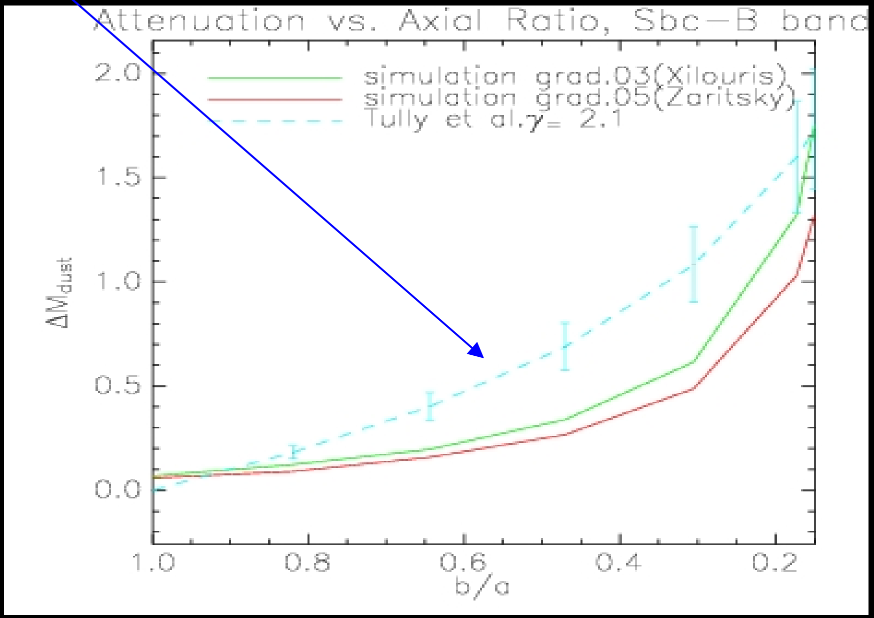
Attenuation against inclination when different metallicity gradients are assumed in two different galaxies, a big Sbc (top) and a smaller spiral (bottom)

Comparison with Observations

Linear

$$A_\lambda = \gamma_\lambda log(\frac{a}{b})$$



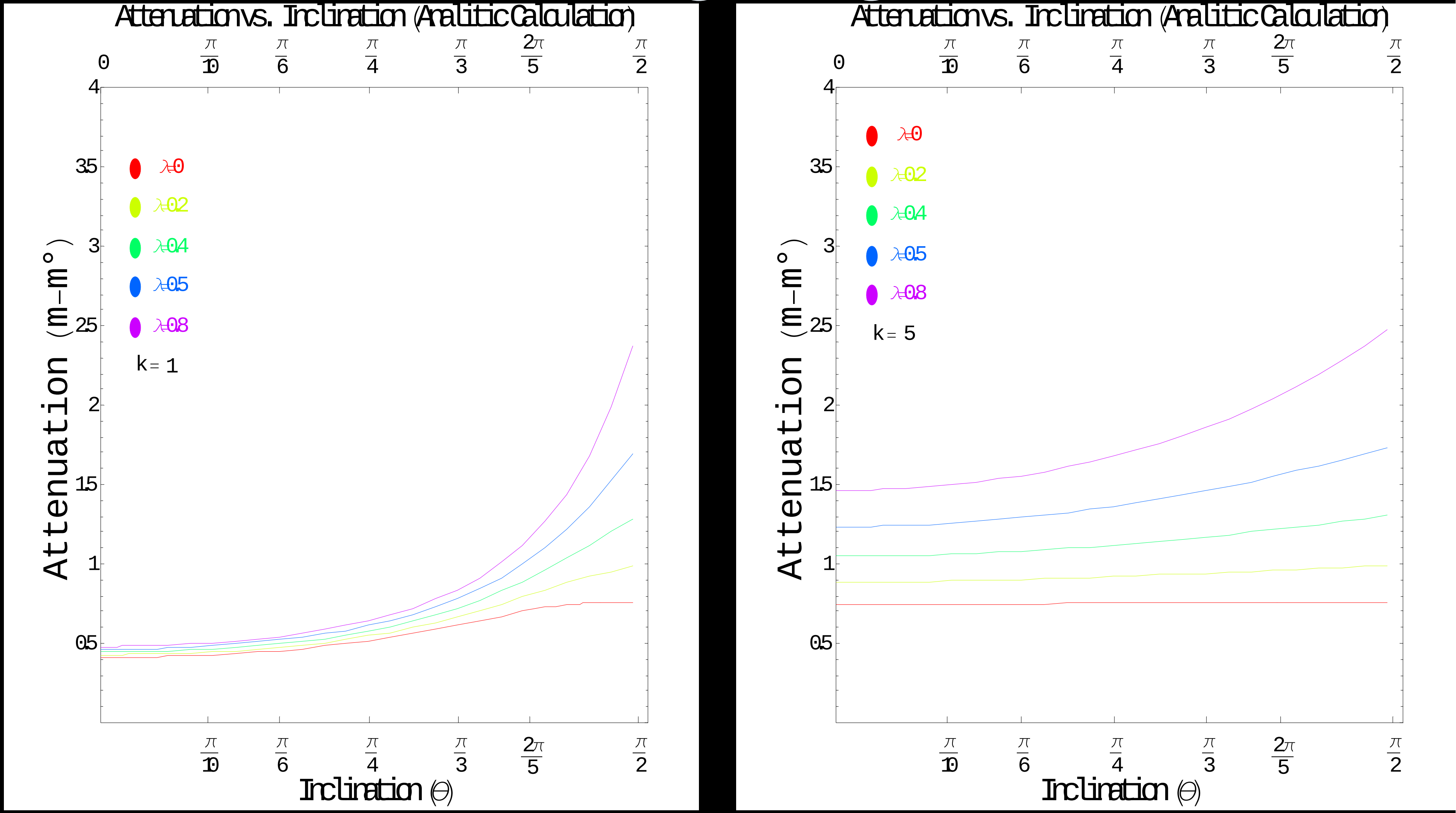


Bi-linear

γ = 0.9 + 0.26 ± 0.15 if log(a/b) < .5

1.1 ± 0.13 if log(a/b) > .5

What is going on?

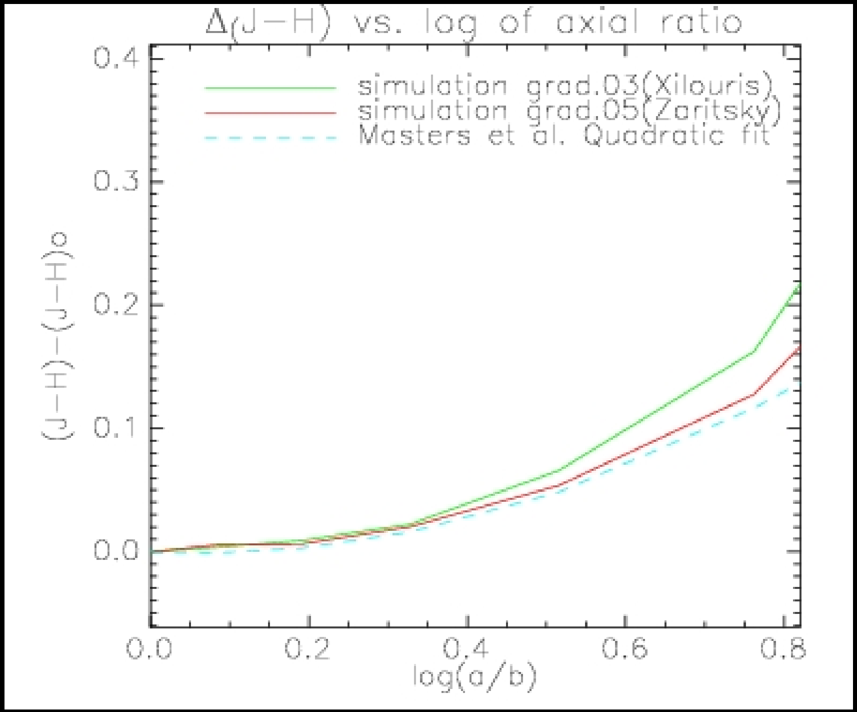


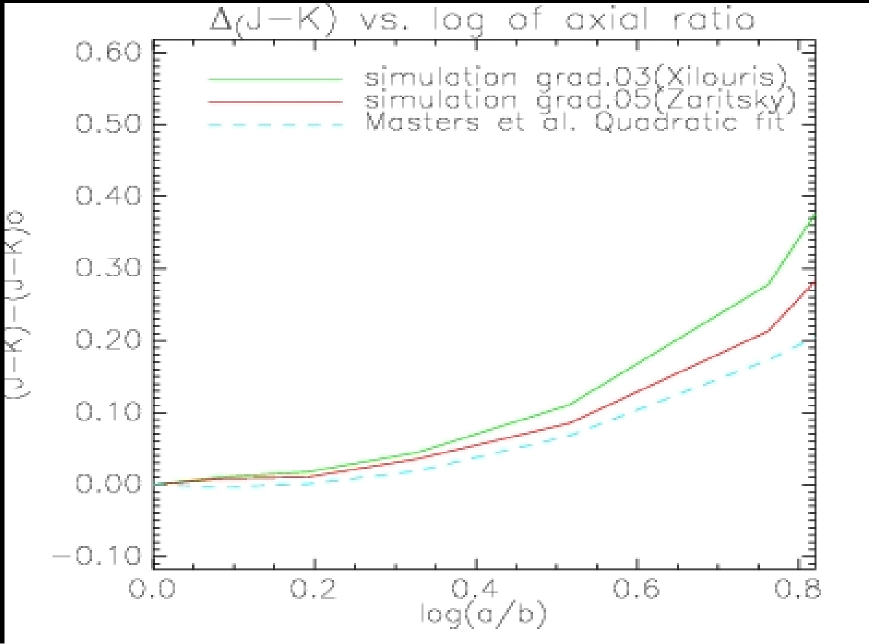
Analytical results of the attenuation dependence on inclination for an infinite slab of stars and dust inside an infinite slab of just stars. λ is equal to the rate between the slab with dust and the slab without dust, k is the total opacity of the system.

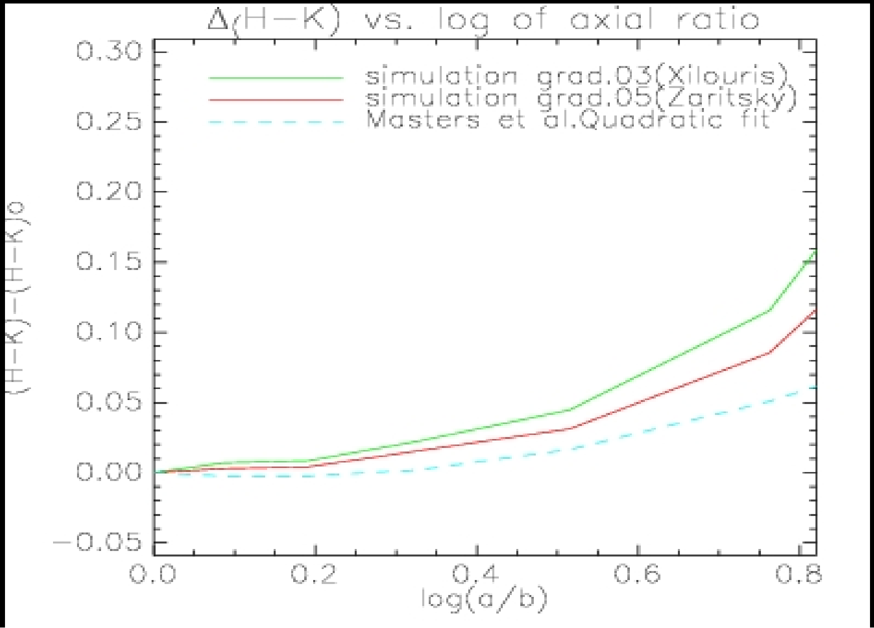
Quadratic fit

$$A_{\lambda\upsilon} = B_{\lambda\upsilon} + C_{\lambda\upsilon}\log(a/b) + D_{\lambda\nu}[\log(a/b)]^2$$

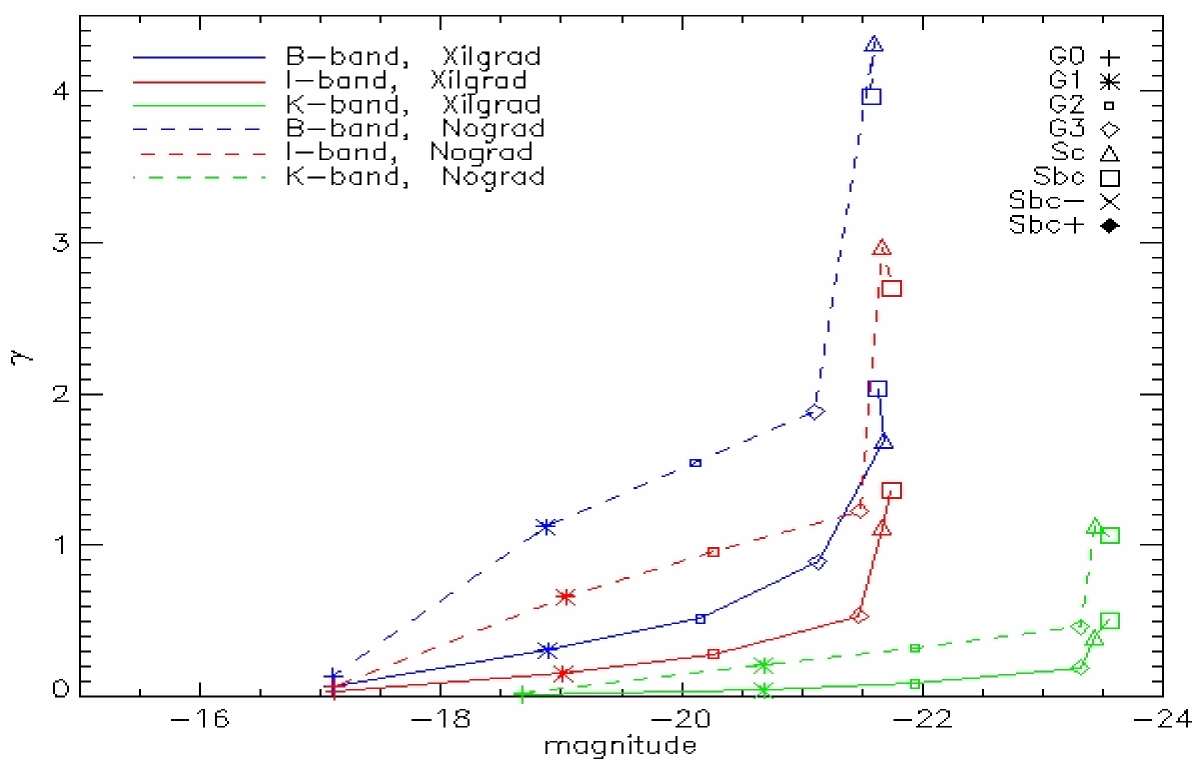
Masters et al. (2003)







Luminosity Dependence on inclination



Dependence of the extinction amplitude parameter γ on absolute magnitude in our simulations. Solid lines represent the values obtained with the Xilouris gradient, whereas dashed lines represent the values obtained with no-gradient.