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The $V_c - \sigma_0$ relation of galaxies

Stéphane Courteau, Michael McDonald and Lawrence M. Widrow

Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario, Canada
email: courteau,mcdonald,widrow@astro.queensu.ca

Abstract. Courteau *et al.* (2007a) reported on the dependence of the ratio of a galaxy's maximum circular velocity, V_c, to its central velocity dispersion, σ_0, on morphology, or equivalently total light concentration. This $V_c - \sigma_0$ −concentration relation, which involves details about the local and global galaxy physics, poses a fundamental challenge for galaxy structure models. Furthermore, not only must these models reproduce the $V_c - \sigma_0$ relation and its various dependences, they must simultaneously match other fundamental scaling relations such as the velocity-size-luminosity and color-luminosity relations. We focus here on the interpretation of parameters that enter the $V_c - \sigma_0$ relation to enable proper data-model comparisons and follow-up studies by galaxy modelers and observers.

Keywords. galaxies: fundamental parameters, galaxies: kinematics and dynamics

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1. Introduction

The $V_c - \sigma_0$ relation is of great interest for galaxy structure models since it links two quantities that depend separately on global and local physics. The galaxy circular velocity, $V_c = \sqrt{GM(r)/r}$ where $M(r)$ is the total mass within r of the center, is directly related to the total mass of the galaxy whereas the central velocity dispersion, σ_0, is a measure of the local central potential. These two quantities could in principle be independent. It is well known that the brightest, bulge dominated (E, S0, and some Sa), galaxies obey closely the relation $V_c = \sqrt{2}\sigma_0$ expected for isothermal gravitational systems (Whitmore *et al.* 1979; Courteau *et al.* 2007a; Ho 2007). The lower surface brightness regime, dominated by later-type spiral and dwarf galaxies, however departs from the isothermal solution and the ratio V_c/σ_0 here scales with surface brightness (Pizzella *et al.* 2005; Buyle *et al.* 2006; Courteau *et al.* 2007a; Ho 2007) or, equivalently, total light concentration or morphological type. The correlation between concentration index and Hubble type is discussed by Strateva *et al.* (2001) in the context of SDSS galaxies. Figure 1 encapsulates the dependence of the $V_c - \sigma_0$ relation on the galaxy Hubble type. The current data (see Courteau *et al.* 2007a for details) show that $V_c \approx 5\sigma_0$ for dIrr galaxies suggesting that these galaxies live in very dominant dark matter halos.

In order to understand and, ideally, model the values of V_c and σ_0 and their dependence on each other, we must pay close attention to their precise definition and how they are being measured.

2. Data

Measurements of the circular velocity V_c differ for gas-rich and gas-poor systems. For the former, V_c is often estimated to be the maximum deprojected orbital velocity, V_{max}, usually measured from emission lines. This is marginally correct so long as $r(V_{max})$ lies beyond the radius where non-circular velocities from asymmetric drift are dominant; for bright spiral galaxies, that radius can be as small as two disk scale lengths (e.g. Courteau

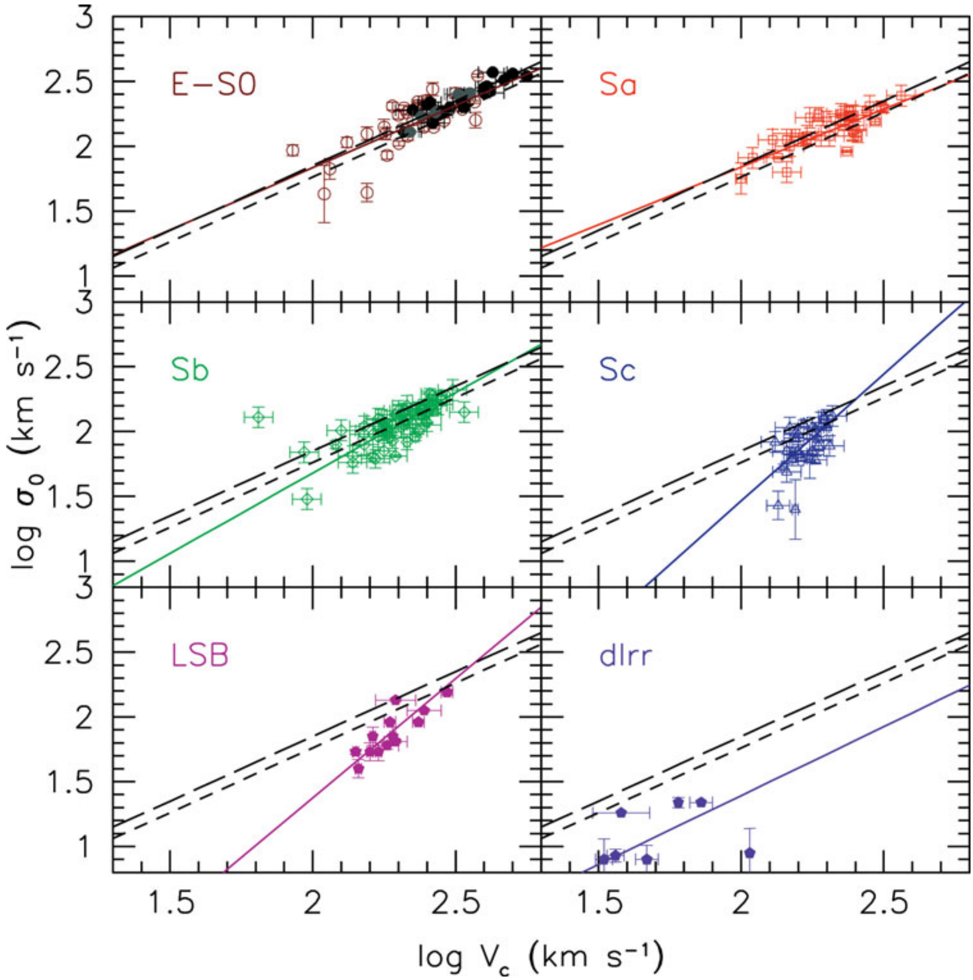

Figure 1. $V_c - \sigma_0$ relation for galaxies of different Hubbles types. The long and short dashed lines represent the $V_c = \sqrt{2}\sigma_0$ and $V_c = \sqrt{3}\sigma_0$ solutions respectively. The solid and open circles in the upper left panel represent E and S0 galaxies, respectively. Galaxies with lower surface brightnesses depart progressively from the nominal $V_c = \sqrt{2}\sigma_0$ solution for isothermal systems, as gauged by the Sc and LSB galaxies. Taken at face value, the $V_c - \sigma_0$ measures for dIrr galaxies suggest that these galaxies live in very dominant dark matter halos.

et al. 2003; Spekkens & Sellwood 2007) but it rises to more than three disk scale lengths at lower surface brightnesses (Rhee *et al.* 2004; Valenzuela *et al.* 2007). Neglect of this effect can have nefarious consequences on estimates of V_c. The measurement of V_c for gas-poor (spheroidal) galaxies is inferred via non-parametric dynamical modeling of the absorption line features and surface brightness profiles of these galaxies (Gerhard *et al.* 1998; Kronawitter *et al.* 2000; Gerhard *et al.* 2001; Cappellari *et al.* 2006).

The one-dimensional line-of-sight (projected) central velocity dispersion, σ_0, is measured from selected absorption lines (e.g. Lick indices) typically within the central 1″ or the radius corresponding to the slit width. A theorist would estimate σ_0 first by building a model for the phase space distribution function (DF) of the stars and then integrating over the DF (see Binney & Tremaine 1987, Eq. 4-57). Alternatively, one can generate an N-body representation of the galaxy from the DF and calculate the rms velocity along

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a given line of sight within a "beam" whose width is chosen to match that of the observations. This N-body representation provides a suitable starting point for numerical simulations to study the formation of bars and bulges which in turn can affect σ_0.

Various observers correct σ_0 to a standard aperture of $r_e/8$, where r_e is the effective radius of the galaxy spheroid (e.g. Jorgensen *et al.* 1995; Cappellari *et al.* 2006; MacArthur *et al.* 2007). This definition is however awkward for disk dominated systems with a bulge as r_e cannot be uniquely determined. Fortunately, aperture effects may be small (Pizzella *et al.* 2004) and the correction to σ_0 for aperture size is here neglected. σ_0 is therefore measured the same way for high and low surface brightness galaxies. Two other effects may bias the determination of σ_0: net rotation of the bulge and contamination from the (largely rotating) disk. The latter has been verified to be small, even in late-type spirals (Pizzella *et al.* 2004). The rotation of the bulge can be estimated on a case-by-case basis and while most studies thus far have found little angular momentum in galaxy bulges more research on this topic, with the largest possible telescopes or numerical simulations, is called for. Thus, much like Gebhardt *et al.* (2000), our aperture dispersions include a contribution from rotationally supported material (i.e., the rms velocity is measured relative to the systemic velocity, not relative to the local mean velocity). The measured dispersion also depends on the inclination of the galaxy; this can be estimated in principle by the strength of the stellar rotation.

V_c and σ_0 are linked, as in Courteau *et al.* (2007a) and Ho (2007), by concentration (figures not shown here). Our data base includes the concentration measure $C_{28} = 5\log(r_{80}/r_{20})$ where r_{80} and r_{20} are the radii measured at 80% and 20% of total light. Theory suggests that V_c/σ_0 is controlled by the degree of compactness of a galaxy as measured either by morphology, B/T, surface brightness, concentration, etc. (Courteau *et al.* 2007a; Peñarrubia *et al.* 2007). A significant advantage of concentration is its non-parametric definition, independence of photometric calibration, and weak dependence on inclination. Concentration indices however depend on the photometric bands and our data base uses SDSS i-band images.

It should be noted that Ho (2007) recently used integrated 21cm line widths and central velocity dispersions from HyperLeda and SDSS for 792 galaxies spanning a broad range of Hubble types to reproduce the results presented in Courteau *et al.* (2007a). His concentrations used a ratio of SDSS i-band Petrosian radii enclosing 90% and 50% of the light. There is global agreement between the two concentration measures of Courteau *et al.* (2007a) and Ho (2007) albeit with noticeable scatter. In spite of these concerns and differences in the global samples and data products, the complimentary studies of Courteau *et al.* (2007a) and Ho (2007) come to close agreement about the dependence of the ratio V_c/σ_0 on concentration.

Nonetheless, in order to reproduce Fig. 1 and the overall $V_c - \sigma_0-$concentration relation of galaxies, especially from theoretical/numerical stand-points (which we have no room to discuss here but see Courteau *et al.* 2007a for an introduction), care must be taken to use quantities as defined above. Our complete data compilation is available at www.astro.queensu.ca/∼courteau/data/VSigmaC28.dat.

3. Further developments

Models of galaxy structure ought to reproduce the $V_c - \sigma_0$ relation and its dependence on concentration, in addition to matching other basic scaling relations of galaxies such as the velocity-size-luminosity relations reported in, for instance, Gnedin *et al.* (2006), Courteau *et al.* 2007b and Dutton *et al.* (2007). Matching these relations at different wavebands, and thus accounting for the color-luminosity relation of galaxies, is another formidable challenge.

One must bear in mind that the data reported here, as well as in Ho (2007), come from widely heterogeneous data bases. While homogenization has been optimised, there is still no substitute to perfectly homogeneous data by design and we urge the community to invest in long-term dedicated surveys of kinematic parameters for galaxies of all types. Only with well-understood dynamical measurements can we construct a complete and robust picture of dynamical evolution of galaxies ranging from the central supermassive black holes and nuclear star clusters to the largest halo structures in galaxies.

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