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The $M_\bullet - \sigma_*$ project

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Abstract. There is an intimate link between supermassive black hole (SMBH) mass ($M_\bullet$) and the stellar velocity dispersion (σ_*) of the host bulge. This has a fundamental impact on our understanding of galaxy and SMBH formation and evolution. However, the scatter, slope and zero-point of the relation is a subject of some debate. For any progress to be made on this relation, the established values of $M_\bullet$ and σ_* must be robust. Over 50% of current $M_\bullet$ estimates have been made using the technique of stellar dynamics. However, there is serious concern over this method that prompts their re-evaluation. In addition, it is not clear how best to define σ_*. The aim of the $M_\bullet - \sigma_*$ Project is to use STIS long-slit spectroscopy, integral field spectroscopy and the latest stellar models, to best estimate the values of $M_\bullet$ and σ_* in as many cases as possible. The project will determine the most appropriate properties of the $M_\bullet - \sigma_*$ relation itself.

Key words. Galaxies: bulges – Galaxies: Evolution – Galaxies: kinematics and dynamics – Galaxies:

1. Introduction

The discovery of the relationship between supermassive black hole (SMBH) mass ($M_\bullet$) and the stellar velocity dispersion (σ_*) of the host bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000) signaled a new and fundamental understanding on the nature of black hole and galaxy formation and evolution; the $M_\bullet - \sigma_*$ relation intimately links the most basic characteristic of a SMBH with an underlying dynamical property of the surrounding galaxy. Consequently, the $M_\bullet - \sigma_*$ relation, that is typically described by $\log M_\bullet = \alpha + \beta \log(\sigma_*)$, has received an extraordinary amount of attention.

The $M_\bullet - \sigma_*$ relation is a member of a family of scaling relations all linking $M_\bullet$ to various properties of the host bulge, and possibly the entire gravitational mass of the host galaxy. For a comprehensive review of all the scaling relations see Ferrarese & Ford (2005). Despite all these other relations, $M_\bullet - \sigma_*$ has traditionally been the preferred as, at its time of discovery, it showed a remarkably small scatter; a smaller scatter than for the other scaling relations and a scatter consistent with the measurement errors alone. Since then, however, Marconi & Hunt (2003) and Graham (2007) have shown that with enough care, scaling relation scatters can be comparable especially when using near-infrared luminosities. Regardless of which scaling relation is "best", it is important to fully investigate them all as the intrinsic scatters themselves contain pivotal information on the precise inter-play between SMBHs and their hosts.

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Reproducing the features of the $M_\bullet - \sigma_*$ relation has become an integral part of SMBH and galaxy formation and evolution models. The relation also has several other significant applications. For example, the $M_\bullet - \sigma_*$ relation may be extrapolated to smaller and larger values of $M_\bullet$, and be used to estimate $M_\bullet$ in systems where the black hole sphere of influence radius (r_h) cannot be resolved. It is therefore especially important to know the values of α and β, and their associated scatters, to high accuracy. To have doubt in either parameter is to introduce large uncertainties in extrapolated values of $M_\bullet$. This in turn has a fundamental impact on our understanding of both black hole and galaxy formation and evolution.

2. The $M_\bullet - \sigma_*$ relation

The $M_\bullet - \sigma_*$ relation has had many attempts to fit its slope, zero-point and scatter to the whole galaxy population (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001; Tremaine et al. 2002) in addition to individual families of galaxies that potentially lie off the relation (e.g. Wang & Lu 2001; Mathur & Grupe 2005; Komossa & Xu 2007). So far, these individual fits have produced considerably different results (β ranges from 3.8 to 4.9, for example). To demonstrate what affect these uncertainties have on the importance of the $M_\bullet - \sigma_*$ relation, we have used the direct $M_\bullet$ and σ_* data compiled recently by (Ferrarese & Ford 2005, Table 2) to construct Figure 1. The fit of Tremaine et al. (2002) is also plotted as these values are typically used by many authors. Taking $\sigma_* = 20\mathrm{km\,s^{-1}}$ (a large globular cluster) the two slopes predict $\log M_\bullet = 4.11 M_\odot$ or $\log M_\bullet = 3.36 M_\odot$. Taking $\sigma_* = 470\mathrm{km\,s^{-1}}$ (a brightest cluster galaxy) the two slopes predict $\log M_\bullet = 9.62 M_\odot$ or $\log M_\bullet = 10.02 M_\odot$.

The aim of the $M_\bullet - \sigma_*$ Project is to produce the most reliable estimate of the $M_\bullet - \sigma_*$ relation to date. It will couple ground-based integral field spectroscopy (IFS) with high spatial and spectral resolution data, from the STIS archive, to estimate $M_\bullet$ in a large sample of galaxies using the latest three-integral, axisymmetric, orbit-based stellar dynamical models.

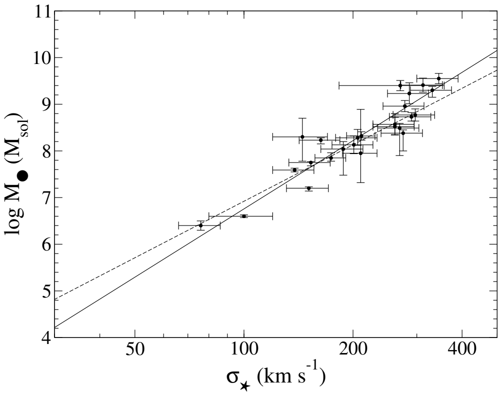

Fig. 1. The $M_\bullet - \sigma_*$ relation (where r_h is resolved) using the Ferrarese & Ford (2005) (β = 4.86, solid line) and Tremaine et al. (2002) (β = 4.02, dashed line) fits.

The project will also examine the accurate determination of σ_* within the host bulges. In addition, the project will identify and address several key issues that surround the uncertainties in determining α and β.

2.1. Estimating $M_\bullet$

Four methods have been used to *directly* estimate the values of $M_\bullet$ defining the $M_\bullet - \sigma_*$ relation. Proper motions have been used in the Milky Way (Genzel et al. 1997; Ghez et al. 2005) and $H_2 0$ masers have been used to estimate $M_\bullet$ in NGC 4258 (Miyoshi et al. 1995). All other estimates have been made using gas and stellar dynamics. Gas dynamics (e.g., Ferrarese et al. 1996; Marconi et al. 2001), are relatively easy to model as long as the nuclear disk is completely dominated by the gravitational potential of the SMBH. Stellar dynamics (e.g., van der Marel 1994; Verolme et al. 2002; Gebhardt et al. 2003), does not suffer from this problem, but is a more complex method that requires a high sensitivity instrument. It is difficult to judge the consistency between estimates made by each method as very few galaxies have been modeled by more than one method.

Given a sufficiently sensitive instrument, and a sufficiently elaborate model, then stellar dynamics is the preferred method for determining $M_\bullet$. Indeed, to date 57% of direct $M_\bullet$ estimations have been made using stellar dynamics; it is the dominant method defining the $M_\bullet - \sigma_*$ relation. Valluri et al. (2004) provide a detailed description of an orbit-based model designed to recover the gravitational potential of a system using stellar kinematics. They carry out detailed analytical testing of this model as applied to a dataset from M32. Valluri et al. (2005) apply the same model to constrain $M_\bullet$ in NGC 205. It is found that a large range in $M_\bullet$ gives equally acceptable fits. The degeneracy in the solution is a function of the number of orbits used in the models and the number of constraining data points.

As M32 and NGC 205 are the only datasets for which χ^2 space in stellar dynamical models has been explored in detail, it is clear that the dominant mass estimates within the current $M_\bullet - \sigma_*$ relation may include un-investigated issues that could have a fundamental impact on our understanding of the relation itself. The $M_\bullet - \sigma_*$ project will address these issues in two key ways. Firstly, it will use a wide range of constraining data points by employing IFS. Secondly, it will serially reduce a large family of dynamical models, that have a wide range of total orbit numbers, on a high performance computing cluster with a large node number.

It has been repeated by many authors (Ferrarese 2002; Marconi & Hunt 2003; Valluri et al. 2004) that resolving r_h (given by $GM_\bullet/\sigma_*^2$) is a minimum requirement for detecting a SMBH. If r_h is un-resolved then estimates of $M_\bullet$ can be tarnished by uncertain contributions from stellar masses. The derivation of r_h was first attempted by Peebles (1972) based on the ad hoc assumption that in a steady state the stellar density is exponentially linked to the total gravitational potential and that σ_* is constant. The black hole removes stars at small radii (via accretion or ejection, for example) and disrupts this equilibrium. The steady state is restored via an increase in σ_* of stars brought in from larger radii.

Although the requirement to resolve r_h has been thoroughly argued it must be noted that this creates a somewhat degenerate problem; you are forced to make an assumption about SMBH demographics (i.e., that they follow the $M_\bullet - \sigma_*$ relation) in order to deduce whether you can detect that SMBH in the first place. Furthermore, you are using the very parameters in the $M_\bullet - \sigma_*$ relation in the calculation of r_h. Nevertheless, with the assumption that SMBHs do follow the $M_\bullet - \sigma_*$ relation, we can plot r_h within the $M_\bullet - \sigma_*$ plane. In addition, we can determine the ability of *HST*, from which most $M_\bullet$ estimates are derived, to resolve r_h at a specific distance (Fig 2).

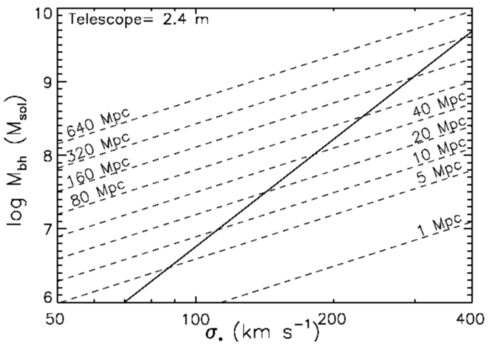

Fig. 2. The ability of *HST* to resolve r_h. Above the dashed lines r_h is resolved and $M_\bullet$ estimates can be made.

Two key points are associated with Figure 2. Firstly, it does not include the sensitivity, and therefore the SMBH detection efficiency, of the telescope. The relatively small aperture of *HST* ensures that many STIS orbits are required before a sufficiently large continuum signal-to-noise is reached for stellar dynamical studies. Secondly, it shows that even at 16 Mpc *HST* is unable to explore a significant area of the $M_\bullet - \sigma_*$ plane (below the dashed lines). If there were a population of bona-fide under-massive black holes, as suggested by Volonteri (2007) for example, *HST* would not be able to detect them; they would not be modeled and the $M_\bullet - \sigma_*$ relation would still remain to appear universal. In short, *HST* has a SMBH "blind spot". To unequivocally define the $M_\bullet - \sigma_*$ relation the entire $M_\bullet - \sigma_*$ plane needs to be detectable over a large enough distance to include a large population of host galaxies.

2.2. Estimating σ_*

One of the problems associated with the fitting of the $M_\bullet - \sigma_*$ relation concerns the values of σ_* used. Ferrarese & Merritt (2000) transformed σ_* to an aperture of $r_e/8$, where r_e is the host effective radius, while Gebhardt et al. (2000) use a value weighted by the host luminosity. The use of different values is understandable considering there is, as yet, no clearly defined aperture size through which σ_* should be determined.

When considering the nature of a LOSVD, the second order of which is usually described as σ_*, one can see that the size and nature of the aperture through which the LOSVD is collected has a fundamental bearing on its observed shape. In addition to the intrinsic variation of σ_* with aperture size (Batcheldor et al. 2005), a velocity field across the aperture will rotationally broaden the LOSVD as a function of the aperture diameter. This will produce an over estimate of the intrinsic σ_*. In the case of an axisymmetric velocity field, the aperture shape and orientation will also have a bearing; a different value of σ_* will be derived from, for example, a long-slit aligned along the major or minor axis of rotation. IFS can be used to address these concerns.

3. Summary

The $M_\bullet - \sigma_*$ relation is one of the most valuable correlations in modern galaxy and SMBH formation and evolutionary models. There are, however, concerns in the ways both σ_* and many $M_\bullet$ estimates have been determined. The latest stellar dynamical models have shown that great care must be used to fully explore χ^2 space around $M_\bullet$. It is essential that r_h is fully resolved, that there are large number of high quality constraints, and that a large variety of orbit families are employed in the models. The most appropriate values of σ_* may not have been determined as it has yet to be clearly defined. STIS long-slit, and integral field spectroscopy can be used to address all these issues and will lead to the most accurate form of the $M_\bullet - \sigma_*$ relation to date.

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