Measuring the mass of high-\(z\) galaxies with NGST

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Abstract. We discuss dynamical mass measurements of high-\(z\) galaxies with the Next Generation Space Telescope (NGST). In particular, we review some of the observational limits with the current instrument/telescope generation, we discuss the redshift limits and caveats for absorption and emission lines studies with NGST, and the existence of suitable targets at high redshift. We also briefly summarize strengths and weaknesses of proposed NGST instruments for dynamical studies.

1 Introduction

During this meeting we have heard of mass measurements at redshifts that were out of the realm of possibilities just a few years ago. However, several obstacles stand between us and the future when dynamical mass measurements will be routinely feasible at \(z > 1\). Among them, the lack of spatial resolution and the atmospheric emission/absorption at infrared (IR) wavelengths (see e.g. the contribution by M. Franx). The Next Generation Space Telescope (NGST) – with its unique combination of large collecting area, superb spatial resolution, and low background – will provide a major contribution to the extension of mass measurements at \(z > 1\).

Here we discuss mass measurements with NGST, focusing on dynamical measurements (lensing and stellar mass measurements are discussed elsewhere in these proceedings, see e.g. the contribution by H. Ferguson). As for any dynamical mass measurement, a spatial scale and a velocity scale are needed. In the following, we will assume that spatial scales are easily measurable even though this is not the case for sub-galactic clumps at very high redshift. Our focus in this contribution will be on emission and absorption line measurements (Sec. 2 and 3) of velocity scales. In particular, we will briefly review the limits of what is feasible with the current technology and present some detailed simulations on the capabilities of NGST for mass measurements. Finally, we will discuss the implications of the choice of NGST-instrumentation for mass measurements.

2 Emission Line Measurements

Kinematical measurements based on emission lines are easy to carry out but hard to interpret. This is because the gas may be far from equilibrium and thus gas kinematics may not be telling us anything about the mass of the host galaxy. One
way to overcome this difficulty is to have access to two-dimensional kinematical information and this is indeed what was needed to solve the same problem in the context of mass measurement in nearby spiral galaxies using HI and black hole mass measurements from the kinematics of nuclear gas disks. NGST presents several advantages in this context because of its high angular resolution. Its uninterrupted wavelength coverage guarantees that strong emission lines will be available over a large range of redshifts. The low background redwards of 2.5 \( \mu \text{m} \) will guarantee high sensitivity for measurements using H\( \alpha \) at \( z \geq 3 \). On the basis of the visibility of H\( \alpha \) one can argue that for objects at \( z \leq 3 \) a detailed 2D kinematic mapping can be carried out from the ground using an adaptive optics fed integral field spectrograph on an 8-meter class telescope. At \( z \geq 3 \) oxygen lines are still accessible from the ground but may be suppressed by the expected low metallicity of most objects at that redshift. Thus, the availability H\( \alpha \) and the sensitivity of NGST make it the ideal instrument at \( z \geq 3 \).

In addition to the availability of lines another issue is the resolving power needed to carry out a measurement. In a nutshell, faint galaxies will on average have lower mass and smaller internal velocities, requiring higher resolving power to be studied. Since on average we expect galaxy mass to decrease with redshift, one will need progressively higher resolving power to study galaxies at increasingly high redshift. This intuitive result is illustrated in Figure 1 where we show, in the left panel, simulated NGST spectra for a typical Milky Way progenitor (OBJ=13) at \( z=3, 5, \) and \( 7 \) and for a bright Milky Way progenitor (OBJ=9) at \( z=7 \). These models have been obtained with a merging tree code. The resolving power needed to measure internal kinematics is in the range 6,000 to 20,000 for \( z \leq 3 \) and 7,000 to 50,000 for \( z \geq 3 \). The right panel shows the correlation between available resolving power and maximum redshift for which a detailed mapping of the internal kinematics of a spiral galaxy can be resolved. For relatively large objects at high redshift NGST is superior to even a 30m ground based telescope.

Fig. 1. Left panels: simulated spectra for the typical (OBJ=13) Milky Way progenitor and for the brightest (OBJ=9) Milky Way progenitor. Resolving powers in excess of 6,000 are needed for \( z \geq 3 \) even for the most massive progenitors of L* galaxies. Right panel: correlation between available resolving power and maximum redshift for which a detailed mapping of the internal kinematics of a spiral galaxy can be resolved. For relatively large objects at high redshift NGST is superior to even a 30m ground based telescope.
16,000. In the right panel we show a relation connecting the available resolving power to the highest redshift that can be probed. This plot has been obtained by assuming the validity of the Tully-Fisher relation and by requiring that for the given exposure time and resolving power sufficient signal-to-noise is achieved to carry out the measurement. The optimal emission lines is used for each redshift. It is clear that for low mass objects NGST is not competitive with large ground based telescopes. However, NGST is superior to 30m class ground based telescopes for massive objects at $z > 2$.

**Fig. 2.** Absorption line dynamics at $0.1 < z < 1$, ground-based limits: evolution of the Fundamental Plane of E/S0 galaxies from $z = 0.8$ to $z = 0$ (from [17]). The average offset of the intercept of field galaxies from the local FP relation as a function of redshift (large filled pentagons), is compared to the offset observed in clusters (open squares). See [17] for references, description, and details.

### 3 Absorption Line Measurements

Stellar absorption lines are a very good probe of velocity scales for several reasons: i) a large fraction of galaxies do not have emission lines, and therefore absorption lines are the only way to go; ii) stars are a good tracer of the velocity distribution of the system, as opposed to emission lines coming from HII regions which might not be in dynamical equilibrium with the galaxy; iii) stellar absorption lines kinematics tend to suffer less from the effects of interstellar absorption, local motions, and winds then emission lines kinematics; iv) if streaming motions are not significant as in massive E/S0 galaxies, interesting dynamical constraints can be gathered without the need for spatially resolved information.

However, stellar absorption lines have to be present, and stellar populations need to be in dynamical equilibrium, in order to obtain meaningful information.
Typical optical absorption lines (e. g. the Mg triplet) need of order $\sim 1$ Gyr to develop in stellar populations, while the time scales can be relatively shorter for other frequently used lines such as the near-IR Ca triplet. On the one hand this is good, because it guarantees that if such lines are present then the stellar populations are almost certainly old enough that the system is in equilibrium. On the other hand, it is worth asking the question of whether systems with stellar absorption lines exist at high redshift. In the following we will illustrate with a few examples the current limits of ground based measurements, we will show why we believe there are interesting targets beyond these limits, and we will explore the feasibility of such measurements with NGST.

Recent studies of the evolution of the Fundamental Plane (FP) with redshift show that E/S0 galaxies do not undergo major structural changes from $z \sim 0.8$ to the present (e. g. [20,16,17]). Such measurements, based on a combination of spectroscopy (velocity dispersion) and imaging (photometric structural parameters) provide important information on the evolution of the internal structure of E/S0 galaxies and their stellar populations (see also the contribution by G. Illingworth). For example, [20] inferred from the evolution of the FP that cluster E/S0 have old stellar populations, while [17] used this technique to show that secondary episodes of star formation are common in massive field E/S0 at $z \sim 0.5$. It would be interesting to extend such measurements to higher redshifts, where we know that some old E/S0 exist, at least in the range $z = 1-2$ ([3,18,11]; see Figure 3). However, long integrations on large telescopes are needed to push such studies significantly beyond $z \sim 1$ because E/S0 become very faint in the optical and sky emission lines severely limit what can be done in the IR. For example, [8] measured the central velocity dispersion of the lens galaxy in the gravitational lens system MG2016+112 ($z = 1.004$) by integrating 8.5hrs with the Echellette Spectrograph Imager (ESI) at the Keck II telescope. Given the excellent sensitivity and resolution of ESI (that allows for a good removal of sky lines in the red/IR), it seems likely that with the current generation of 8-10m class telescopes such measurements will be limited to bright E/S0 at $1 < z < 1.5$.

As shown in the right panel of Fig. 3, the redshift range $z = 1-2$ would be easily within reach with NGST (see also [14]), and even objects beyond $z \sim 2$ could be targeted, if they exist. Based on calculations similar to the one used in Fig. 1 (right panel), adopting the FP instead of the Tully-Fisher relation as luminosity-velocity scaling law, at $z > 1$ NGST will be significantly better than a 30-m telescope, especially for large masses. Recent studies suggest that old stellar populations indeed exist at $z > 2$. For example [10] found that the colors of Lyman-$\alpha$ selected galaxies at $z \sim 2.4$ are consistent with those of an old stellar population ($\sim$ Gyr of age) – responsible for the observed red colors – with a sprinkle of starbursting population – responsible for the observed emission lines – (see also [4]).

### 3.1 The Internal Mass Distribution of High Redshift Galaxies

So far, we only discussed absorption line kinematics in the absence of spatially resolved information. However, spatially resolved kinematics have been very im-
portant in our study of the local Universe. For example it has provided crucial constraints on the internal structure of E/S0 (e. g. [2,6]), and Hubble Space Telescope (HST) subarcsecond resolution spectroscopy has been used to prove the existence of black holes at the center of massive E/S0. Unfortunately, the small aperture of HST and the seeing-limited spatial resolution of ground based telescopes have so far basically confined spatially resolved kinematics to the local Universe. As an example of the current observational limits, [15] have recently started a kinematic survey of gravitational lenses. Under the best observing conditions (seeing 0′.6) – with long integration times at the Keck-II Telescope – they were able to measure velocity dispersion profiles extended beyond the effective radius for lens galaxies at z < 0.5. Although the extended profiles provide valuable and unique information on the mass distribution, a higher spatial resolution is needed to study in detail the mass distribution within the central kiloparsecs. NGST – with its combination of large collecting area and superb spatial resolution – offers the tremendous opportunity to explore spatially resolved kinematics at cosmological distances. With a typical resolution ≤ 0′.1 NGST will be able to study in detail the mass distribution of E/S0 and its evolution with redshift.

4 Mass Measurements with NGST: Instrumentation

Both emission and absorption line studies of the kinematics of high redshift galaxies require a resolving power of at least 3,000, i.e. somewhat higher than what is currently in the baseline for NGST. The need for high resolving power is stronger for emission line measurements since they can be carried out on intrinsically fainter objects. Because of this reason there is a strong rationale for a two-dimensional spectroscopic capability at R≥3,000. This capability could be

\[ \text{Fig. 3. Absorption lines dynamics at } z > 1: \text{ targets for NGST. Left: spectral energy distribution of an extremely red object with E/S0 morphology at } z \sim 1.8 \text{ (from [18,11]). Right: comparison of the performance of NGST, a 10m ground based telescope and a 30m ground based telescope.} \]
in the form of an integral field spectrograph \([1]\) if budget, volume, and weight constraints allow it. Alternatively, it could be provided by a multi-object spectrograph based on a configurable slit array provided the configuration time is short enough. Such a spectrograph would allow one to step the slit over resolved objects to be mapped in two dimensions while integrating on fainter sources \([9]\).

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