Astro2010 Decadal Survey White Paper: The Quest for a Physical Understanding of Galaxies Across the Cosmic Time

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Abstract

In the CDM hierarchical cosmology, the concept of "dark matter halo" as the hosting structure of the visible galaxies is a central one. Most of the mass at any given time is bound within halos; visible structures form when the baryonic gas accretes, cool and forms stars at the bottom of its potential well. The physical properties of halos, primarily the mass, are thought to be responsible for the astrophysical properties of the galaxies and their evolution. And yet, we still do not have any rigorous empirical characterization of the halo and its properties, and how the halo/galaxy systems evolve through the cosmic time.

The ability to perform medium-resolution (R∼few thousand) spectroscopy in the optical window (where the relevant diagnostic features will be observed) down to $z_{AB}\sim28$ mag will open the halo/galaxy paradigm to direct empirical investigation. With such capabilities we will measure the mass of halos on spatial scales up to ∼100 kpc, as well as their density profile, shape and dynamical state, at redshift up to $z\sim3$. This is a crucial epoch for galaxy formation, because it is when the stellar mass density in galaxies increases by ≈2 orders of magnitude and the correlations between the morphology, spectral type, luminosity and dynamics of galaxies, namely the "Hubble Sequence", are established.

We offer the example of a 16-meter class space telescope with a multi-object spectrograph. This instrumental combination will make it practical to use galaxies at $z>3$ in the background of targeted halos around galaxies at $z<3$ as beacons, and study the kinematics of the gas in the intervening halo by means of absorption spectroscopy along a large number of lines of sight through that halo. There are on average ∼26 $z>2.5$ Lyman-break galaxies down to $z_{AB}<28$ in the background of a spherical volume of radius $r=100$ kpc centered around a galaxy at $z\sim2$, whose featureless UV continua are ideal to detect intervening optically-thick (MgII λλ2796,2803) absorption systems. Probing the gaseous halos of galaxies at $z<1$ with MgII absorption systems in the spectra of distant QSOs is commonly done today, but the degeneracy between shape and inhomogeneous covering factor in a multi-phase medium cannot be broken with only one line of sight. Once galaxies can replace QSOs as tracers of absorption systems, we will be able to directly test the key physical properties of the halos and investigate how they determine those of the visible galaxies. The "galaxy absorption systems" will also yield a variety of information on the metallicity and physical state of the gas, which is crucial, and currently acutely missing, for understanding of the physics of star formation (e.g. gas accretion and feedback). Most importantly, it will become possible to test the idea that the halo is a universal feature of every galaxy, not just those selected because they give origin to QSO absorption systems.

The Quest for a Physical Characterization of Galaxies Across the Cosmic Time

Dark matter halos are the link between galaxy formation and cosmology. In order to test the theory and to understand galaxy formation in a cosmological context, it is essential to establish the physical connection between the properties of the galaxies (stellar mass, star-formation and chemical enrichment history, gas accretion and feedback, nuclear activity), and those of the dark matter halos (mass, dynamics and density profile). From current observations, we know that the epoch $1<z<3$ is a crucial one for galaxies, because during that time their star formation activity is at least ≈one order of magnitude higher than at the present time (Madau et al. 1996) and the average stellar mass density has increased by nearly two orders of magnitude (Dickinson et al. 2003). During the same time we have also observed the onset of the correlations and scaling laws between morphology, luminosity, dynamics and spectral types (e.g. Kriek et al. 2008; Scarlata et al. 2007; Erb et al. 2006), namely the assembly of the Hubble Sequence. It is of fundamental importance, therefore, on one hand to obtain a complete census of all types of galaxies at least up to z~3; on the other hand to measure the properties of the halos, study how they evolve and how they relate with those of the galaxies. In particular, the next generation of observations will have to answer the following questions:

1) What is the mass (visible+dark) of galaxies, and how does it evolve with time?
2) What is the dynamics and density profile of the halos?
3) How do the properties of the halos and those of the galaxies depend on each other?

The Total Mass of Galaxies

According to current N-body simulations, the mass of the dark-matter halos of galaxies is a fundamental parameter for the following reasons: 1) the mass of a halo determines how much gas is available for galaxy formation; 2) the gas cooling rate is largely determined by halos mass (Keres et al. 2006); 3) The assembly history of galaxies is largely determined by the halo merging history which, on average, is determined by halo mass (Lacey and Cole 1993); 4) the clustering of galaxies is largely determined by their host halo mass (Mo and White 1996).

Currently, three types of mass measures have been made for distant galaxies, stellar mass from multi-band photometry fitting to SED models (e.g. Papovich et al. 2001; Yan et al. 2006); dynamical mass from the kinematics of stars in optically visible regions (Pettini et al. 1998; Erb et al. 2004; Genzel et al. 2008); and total mass derived from spatial clustering (Giavalisco & Dickinson 2001; Lee et al. 2006). In broad terms, the dynamical measures return the smallest value of the mass, the clustering mass is larger by at least an order of magnitude, and the stellar mass is roughly intermediate between the two. The only direct measure is that of the dynamical mass; the stellar mass and clustering mass require theoretical models to actually extract the value of the mass from the observables, namely stellar population synthesis models and stellar initial mass function (which is unconstrained), and an initial dark-matter mass spectrum, respectively.

While the stellar mass is often used as a proxy for the total mass, this is not an adequate approximation, especially during an epoch when the stellar mass evolves very rapidly. Furthermore, the three types of measure are intrinsically different and subject to very different observational systematic errors: the dynamical and photometrical measures only yield the mass inside the observable region at the targeted wavelengths, which is biased in surface brightness toward the brightest parts of the emitting volume. At high redshift, most of the signal comes from the central part of the galaxies, and these measures critically depend on the image quality of the data, especially the spectroscopic ones (e.g. Erb et al. 2004). Accounting for the surface brightness bias and the varying image quality, the uncertainty of the stellar population synthesis models and the observational errors, dynamical and stellar mass are roughly in quantitative agreement, consistent with the fact that the dark matter contribution is small on the central parts of the visible part of the galaxies. Clustering returns the mass spectrum of the galaxies whose clustering is being measured, but the numbers actually depend on assumptions for the dark matter mass spectrum, and thus such mass estimates are at most useful consistency check, not real measures. How can we reliably measure the mass of a large number of distant galaxies?

Evidence of Extended Halos Around Galaxies

There is direct empirical evidence that at least relatively bright, hence presumably massive, galaxies at redshift up to z~1 have gas halos extending up to radii r~100 kpc, and that these halos are gravitationally bound, thus tracing dark matter halos. This comes from the optically-thick absorption systems (MgII) observed in the spectra of distant QSOs. A number of groups (e.g. Bergeron et al. 1992; Steidel et al. 1993) have found that at least up to redshift z~1, strong optically-thick absorption systems (e.g. those with MgII equivalent width larger than 0.3 \AA) are always caused by gas located in spatial proximity of bright (L>0.3L*) galaxies, spanning the whole range of spectral types, intervening along the line of sight to the QSOs. More precisely, the observations have shown that every time a QSO has an strong, optically-thick absorption system, such as MgII, at a given redshift z_{abs},(the redshift of the QSO, higher than that of the absorption system, is not relevant here), there always is a bright galaxy within an impact parameter up to ~100 kpc from the QSO, whose emission redshift z_{em} *is the same as the absorption redshift*, namely $z_{em} = z_{abs}$. The impact parameter is up to ~one order of magnitude larger than the optical size of the galaxy (e.g. the half-light radius), implying that the gas that gives origin to the absorption system resides in an extended halo around the visible galaxy.

The sparse statistics, however, and the degeneracy between the covering factor of the gaseous halo and its size and shape (whether spherical or a disk) do not allow one to make firm conclusions on the nature of the physical association of the gas and the individual galaxy. For example, some authors report a trend of increasing level of ionization of the gas (e.g. the MgII to CIV strength ratio) with larger impact parameter, consistent with a density gradient, which would support the idea that the gas resides in a gravitationally bound halo around the galaxies (Steidel et al. 1997); others do not find such evidence (Churchill et al. 2003). The fact is that with only one line of sight (that to the QSO) available in each case, the statistics of impact parameter alone cannot simultaneously constrain the geometry of the gas halo and its covering factor. A multi-phase, patchy medium will generally result in different kinematics, column densities, temperatures and ionization conditions of the absorbing troughs along different line of sights. Thus, the fact that a known strong optically-thick QSO absorption systems can *always* be explained by a bright galaxy at the same redshift with impact parameter $r \leq 100$ kpc from the line of sight to QSOs is consistent with the gas being hosted in a gravitationally bound halo, but does not prove that every galaxy is associated with such a system. The fact that there are bright galaxies within a similar impact parameter that do not cause optically-thick absorption systems (Churchill et al. 2003) does not rule out the halo interpretation, if the gas is in a multi-phase and its distribution is patchy. Similarly, high-resolution spectroscopy capable to resolve the individual clouds of the absorbing complex has in some cases shown radial velocity distribution which is consistent with extended rotating disks at galacto-centric distance up to ~50 kpc (Steidel et al. 2002), but in other cases has revealed a complex kinematics with no obvious evidence of rotation (Churchill et al. 2003; 2007).

Major progress in understanding the structure and dynamics of the halo will be achieved if we can probe multiple lines of sight through the individual systems and if we can study *every* *galaxy,* not just those selected for causing QSO absorption systems. This will become possible when sufficient light gathering power enables spectroscopy at optical wavelengths of background galaxies, as opposed to QSOs, to serve as the tracers of absorption systems.

Probing the Halo of Galaxies at $1<z<3$

Star-forming galaxies with relatively un-obscured UV emission (Lyman-break galaxies) are very common at $z>3$, and their featureless UV continua are basically as good as those of QSOs to identify absorption systems. This is illustrated in Figure 1, which shows a composite UV spectrum derived from the spectra of local star-forming galaxies taken with HST and the GHRS and FOS (Tremonti et al., private communication) and covering the rest-frame region λλ1150-3000. With sufficient S/N, intervening MgII absorption can be detected with relative ease in long stretches of the spectrum blue-ward of the 2800 Ang. For example, if the target galaxy is at $z=2$ and the background one at $z=3$, the MgII absorption is observed around $\lambda_o\sim8400$ Ang, corresponding to rest-frame $\lambda_r\sim2100$ Ang, a featureless region ov the spectrum.

Lyman—break galaxies are relatively abundant. Based on number counts from the Hubble Ultra Deep Field and numerical simulations to model incompleteness as a function of limiting magnitude, we estimate that there are on average $\sim7, 26$ Lyman-break galaxies at $z\geq2.5$ down to $z_{AB}<27, 28$ in the background of a spherical volume of radius $r=100$ kpc (physical coordinate) centered around a galaxy at $z\sim2$. To first order, these background galaxies will be distributed at random around the $z\sim2$ galaxy (we have neglected any contribution from magnification by gravitational lensing), and each will provide an independent line of sight through its halo. Such capabilities, in other words, offer the possibility to sample the kinematics and density profile of *individual* halos with high spatial resolution.

If we can obtain spectra of these galaxies with enough resolution and S/N ratio to observe the redshift and velocity structure of the MgII absorbing gas, we will be able to extract accurate information about the kinematics of the halo gas and its spatial distribution. From comparison with the systemic redshift of the galaxy, it will be possible to reconstruct the dynamics of the gas as a function of galacto-centric distance, and from this extract the gravitational mass and density profile of the halo. A survey of suitable size will yield the statistical distribution function of the shape of the halo, and from the detection statistics and distribution of equivalent width we will derive the covering factor of the absorbing gas.

As an example we have considered the case of a 16-meter optical space telescope and an optical multi-object spectrograph. This combination can secure spectra of a compact source such as a Lyman-break galaxy (we assume half-light radius $r_{1/2}\sim$ 0.2 arcsec, see Ferguson et al. 2004) as faint as $AB=27$ with resolution $R=5{,}000$ and $AB=28.2$ with $R=2000$ (S/N=10 per resolution element; $T_{exp}=100{,}000$ sec). Spectral resolution $R=5000, 2000$ corresponds to velocity resolution of $\Delta v\sim60, 150$ km/s, which means that the data will resolve velocity fields ≈ x10 times smaller than the Keplerian rotation expected at up $r\sim100$ kpc from a galaxy with $M\sim10^{12}\ M_\odot$.

A bounty of other fundamental data will also be returned by this type of observations when brighter sources are available. For example, we expect ≈0.7, 0.17 galaxies at $z\geq2.5$ per halo (roughly one every 1.5, 5 halos) to have $AB\leq25.5, 23.5$. At this flux level the 16-meter optical space telescope mentioned above will be able to obtain spectra with R=10,000 and S/N=20, 100 per resolution element. This is sufficient sensitivity to measure the column density of MgII and other low-ionization species from the damping profile of the lines and reconstruct the metallicity of the gas. Together with the kinematics, this information is crucial to understand the nature of gas outflows and inflows and thus investigate feedback and gas accretion, including the metal fraction segregated in the hot phase.

Conclusions

The next generation of optical space telescopes will enable the empirical investigation of one of the most basic and thus fundamental concepts of galaxy formation, namely the dark matter halo and its properties. They will also allow us to study currently hardly accessible phenomena such as gas accretion and feedback. The 30-meter class of ground-based telescopes with AO and JWST will measure the kinematics of the stars and derive the dynamical mass of the visible galaxies in the innermost r~10 kpc of the halo, virtually at all redshifts where galaxies have been observed. They will also yield the metallicity of the stars and that of the HII regions. Facilities such as ALMA and the 50-meter Large Millimeter Telescope (LMT) will provide information on the cold gas (from CO emission) and the star formation rate (from cold dust). In combination with the data on the hot phase in the outer volume of the halo from the type of experiments outlined above, the new generation facilities will allow us to derive a complete picture of the complex interplay of the physical process that take place in both the dark and visible components of galaxies and provide an empirical test of the most fundamental predictions of the theory.

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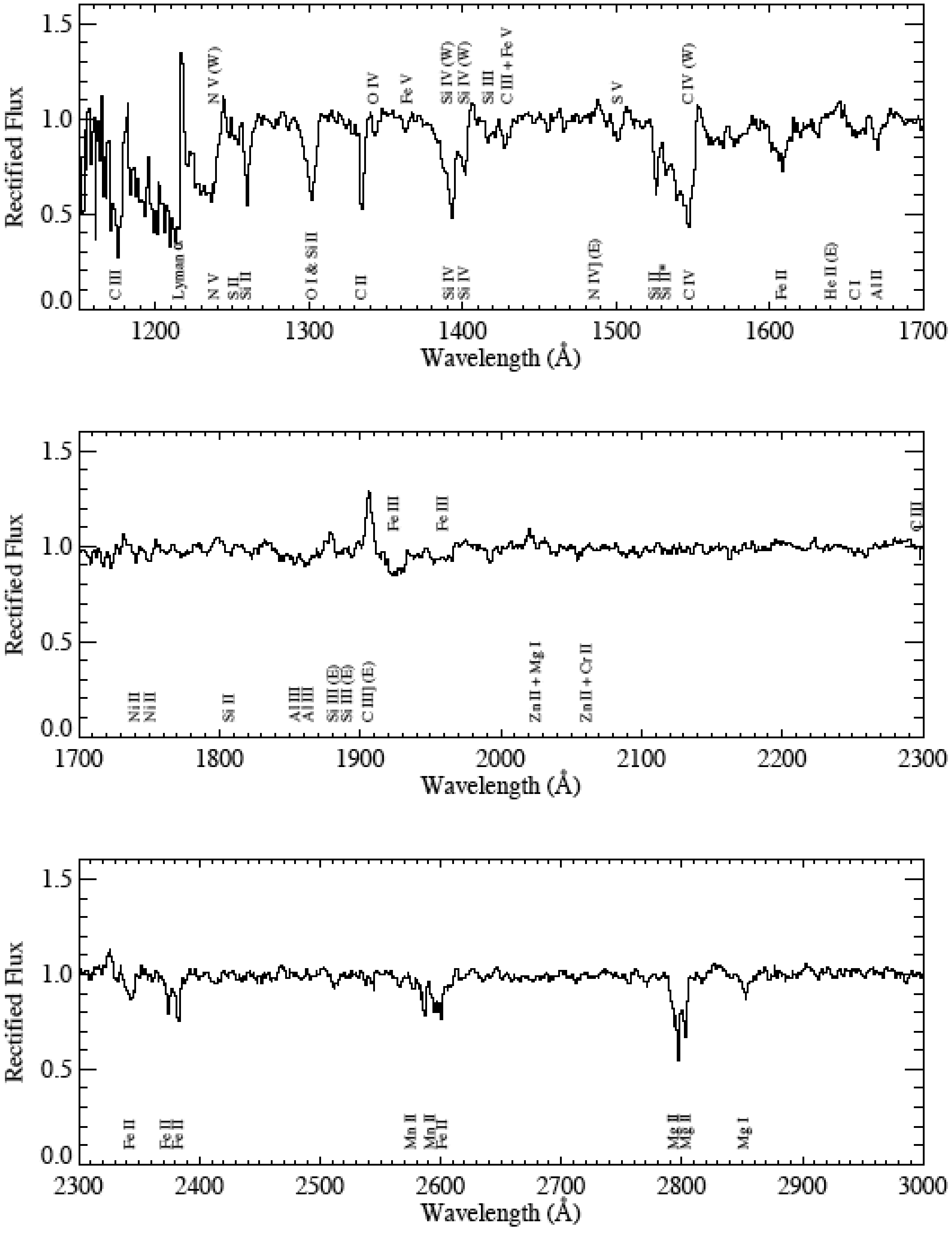

Figure 1. Starburst composite spectrum constructed from HST/GHRS and HST/FOS observations (Tremonti et al. private communication). Prominent interstellar lines are labeled below the spectrum, stellar wind and photospheric features above it. The stellar wind lines (W) typically have both a stellar and interstellar component. Note the large featureless spectral range, where the primary absorption feature (MgII) will be observed, at 1550<λ<2800 Ang (see text).