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What Regulates Galaxy Evolution? Open questions in our understanding of galaxy formation and evolution

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ABSTRACT

In April 2013, a workshop entitled "What Regulates Galaxy Evolution?" was held at the Lorentz Center. The aim of the workshop was to bring together the observational and theoretical community working on galaxy evolution, and to discuss in depth of the current problems in the subject, as well as to review the most recent observational constraints. A total of 42 astrophysicists attended the workshop. A significant fraction of the time was devoted to identifying the most interesting "open questions" in the field, and to discuss how progress can be made. This review discusses the four questions (one for each day of the workshop) that, in our opinion, were the focus of the most intense debate. We present each question in its context, and close with a discussion of what future directions should be pursued in order to make progress on these problems.

Contents

1. Introduction

In the last decade, a number of observational tests of the standard cosmological paradigm have ushered in a new era of "precision cosmology". Our current standard model for structure formation is able to reproduce simultaneously a number of important observational constraints, ranging from the temperature fluctuations in the cosmic microwave background, the power spectrum of low redshift galaxies, to the acceleration of the cosmic expansion inferred from supernovae explosions. While the cosmological paradigm appears to be firmly established, a theory of galaxy formation continues to be elusive, and our understanding of the physical processes that determine the observed variety of galaxies is at best rudimentary. Although much progress has been made, both on the theoretical and observational side, understanding how galaxies form and evolve remains one of the most outstanding questions of modern astrophysics. In addition to being an interesting question on its own right, galaxy formation also has important implications for cosmological studies. Indeed, at least some cosmological probes use galaxies as tracers (e.g., those based

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on measurements of galaxy clustering). A better understanding of the galaxy formation process is therefore crucial in order to improve our knowledge of the mass-energy content of the Universe.

These are exciting times to study galaxy formation: a wealth of new data are expected from ongoing and planned photometric and spectroscopic surveys of the local and more distant Universe, at different wavelengths. In parallel, the field of computational astrophysics has progressed rapidly thanks to increasing computational power and to the development of more sophisticated numerical algorithms.

In April 2013, the authors of this paper organised a workshop at the Lorentz Center[1] to bring together the observational and theoretical community and discuss in depth of the current problems in galaxy formation, as well as to review the most recent observational constraints. A total of 42 astronomers participated in the workshop, including theorists and observers working on a wide range of topics in galaxy formation, from dwarf galaxies, to massive galaxies, isolated galaxies and cluster galaxies, from very high to very low redshift. A significant portion of the workshop was devoted to identifying the most interesting open questions in galaxy evolution, and how progress can be made on these problems. Many interesting questions were debated. Below, we provide a summary of the four questions (one for each day of the workshop) that, in our opinion, were the focus of the most intense debate. We will discuss those four questions in their context, and close with an outlook on what areas in galaxy formation we believe are especially promising to help making progress on the identified problems. In particular, the four questions selected are: (i) Are we reaching a fundamental limit in our ability to measure properties such as stellar mass and star formation rates? (ii) What is the star formation and assembly history of galaxies with mass below $10^9\,M_\odot$? (iii) Does the central-satellite division provide the right framework to study galaxy evolution? (iv) We understand which processes affect galaxies in different environments. Do the details matter?

Since they were selected simply based on the interest they generated, the four questions are quite different in nature: (i) and (iii) are technical, (iv) a somewhat philosophical one, and (ii) is more a standard science question.

2. Question 1 – Are we reaching a fundamental limit in our ability to measure properties such as stellar mass and star formation rates?

Two of the most fundamental parameters that describe a galaxy are its total mass in stars, and the rate at which stellar mass grows via star formation, the star formation rate (SFR). Measuring the evolution of stellar masses and SFRs both for individual galaxies and for the Universe as a whole occupies a substantial fraction of the observational resources devoted to the study of galaxy formation (see for example Kauffmann et al., 2003; Brinchmann et al., 2004; Salim et al., 2007; van Dokkum et al., 2010; Baldry et al., 2012; Muzzin et al., 2013, just to mention a few). Given their important role for assessing the success of theoretical models (e.g., De Lucia and Blaizot, 2007; Schaye et al., 2010; Weinmann et al., 2012), increasing the precision with which stellar masses and SFRs are measured, over a wide range of redshifts and halo masses, continues to be a major goal of the observational community.

Over the last two decades, incredible progress has been made in obtaining high-quality data for this purpose. In particular, the Sloan Digital Sky Survey (SDSS) has provided high-quality photometry and spectroscopy which have allowed the measurement of stellar masses and SFRs for millions of galaxies (Kauffmann et al., 2003; Brinchmann et al., 2004; Blanton et al., 2005). While no survey complementary to the SDSS exists for the high-redshift Universe yet, the coming of wide-field NIR and MIR cameras, the WFC3 camera on HST, as well as significant improvements in photometric redshift techniques have opened up studies of the stellar masses of samples of up to hundreds of thousands of galaxies, up to as far as $z \sim 8$ (e.g., Marchesini et al., 2009; Labbé et al., 2010; Muzzin et al., 2013; Ilbert et al., 2013). Likewise, access to the FIR and Sub-mm from *Spitzer*, *Herschel*, and now *ALMA* have allowed us to study dusty star formation up to $z \sim 6$ (e.g., Chapman et al., 2005; Daddi et al., 2007; Riechers et al., 2013), and *GALEX* has made the study of SFRs from the rest-frame UV available in the local Universe (e.g., Martin et al., 2005; Schiminovich et al., 2005; Salim et al., 2007).

With this extraordinary increase in the sample sizes and data quality for distant galaxies, it has become increasingly clear that the dominant source of uncertainty is provided by *systematics* in the conversion of the photons we observe, into physical quantities (Conroy, 2013). Without an improvement in our understanding of these systematic uncertainties, it is unclear whether we will be able to take advantage of the nearly overwhelming samples of galaxies that will be available for study from surveys with upcoming telescopes such as *LSST*, *Euclid*, and *WFIRST*. Can we really develop techniques to reduce systematic uncertainties in deriving key quantities such as stellar mass and SFRs, or are we truly reaching a fundamental limit in our ability to do so?

Stellar masses are typically determined for galaxies by fitting their spectral energy distributions (SEDs) measured from either spectra, or broadband photometry to synthetic spectra derived from stellar population synthesis (SPS) codes. A thorough discussion of this process, and the inherent challenges with it can be found in the recent review by Conroy (2013). In brief, SPS models encode the current state-of-the-art knowledge of stellar evolution both on and off the main-sequence, and use isochrones combined with both real and synthetic spectra for stars to produce composite SEDs that the data can be fit to. Not all SPS models are alike, with each employing slightly different isochrones and/or treatment of the various phases of stellar evolution. Therefore, for identical raw observational data, different stellar masses are derived using different SPS codes. The difference between SPS codes was recently highlighted by the various treatments of the thermally-pulsating asymptotic branch phase (TP-AGB) of stellar evolution (see Section 6.2). This is challenging to model, yet can have a large effect on derived synthetic SEDs. Because of the TP-AGB phase, and other differences between the codes, most recent observational studies have concluded that the largest systematic uncertainty in deriving stellar masses currently is the uncertainty in how to treat stellar evolution (i.e., the SPS codes themselves).

This is illustrated in the left panel of Fig. 1 (from Muzzin et al., 2009) that shows the effect of varying assumptions parameters in the SED fitting to determine the systematic differences in the derived stellar mass of individual massive galaxies at $z \sim 2$. Parameters were varied relative to a default template set: Bruzual and Charlot (2003) SPS models, the Calzetti dust law, and solar metallicity. Fig. 1 shows that the largest systematic uncertainty in the determination of stellar masses for individual galaxies is the choice of SPS model, and this difference is a factor of $\sim$1.6. The right panel of Fig. 1 (from Marchesini et al., 2009) shows the same approach but this time the effect on the full stellar mass function at $z \sim 1.7$. The most extreme effect on the stellar mass function is the use of bottom light initial mass functions (IMFs). Thereafter, the next largest effect is the choice of the SPS model. Note that a bottom light IMF is disfavoured by more recent data (e.g., Conroy and van Dokkum, 2012; Shetty and Cappellari, 2014, and references therein).

[1] http://www.lorentzcenter.nl/lc/web/2013/528/info.php3?wsid=528.