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GALAXY FORMATION: A WHITE PAPER FOR THE CANADIAN LRP 2010

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ABSTRACT

The challenge of galaxy formation is to determine the physical conditions under which galaxies arose in the early Universe. Canadian strengths in this field include 1) the search for the sources responsible for reionisation, 2) charting the mass assembly history in galaxies and 3) determining the origin of the black hole-galaxy connection at early cosmic times. We outline the possible directions to be taken by future efforts in addition to noting the important role to be played by future facilities and initiatives.

1. IDENTIFYING THE SOURCES OF REIONISATION

The past decade has seen major advances in our understanding of galaxy formation. Young galaxies populated by massive stars are thought to be a major contributor of energetic ultra-violet (UV) photons responsible for the reionisation of the Universe. Observations of near total absorption by the intergalactic medium (IGM) in the spectra of high-redshift quasars (Fan et al. 2006) indicate that the process of reionisation is nearly complete by $z = 6$. In addition, the polarisation cross correlation signal observed by the Wilkinson Microwave Anisotropy Probe (WMAP; Spergel et al. 2007) supports an extended epoch of reionisation over the interval $7 < z < 20$. These observations highlight but do not pinpoint the rise of UV photons in the Universe. Essentially they have two sources: active galactic nuclei (AGN) and massive star formation – presumed to occur in young galaxies.

The epoch $z = 7$ represents an important observational hurdle which must be overcome in order to reveal the formation processes at work during the so-called “dark ages”. Even a small ($\tau \sim 10^{-5}$) amount of neutral hydrogen is sufficient to almost completely absorb light at wavelengths $\lambda < 1216$Å. At $z > 7$ this corresponds to observed wavelengths $\lambda > 1\mu$m and thus searches for high redshift galaxies must be undertaken at near-infrared (NIR) wavelengths and beyond. The advent of the Hubble Space Telescope (HST) WFC3 has revealed tantalising evidence of bright drop-out selected galaxies at photometric redshifts $7 < z < 10$ (e.g. Bouwens et al. 2010). However, such sources present apparent AB magnitudes of 27 or greater and spectroscopic confirmation remains a considerable observational challenge.

Such considerations have led to numerous Canadian efforts to detect galaxies at $z > 7$. Willis et al. (2005, 2008) and Hibon et al. (2010) have performed a succession of exceptionally deep narrow-band (NB) NIR surveys for $z > 7$ Lyα emitting galaxies. NB surveys highlight the contribution of the Lyα line and generate samples of robust emission line candidates well suited to follow-up spectroscopy. Though these attempts have placed currently the most stringent limits upon the $z > 7$ Lyα luminosity function (LF) they are clearly pathfinder-type experiments that need to be extended to fainter limits and wider areas to detect appreciable numbers of bona-fide candidates.

The Universe at $z > 7$ represents prime discovery space for the James Webb Space Telescope (JWST), but searches from the ground may yield interesting results before 2015. One program with Canadian involvement will make use of the Flamingos-2 Tandem Tunable Filter (F2T2) which will appear on Gemini as soon as the telescope’s Multi-Conjugage Adaptive Optics system is deployed (currently scheduled for 2011). This device is an infrared-optimized scanning tunable filter which will be mounted inside the Flamingos-2 imaging spectrograph on the Gemini South Telescope. This filter is a de-facto engineering prototype for the James Webb Space Telescope’s Tunable Filter Imager and has been optimized to undertake the Gemini Genesis Survey, an ultra-deep search for the first generation of star-forming galaxies at redshifts $8 < z < 12$ using foreground gravitational lensing to boost the visibility of very distant galaxies.

In the coming decade it is clear that JWST and a ground-based Thirty-Metre Telescope (TMT) will drive important new discoveries at $z > 7$. JWST/NIRSPEC will perform low resolution NIR spectroscopy to AB = 29 and NIRCAM will detect sources to AB = 31. This will permit spectroscopy of the brightest sources to $z = 10$ and photometry of continuum selected sources to $z = 15 - 20$. JWST will reveal the UV luminosity output of galaxies over a wide luminosity range during the extended reionisation epoch indicated by WMAP. Furthermore, JWST will form an important partnership with a ground based TMT which, imaging to brighter limits over much wider areas, will provide the crucial normalisation of the bright end of the UV LF at these redshifts. The future will also bring increased synergy with radio facilities as projects such as the Square Kilometer Array (SKA) map the high-redshift distribution of hydrogen 21cm emission and thus reveal the three dimensional structure of the IGM and complete the physical link between galaxies and reionisation.

2. THE ASSEMBLY HISTORY OF GALAXIES

2.1. *Deciphering the alphabet soup*

From the perspective of direct galaxy observations the past decade has been marked by considerable observational advances. Large optical telescopes in partnership with HST have revealed and studied large populations of high-redshift galaxies. Deep imaging campaigns using photometric continuum drop-out and narrow-band excess techniques have extended our knowledge of the most distant galaxies from redshifts three to those approaching seven, with sample sizes ranging from thousands to tens of galaxies at the the extremes of these redshift limits (e.g. Steidel et al. 2003; Taniguchi et al. 2005). The global context of galaxy formation revealed by these studies may be expressed by considering the volume averaged star formation rate density (SFRD) as a function of redshift (Figure 1). Current studies show a steady accumulation of stellar mass in galactic structures from $z \sim 7$ with a broad peak in global star formation occurring between $1 < z < 3$ (Bouwens et al. 2010). Canadians have played a leading role in defining this picture from the beginning (e.g. Lilly et al. 1996; Sawicki, Lin & Yee 1997) in addition to highlighting the important contribution of sub-L^* (i.e. "normal") galaxies to the stellar content of the Universe (Sawicki & Thompson 2006).

The epoch $z \sim 2$ forms a bridge between the epoch of first galaxies at higher redshifts and the galaxies in the present-day Universe. Various selection techniques have by now produced a veritable alphabet soup of galaxy types at $2 < z < 4$, including LBGs, BXs, BMs, DOGs, XBONGs, BzKs, DRGs, LAEs, and SMGs. It is at present still somewhat unclear how these different classes of objects are related to each other or to those at other epochs (although most of them have been claimed at one time or another to be the progenitors of present-day massive galaxies). Despite this confusion, measurements of properties such as metallicities, stellar population ages, dust content, or sizes, are starting to suggest that these $2 < z < 4$ objects may be different from objects in the $z = 0$ Universe, but – at the same time – may be more evolved than objects at even higher redshifts.

Our understanding of high-redshift galaxy populations is currently phrased in the language of observational techniques and not in terms of a physically motivated model. However, understanding the physics determining galaxy formation and evolution will require data sets comprising large samples of galaxies drawn over the redshift interval $2 < z < 6$ (i.e. encompassing the current zoo of high-redshift populations) and employing a range of diagnostic techniques such as spectral energy distribution (SED) fitting, which gives estimates of stellar masses, stellar population ages, and dust-corrected star formation rates (e.g. Sawicki et al. 1998); spectroscopy in the rest-frame UV and optical, which tells us about the evolutionary stages of stellar populations, mass outflow rates and the metallicity of the interstellar medium (ISM); and clustering studies, which — when compared with theoretical predictions of dark matter clustering — give us estimates of dark matter halo masses of these distant galaxies.

Canadians have made important contributions to our understanding of the multi-wavelength properties of high-redshift galaxies. These include seminal SCUBA surveys such as the Canada-UK Deep Submm Survey (Webb et al. 2003), the SCUBA Half-Degree Extragalactic Survey (Coppin et al. 2006) and the HDF Super-map (Borys et al. 2004). At slightly shorter wavelengths, Spitzer MIR observations of NIR-selected Distant Red Galaxies (DRGs) indicate that such IR-luminous galaxies become increasingly important to the SFRD by $z \sim 2$ (Webb et al. 2006), as mergers and burst-mode star formation become dominant. FIR observations are sensitive to dust reprocessed stellar emission and therefore represent an important diagnostic of the total galactic star formation rate – which in some cases may be overlooked by optical surveys. Although the few hundred highly luminous sub-mm galaxies (SMGs) revealed by SCUBA indicated that FIR emitting galaxies are significant contributors to the SFRD at $z \sim 2$, more ambitious surveys were limited by the mapping speed of the instrument. Facilities such as Herschel and SCUBA2 will reveal the FIR galaxy population in greater detail by reaching substantially deeper depths and covering larger areas (i.e. orders of magnitudes compared to SCUBA) over a wider and more interesting wavelength range.

The key issue for the next decade is to determine which among the various $2 < z < 4$ galaxy types are the direct descendants of the $z > 5$ objects and by what processes did they evolve? Progress will depend upon multi-wavelength observations of "typical" (L^* and fainter) galaxies and will require partnerships between next generation facilities such as TMT and ALMA in order to link the unobscured and obscured modes of star formation across a wide range of mass-selected galaxies.

2.2. *Dynamical fingerprints of the formation epoch*

A critical question that lies within the reach of the coming decade is the origin of dynamical structure of massive galaxies. Integral-field unit (IFU) spectroscopy is crucial for understanding the formation of massive disks, since slit spectroscopy has given contradictory results as kinematic and morphological axes are not necessarily correlated (Erb et al. 2006). Even at intermediate redshift ($z \sim 0.6$), it has been demonstrated that galaxies are already kinematically complex and that 3D integral field spectroscopy is essential to physical understanding and kinematic modeling (Rix et al., 1997; Flores et al. 2006). To date the integral field spectrograph march to higher redshifts ($1 < z < 2$) has been led by VLT (SINFONI, Forster Schreiber et al. 2009) and Keck (OSIRIS, Law et al. 2009) with large allocations being invested on each telescope (600 hours for the SINS survey on the VLT alone).

Such high redshift IFU studies currently disagree on the importance of large-scale rotation as a means of support, possibly pointing to a scenario where gas is first accreted at high rates via cold flows along cosmic filaments. A program being undertaken with Gemini's NIFS IFU (which probably has the highest throughput of any 8m-telescope IFU) plus ALTAIR LGS suggests that the origin of these discrepant results may simply be sample selection effects, largely driven by an absence of natural guide stars in existing deep fields used to define the samples. Canadian researchers are leading attempts to use NIFS/ALTAIR to determine the kinematic structure (as traced by the Hα line) of high-redshift galaxies – both by performing IFU spectroscopy of a representative sample of bright galaxies at $z = 2$ (Abraham) and by performing IFU spectroscopy of lensed $z > 1$ galaxies to obtain an additional resolution boost (Crampton). Another major impediment to defining a suitable sample is the extraordinarily expensive nature of these observations, which require $\sim$ 10h integrations per galaxy on an 8m telescope to have reasonable signal-to-noise. Two solutions to this problem are on the horizon: (1) obtaining more photons with a 30m-class telescope, or (2) building an IFU system with significant multiplexing. One example of such a system is VLT MUSE, although this will not incorporate a high-resolution adaptive optics system.

3. THE ORIGIN OF THE BLACK HOLE-GALAXY CONNECTION

The galaxies at $z > 6$ discovered by deep HST imaging come from surveys of very small volumes and do not probe a wide range of cosmic structures. In contrast, luminous quasars have black holes (BHs) with masses $\sim 10^9 M_\odot$ which, based on local black hole scaling relationships, are expected to reside in the rarest, most massive peaks in the dark matter distribution. Therefore they provide an excellent route to studying massive galaxies at high redshift. Dedicated efforts by Canadian researchers using CFHT and Gemini observations have been exceptionally successful at identifying large samples of high-redshift quasars (comparable in numbers to Sloan samples yet extending to fainter absolute magnitudes; Willott et al. 2005, 2007, 2009, 2010)

Studies of $z > 6$ quasars have shown that (i) the nuclear regions of such galaxies have high metallicities (Freudling et al. 2003); (ii) their black holes are accreting at close to the Eddington limit (Willott et al. 2010); (iii) their host galaxies are strongly star forming (Wang et al. 2008); (iv) the one case of a measured galaxy dynamical mass is a factor of > 10 below that expected based on local black hole scaling relationships (Walter et al. 2004); (v) reionization of the intergalactic medium was largely complete by $z = 6$ (Fan et al. 2006); (vi) accreting black holes provide a very small contribution to the intergalactic photo-ionizing background at $z = 6$ (Willott et al. 2009).

The growth of BH masses in distant galaxies can be viewed as both a tracer of mass assembly and a key component in galaxy evolution. From a theoretical perspective, Canadia researchers have helped develop jet and wind feedback models that underpin the BH-galaxy connection. While these scenarios are based upon modest assumptions (e.g. Thacker et al. 2006), many key aspects of the accretion models do not stand-up under close scrutiny and will be revised in the near future. In particular, an accurate treatment of radiative transfer and magnetohydrodynamic effects around the Bondi radius is necessary to understand activity of the SMBH (e.g. Pen et al. 2003; Proga et al. 2008).

In the future, ALMA will allow a detailed investigation of the evolutionary states of high-redshift quasar host galaxies by high resolution observations of dust, molecular and atomic lines. It will also provide dynamical masses to determine the BH-galaxy mass relationship. JWST will have sufficient spatial resolution and sensitivity to separate the quasar and host galaxy emission to determine star formation histories and masses. Absorption line spectroscopy with JWST, and later TMT, will determine the metal enrichment of the IGM as a function of distance from the quasar. SKA will be able to measure the HI absorption spectrum along the line-of-sight to distant radio-loud quasars to directly determine the IGM ionization state well into the epoch of reionization.

4. THE NEXT DECADE

Canada's future role among the leaders in the field of galaxy formation will be driven in large part by initiatives in a number of specific areas.

Among the pending decisions perhaps the most important is whether to commit to the TMT project. TMT (or other ELTs that deliver diffraction limited performance) will be extremely powerful in studying galaxy formation because they will deliver both the spatial resolution and the flux necessary to disentangle the images of high redshift galaxies on relevant spatial scales. TMT will have 5× the resolution of JWST and will be able to make 2D spectral maps of several galaxies simultaneously. TMT plans to deliver diffraction limited performance right from the start in contrast to other ELTs. We therefore reaffirm at this stage the tremendous advances in galaxy formation that partnership in TMT, or for that matter any other 30m class optical facility, would bring.

Canada is currently a partner in JWST, ALMA, Gemini, Herschel, CFHT and JCMT. JWST and ALMA in particular will deliver a tremendous expansion of discovery space for galaxy formation studies. Canada must remain a strong partner in these endeavours.

Gemini represents Canada's only 8m-class telescope facility and continued access will be required to develop our view of the $z < 7$ Universe from pathfinder projects dealing with the brightest galaxies to mature studies of typical (L^* and fainter) galaxy populations. However, Gemini currently lacks a strategic instrumentation plan – a key requirement to remain competitive in the next decade. Furthermore, introducing a straightforward TAC process for dealing with large programs will encourage the execution of ambitious science projects.

Herschel and JCMT-SCUBA2 will allow Canadians to continue their major contributions into the origin of dust obscured star formation at high-redshift. Both facilities are operating under limited future horizons and it is important that surveys such as the Cosmology Legacy Survey are supported until their completion.

Bold instrumentation programs have ensured that CFHT has remained a world class wide-field imaging facility. Data from the MegaCam and WIRCam instruments continue to underpin a variety of studies of the distant Universe (e.g. high redshift galaxy and quasar selection). Continued efforts to improve the facility image quality and the successful development of the IMAKA GLAO wide-field imager will maintain CFHT's leading position. However, future projects such as the LSST will completely supersede all optical ground-based, wide-field imaging studies. It is clearly important to remain aware of the immense impact of the LSST project and the benefits of Canadian involvement.

Although the SKA potentially lies beyond the coming decade it is clearly a critical component of reionization studies. In the coming decade, JWST and TMT will be mapping the sources of reionization but it will be only with SKA that we will obtain a full picture of the time dependence and geometry of reionization.

We make a final note that investment in new facilities alone does not guarantee that Canada will maintain its position at the forefront of galaxy formation studies. Without accompanying investment in scientists, particularly at the post-doctoral level, Canada will lag behind scientists in the USA and Europe funded by a) research grants tied to JWST and ALMA observing time and b) competitive national post-doctoral fellowships. In terms of science per dollar this is one of the most cost-effective methods of capitalizing on Canadian investments in astronomy infrastructure and further raising Canada's scientific profile.

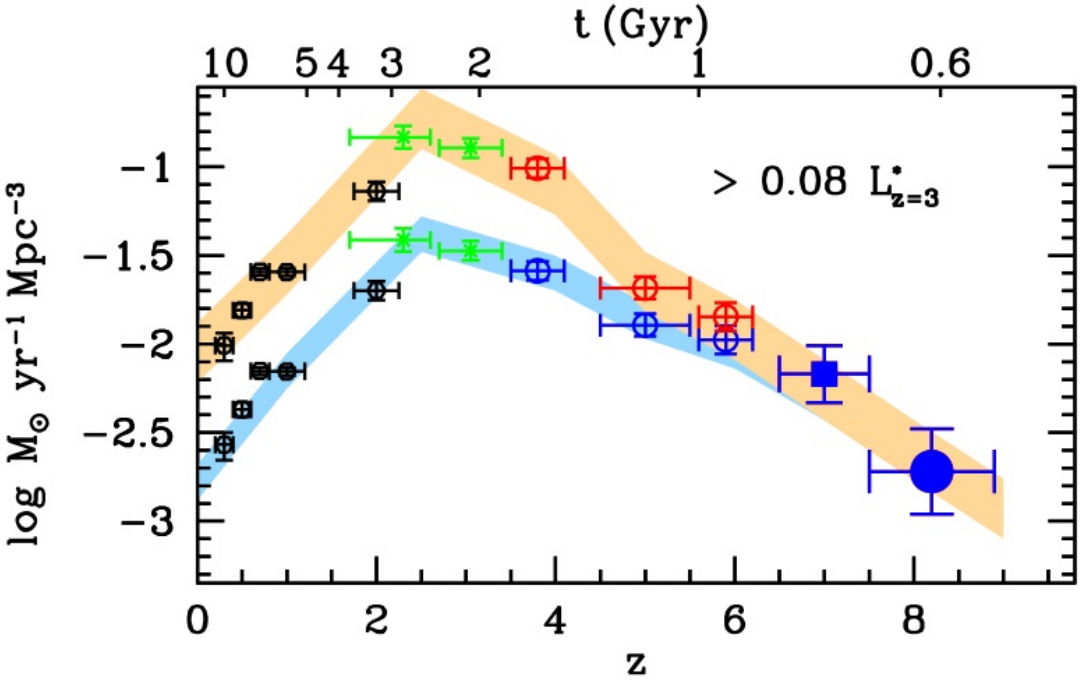

Fig. 1.— Determinations of the UV luminosity density and SFR density, integrated to 0.08 $L^*_{z=3}$ (−18.3 AB mag) as a function of redshift. The lower set of points (and blue region) show the SFR density determination inferred directly from the UV light, and the upper set of points (and orange region) show what one would infer using dust corrections inferred from the UV-continuum slope measurements. (Abridged from Bouwens et al. 2010)

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