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EXTRAGALACTIC STAR FORMATION: A WHITE PAPER FOR THE 2010 LONG RANGE PLAN

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ABSTRACT

A galaxy's observable properties are driven largely by the formation of stars within. While tremendous progress is occuring in observation and modeling of Milky Way star-forming regions, the study of external galaxies is critical for understanding the full star formation history of the Universe. Extragalactic star formation studies probe physical conditions not present in the Milky Way, providing the essential link between the global properties of galaxies and the details of individual star-forming clouds, clusters, and complexes. Open questions in the field include the relations between star formation tracers, the universality of the IMF, and the most appropriate star formation 'recipes' for use in galaxy formation simulations. The highest priorities for research in extragalactic star formation are completion of the JCMT Legacy Surveys, full use of ALMA and JWST, participation in large-aperture far-infrared/submillimetre observatories, and continued support of high-performance computing.

Subject headings:

1. INTRODUCTION

The visible Universe shines by starlight. Although a minor component in the mass of the Universe, stars produce much of the radiation and all of the heavy elements that make the Universe an interesting place. Stars and star formation have profound effects on their surrounding galaxies. The process of star formation involves enormous ranges in scales of time, length, density and pressure, and remains one of the more mysterious phases of the stellar life cycle. In the past decade, Canadian astrophysicists have made great strides in understanding star formation in the Milky Way, from identifying clump mass distributions in molecular clouds (Johnstone et al. 2000) to modeling episodic accretion onto young stellar objects (Vorobyov & Basu 2006) and stellar winds powered by accretion in pre-main-sequence stars (Matt & Pudritz 2005). Many mysteries remain.

But solving the mysteries of star formation in the Milky Way is not enough! The Milky Way is a relatively quiescent galaxy, with a star formation rate of a few solar masses per year. Understanding the history of star formation over cosmic time requires knowing what star formation is like in galaxies with a much wider variety of conditions, including star formation rate, metallicity, and external environment. The importance of large scale dynamical effects for triggering and regulating star formation is not easily studied from our position within the Milky Way, and our knowledge of its global properties (mass, SFR, etc) is also poor. All of these point to the necessity of studying star formation in external galaxies.

Canadian observational astrophysicists are active in numerous sub-areas of extragalactic star formation, including deep extragalactic millimetre and sub-millimetre surveys (e.g. Chapin et al. 2009, Fig. 1), infrared and sub-millimetre studies of the dust and molecular gas in nearby galaxies (e.g. Wiebe et al. 2009; Wilson et al. 2009, Figs. 2 & 3) and optical studies of extragalactic H II regions (e.g. Binette et al. 2009, Fig. 4). This work makes use of numerous existing facilities over a wide range of wavelengths. Canadians are also poised to make use of newly available facilities such as JCMT/SCUBA-2 and the Herschel Space Observatory, through both large programs such as the JCMT Legacy Surveys and Herschel Key Programmes and smaller, focused studies. The improved sensitivity and angular resolution of upcoming facilities including ALMA and JWST will enable exploration of previously inaccessible regions of parameter space in extragalactic star formation.

Theoretical studies of star formation by Canadians have generally involved simulations of the local details of star formation (e.g. Urban et al. 2010; Martel et al. 2006) or of cosmological-scale hydrodynamics (McNally et al. 2009; Brook et al. 2007). In the latter, star formation is included by 'prescription', since following the details of gas from intergalactic distance scales down to the sub-parsec scale on which star formation takes place is computationally prohibitive. Simulations of star cluster formation have only recently become feasible, and cannot yet follow the detailed formation of individual stars.

Studies of star formation fall into several regimes depending on the distances to the objects involved: low-mass stars, high-mass stars, molecular clouds, nearby galaxies, or distant galaxies. The physical connection between these scales is still tenuous in some cases, and a major focus of star formation studies for the next decade will be to understand the connections from both observational and theoretical perspectives. The study of extragalactic star formation also has connections to other areas of astrophysics, particularly those discussed in related LRP white papers on Galactic star formation (Johnstone), galaxy formation (Willis), star clusters (Harris), and resolved stellar populations (Venn/McConnachie).

2. OBSERVATIONS

2.1. *Science questions*

Molecular gas properties: Stars form from molecular gas, so observations which directly detect the emission from molecules are critical for investigating star formation. Our cursory knowledge of molecular gas properties is one of the biggest barriers to understanding galaxy-wide star formation. The surface density of star formation in a galaxy is related to its globally averaged gas surface density (Kennicutt 1998b), but how does this relation work, physically? Which gas properties (densities, temperatures) best trace the star formation? What is the minimum gas surface density and/or metallicity for star formation to take place? Do the answers to these questions vary with galaxy properties, and if so, how? The key observations to address these questions are high-sensitivity observations of nearby galaxies which show both the the high-density gas in spiral arms and nuclear rings and low-column-density gas in interarm regions and at large radii. While CO observations trace the high column density molecular gas for samples of nearby galaxies out to the distance of the Virgo cluster, the low-density gas is not as well-mapped. Higher spatial resolution than is presently available will permit the resolution of individual molecular clouds in nearby galaxies. Both of these goals will be met with ALMA; its sensitivity will also allow extension of these studies to more extreme cluster environments such as the Coma cluster.

Dust as a tracer: Dust is ubiquitous in the interstellar medium of galaxies and is found around both newly forming and evolved stars. Both dust and PAH emission from distant galaxies are easy to detect, especially because high-z galaxies are dustier than local galaxies. But using dust as a proxy for molecular gas in studies of star formation rate density (Calzetti & Kennicutt 2009) requires answers to many questions. How do dust composition and dust-to-gas ratio vary with metallicity? For example, we know that PAHs have different emission characteristics at low metallicity: is the same true of dust grains? This requires detailed comparisons of dust components in local calibrator galaxies and our Milky Way, with infrared and sub-mm imaging and spectroscopy. Surveys with *Spitzer* have made the first steps in this direction, and *Herschel* projects will go further. Completion of the JCMT Nearby Galaxies Legacy Survey, which has already surveyed the CO molecular gas of a sample of nearby galaxies and will survey the dust content with SCUBA-2, is a key ingredient. Reaching more distant, lower-surface brightness galaxies will require the increased sensitivity of ALMA and large single-dish facilities. Comparing dust emission to ultraviolet tracers of star formation rate is also aided by space-based UV imaging (e.g., the forthcoming UVIT mission): the far-UV regime is dominated by young OB stars and is less sensitive to age-metallicity degeneracy effects (Pellerin & Robert 2007).

Conditions for star cluster formation: Most stars form in clusters (Lada & Lada 2003) and it is believed that most clusters eventually dissolve to produce the field population that we see in galaxies today. Given that the star formation rate was higher at high z (Hopkins & Beacom 2006), we expect that many of today's stars formed in massive star clusters. The most massive young star clusters locally are found in merging galaxies like the Antennae (Wilson et al. 2003). But what are the physical conditions of pressure, temperature and density in these forming clusters? How do they compare to the conditions expected in starburst and other high-redshift galaxies? Are the spatial and mass distributions of stars in young clusters consistent with being 'field star generators' ? The high angular resolution of ALMA is critical for measuring properties of the molecular gas involved in star cluster formation. Determining stellar spatial distributions and constraining the IMF requires high-resolution near-infrared imaging and spectroscopy.

Magnetic fields and star formation in nearby galaxies: In recent theoretical studies, magnetic field strengths have been demonstrated to have a dramatic effect on gravitational fragmentation scales and infall motions (Basu et al. 2009a,b). Observationally, there are correlations between the mean direction of the magnetic field in spiral arms and that in giant molecular clouds (Li et al. 2006) and between magnetic field directions on 100 pc scales and ~ 0.3 pc scales of dense cores (Li et al. 2009). Both results imply that magnetic energy is significant in star-forming regions and dominates the turbulent energy. But what role (if any) do magnetic fields play in regulating star formation on galaxy-wide scales? (How) do magnetic fields drive the infrared-radio correlation for star forming galaxies? The global properties of the Milky Way magnetic field are particularly poorly constrained (Beck 2009), so answers to these questions are likely to come from observations of synchrotron emission in nearby galaxies with the EVLA or SKA.

IMF universality: Massive stars dominate the radiative output in nearly any stellar population mix that includes them. Their ionizing flux powers the most common star formation indicators (Hα, UV, PAH emission) , so any conversion from these indicators to a total star formation rate (Kennicutt 1998a) relies on an assumption about the stellar IMF. Although studies in the Milky Way do not indicate major variations in the IMF (Bastian et al. 2010), the situation is not as clear for external galaxies: while some studies support a universal IMF (Pellerin & Robert 2007), a 'top-heavy' IMF has been also been advocated (e.g., Davé 2008; Smith & Gallagher 2001). So, is the IMF universal or not? Constraints on the IMF of young stellar populations can be made through integrated near-infrared spectroscopy of star clusters (e.g. Greissl et al. 2010) and integral field spectroscopy of star-forming regions. To make use of these techniques, Canadian astronomers need continued access to 8-m class telescopes. To settle the issue of IMF universality, direct measurement of the stellar IMF in a variety of galaxy environments is needed. High spatial resolution is required to observe galaxies outside the Local Group, and this must go from UV to near-infrared wavelengths to be sensitive to the full range of stellar masses. Large ground-based telescopes can make the necessary near-IR observations while a large space UV/optical telescope is required for the shorter wavelengths.

Star formation rates of high-redshift galaxies: the discovery that 'SCUBA sources' in extragalactic blank-field surveys were high-redshift, star-forming galaxies (Smail et al. 1997) led to much tighter constraints on the history of star formation in the early Universe. Many more of these galaxies will be discovered and studied in the JCMT Cosmology and All-Sky Legacy Surveys. But what is the true star formation rate of these objects? Are they super-starbursts, HyperLIRGs, or something else? Accurate measurements of SFRs in these galaxies have suffered from the difficulty in cross-identifying submillimetre galaxies with optical galaxies having measured redshifts; the modest number of observed submillimetre bands has also limited the accuracy of derived spectral energy distributions. Upcoming facilities should solve the issues of spatial resolution and wavelength coverage, but as usual in astronomy, much of the physics is in the spectroscopy. In particular, the [CII] 158 μm line is an important ISM coolant and SF indicator for dusty galaxies (Baes et al. 2009) and observing this line in distant galaxies requires a large single-aperture facility.

2.2. *Outlook and facilities*

Ten years from now we should have a much better grasp of how the basic ingredients (gas, dust, magnetic fields) combine to produce star formation on galaxy-wide scales. Answering the big questions in extragalactic star formation requires multi-wavelength observations using a variety of facilities. Of the existing and near-future facilities, support for **ALMA** and completion of the **JCMT Legacy Surveys** will have the strongest impact on the field; access to **JWST** and **Gemini** are also important. Priorities for new observational facilities are: **High-sensitivity far-infrared** data from a cooled far-infrared space telescope (SPICA) or a large, filled-aperture telescope at an exceptional site (CCAT) would allow the mapping of dust and molecular gas in nearby galaxies and the measurement of the [CII] line in high-redshift galaxies. **Diffraction-limited near-infrared** imaging and spectroscopy with a large ground-based telescope like TMT is needed for determining the spatial structure and IMFs of young massive star clusters. **High-sensitivity radio** observations with the SKA or EVLA+VLBA would detect the radio emission from the youngest massive clusters (Johnson 2004) and also provide much more detailed views of magnetic fields in star-forming external galaxies. **Space-based UV and optical imaging** with higher sensitivity and angular resolution than currently available are required to determine the IMF and to do detailed mapping of UV star-formation tracers in nearby galaxies.

3. THEORY

3.1. *Science questions*

Star cluster formation and destruction: The previous section outlines why star cluster formation is a key ingredient in the study of extragalactic star formation. Isolated star formation is thought to be reasonably well-understood, and the focus in the simulation community is now on clustered star formation. While Canadian astrophysicists have a long tradition of observational studies of star clusters, theoretical studies have been scant, with a few exceptions (e.g. Murray 2009; McLaughlin & Pudritz 1996). Combined simulations of star and cluster formation are just now becoming possible (e.g. Urban et al. 2010). The main challenge of these studies is: can the observed IMF be reproduced? So far this has not been done successfully. At present, dynamic range is a large issue: often simulations that form the most massive stars have trouble resolving low-mass stars, which makes it difficult to study the IMF. The solution is to use more particles, which requires faster computers.

Star formation recipes in galaxy formation: The formation of individual stars cannot yet be followed in galaxy formation simulations due to the small length scales involved. Star formation must therefore be included by means of 'recipes' which specify the densities of gas and efficiencies under which stars form. While existing recipes generally match the (galaxy-wide) Schmidt-Kennicutt law (Kravtsov 2003), there are deviations for low-mass galaxies and individual star-forming regions. So how can we best implement star formation recipes to more closely match real galaxies: will including the different phases of the interstellar medium suffice? And how can we best model feedback of star formation on the evolution of galaxies and the intergalactic medium? How can simulations reproduce the enriched volume fraction and metallicity of the IGM (Pieri et al. 2007; Germain et al. 2009) and the suppression of dwarf galaxies by ram-pressure stripping of precollapsed halos by outflows (Scannapieco et al. 2001; Mashchenko et al. 2008).

Combining theory and observation: Because star-formation simulations are so computationally intensive, only a limited number of studies attempt to explore parameter space in comparison with observations. In Galactic star formation, Kirk et al. (2009) recently compared a suite of star formation models to observations of the Perseus molecular cloud. The time is right to extend this work to larger-scale galaxy properties, similar to the 'mock observations' of galaxy formation simulations carried out in the last few years. Canada has several leading groups in observational and theoretical galaxy formation and bringing them together will strengthen their work.

3.2. *Outlook and facilities*

Canadian theoretical astrophysicists are poised to make contributions to a number of open issues in galactic-scale star formation. **Continued support of high-performance computing and personnel** is necessary to make these contributions count. In the next decade, theoretical studies of extragalactic star formation will close in on full star cluster formation simulations, improve the "sub-grid physics" used in galaxy formation simulations, and combine theory and observation. Studies of star formation are computationally intensive and require large-scale high-performance computing facilities. "More computers" is not necessarily the answer to any simulation problem, but faster computers usually help. The personnel who maintain computing infrastructure and figure out how to make the best use of it are key contributors to progress in this field. CITA plays an important role in supporting postdoctoral fellows, but additional support for postdocs would help Canadians to keep up with this fast-moving field.

4. SUMMARY

The study of star formation in external galaxies is poised to make major leaps forward in the next decade. Progress in the field will depend on the success of newly available facilities and Canadian progress also depends on our participation in emerging facilities such as SPICA, CCAT, TMT, and SKA. The **facilities most important to extragalactic star formation** observe at mid-infrared to submillimetre wavelengths: JCMT, ALMA, JWST and SPICA. **Person-power** is also critical: the current funding structure lacks support for dedicated postdoctoral fellows who can carry out large surveys and extensive simulations. The field of extragalactic star formation draws on Canadians' strengths in observations and simulations of galaxies, star clusters, and protostars: with careful choices we will play important roles.

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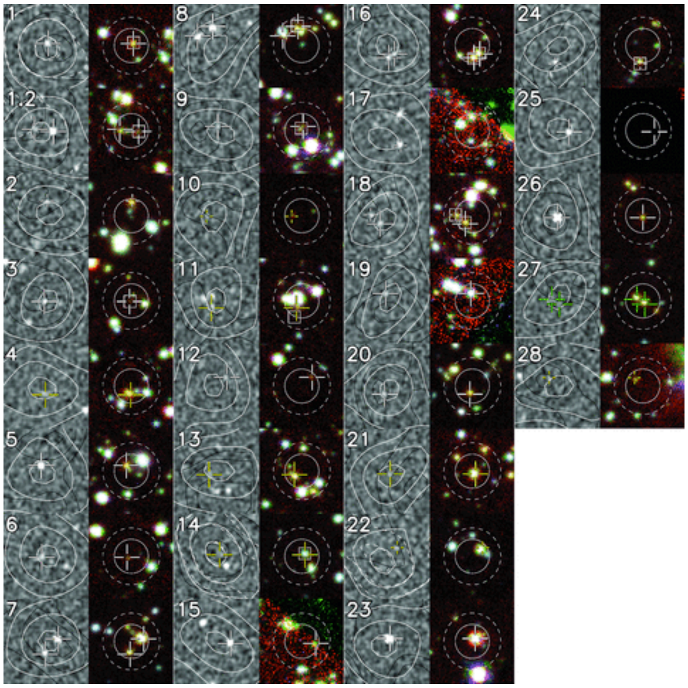

FIG. 1.— AzTEC mm-source counterpart identifications in the GOODS-N deep field. Contours are mm observations; coloured images are from *Spitzer*/IRAC. From Chapin et al. (2009).

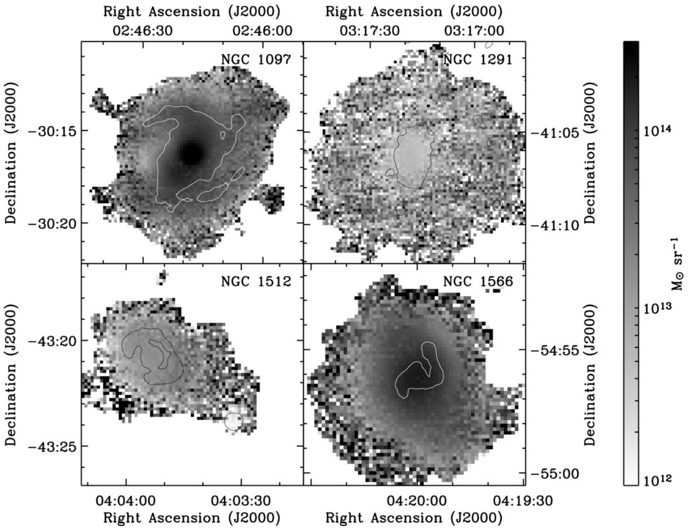

FIG. 2.— Dust column density maps based on BLAST and *Spitzer* MIPS observations of four nearby galaxies. From Wiebe et al. (2009).

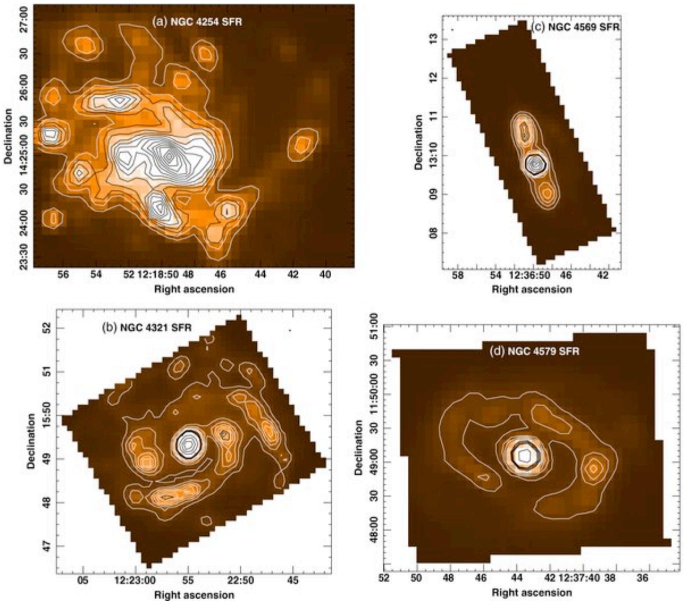

FIG. 3.— Star formation rate density maps for four spiral galaxies in the Virgo cluster, based on HARP-B observations made as part of the JCMT Nearly Galaxies Legacy Survey. First results suggest that the CO $J = 3 \rightarrow 2$ line is a better tracer of the star formation rate density than the more commonly used $J = 1 \rightarrow 0$ line. From Wilson et al. (2009).

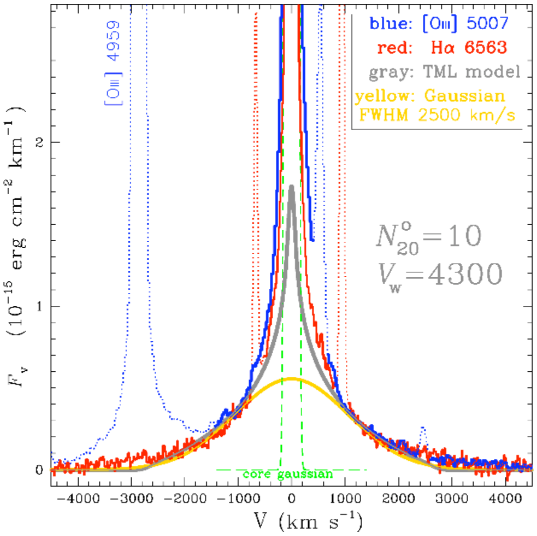

FIG. 4.— Gemini GMOS/IFU spectrum of stellar supercluster A, located in an H II region within the dwarf galaxy NGC 2366. Note the extremely broad emission lines, with FWHM > 2300 km s^{-1}, hypothesized to be due to interaction of a high-velocity cluster wind with the interstellar medium. From Binette et al. (2009).

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