# THE EXTRA-GALACTIC INTERSTELLAR MEDIUM AND INTERGALACTIC MEDIUM

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## ABSTRACT

The study of the interstellar and intergalactic media (ISM and IGM respectively) represent the interface between numerous areas of astrophysics, connecting stellar processes with the galactic scale and beyond. There is considerable expertise in Canada with individuals working on various aspects of the field with a broad range of techniques and facilities. In the next decade, this diverse community can be united by telescopes and instruments that extend observations into a common redshift range. Key facilities include the SKA, a > 30-m optical/NIR telescope and a rejuvenated instrument program on Gemini. High resolution imaging with adaptive optics and high resolution spectroscopy, with particular emphasis on wide wavelength coverage and blue sensitivity are vital instrument capabilities.

*Subject headings:*

## 1. THE ROLE OF THE ISM/IGM IN ASTROPHYSICS

In the lofty quest for insight into the evolution of the universe on scales from stars to galaxies and extending to their large-scale clustering, the study of the interstellar and intergalactic media (ISM and IGM respectively) lies at an intersection. Stars themselves are formed from the dense component of the ISM, which requires an understanding of cooling mechanisms, molecular cloud chemistry and magnetic fields (**Kirk, Johnstone & Basu**[3] 2009). Understanding these initial ISM conditions shapes the IMF, one of the fundamental scalings in astronomy (Urban, **Martel** & Evans 2010). Indeed, simple metrics of ISM density correlate with the rate of star formation. The stars synthesize the chemical elements that enrich the ISM, in addition to dust which is produced in the atmospheres of cool stars. When present in large numbers, the relationship between stars and the ISM can become more tumultuous, producing winds and outflows, connecting the ISM with the IGM and dispersing the stellar products further afield (Pieri, **Martel & Grenon** 2007; **Germain**, Barai & **Martel** 2009). Clusters of galaxies are typified by a hot intra-cluster medium (also enriched with metals) which may play a crucial role in shaping their constituent members through ram pressure interactions with the ISM (**McCarthy** et al. 2008; **Balogh, Navarro & Morris** 2000). Finally, the IGM, the fabric into which the galactic structures are woven, is a blueprint of the universe's density (e.g. **Babul** 1991) and a cosmological tool for probing the history of its ionization, enrichment and baryonic content (e.g. **Ellison** et al 2000). The interplay between UV radiation and neutral hydrogen is now being explored as a technique to discover the highest redshift galaxies at redshifts of 7 and beyond (**Willis** & Courbin 2005; **Willis** et al 2008; **Mentuch** et al. 2008). Given its connection with so many facets of astrophysics, the importance of the ISM and IGM as a field cannot be over-stated.

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## 2. ISM AND IGM RESEARCH IN CANADA

At low redshifts ($z \lesssim 0.1$), it is fairly straightforward to study the various components of the ISM in a direct manner. For example, HI 21cm maps are an important diagnostic for understanding general models of galaxy evolution (e.g. **English** et al. 2003; **Irwin** et al. 2009), specific responses of galaxies of different masses to their environments (e.g. **Carignan** 1999; **English** et al. 2010) and the rate at which gas is turned into stars. Lyman alpha absorption observed in the UV can also be used to probe to column densities below the sensitivity of 21cm maps (e.g. **Coté** at al. 2005). Although the gas mass of a galaxy may be dominated by HI, studies of the ISM extend to many other components, including molecules (**Irwin** et al. 2007; **Rosolowsky** et al. 2007; **Wilson** et al. 2008, 2009), dust (e.g. Cartledge et al. 2005) and HII regions (e.g. **Lee** et al. 2007; **Ellison** et al. 2008; **Rosolowsky** & Simon 2008; **Coté** et al. 2009).

At high redshift, observational techniques can be largely divided into two regimes - direct identification of high redshift galaxies or the use of quasar absorption line spectroscopy. The former technique has proved enormously successful after reaching maturity in the last decade. For example, large numbers of massive sub-mm galaxies at $z \sim 2$ have been discovered with SCUBA (**Chapman** et al. 2003) whose molecular and dust content provides insight in star formation, gas consumption and dust temperatures (e.g. **Chapman** et al. 2004, 2008; **Webb** et al. 2003, 2007). A key project for Canadian involvement has been the Gemini Deep Deep Survey (GDDS, **Abraham** et al. 2004), a complete K-band selected sample of galaxies with $0.4 < z < 2$ which takes advantage of GMOS's specialized nod-and-shuffle technique (**Crampton & Murowinski** 2004) to characterise ISM metallicities at $z \sim 1$ (Savaglio et al. 2005). However, despite advances in understanding the broad-brush properties of the high $z$ ISM, the 'direct' observations of galaxies rarely yield a detailed census of ISM composition. This is the strength of the second commonly used technique in the field, that of quasar absorption line (QAL) spectroscopy.

The tremendous advantage of the QAL technique is that galaxies can be studied to arbitrarily high redshifts without the need for direct detection. The technique can be applied across the electromagnetic spectrum to probe all phases of the ISM from the coldest neutral hydrogen seen in 21cm absorbers (e.g. **York** et al. 2007), to molecules (**York** et al. 2006) and even inferences of dust content in the optical, IR and X-ray (Wang et al. 2004; **Ellison, Hall** & Lira 2005; **Hall** et al. 2006; **Ménard & Chelouche** 2008; **Ménard** et al. 2008). Moreover, the simplicity of this technique means that chemical abundances of galaxies studied in absorption have errors similar to those of stellar abundances measured in Milky Way and nearby dwarf galaxies (e.g. **Venn** et al. 2004)! Numerous studies have used high resolution echelle spectra to determine the abundances of galactic-scale absorbers (namely the damped Lyman alpha systems, DLAs) at $z \sim 3$. Such studies have established the typical rate at which (QAL-selected) galactic metallicity evolves from $z \sim 0.5$ to $z \sim 4$ (e.g. Pettini et al. 1997) and the abundances of dozens of different elements in several hundred galaxies including those as metal-rich as the sun, (e.g. Dessauges-Zavadsky, **Ellison** & Murphy 2009) to those as metal-poor as the IGM (**Ellison** et al. 2010). QAL spectroscopy also represents the *only* technique with which the chemistry of the IGM can be probed. Perhaps the most profound result in this field is that the IGM is not pristine, but contains significant enrichment by heavy elements such as carbon, silicon and oxygen (e.g. **Ellison** et al. 2000) and that this enrichment is present out to at least redshift 5 (Pettini et al. 2003).

In closing this section, it is worth-noting that absorption line spectroscopy has applications beyond the simple characterization of the ISM and IGM and is an important cosmological tool. For example, shifts in the predicted wavelength of metal, molecular and atomic hydrogen lines are placing tantalizing constraints on the time evolution of fundamental constants such as $\mu$ (the ratio of the electron-to-proton mass) and $\alpha$ (the fine structure constant) (e.g. Kanekar et al. 2010; Malec et al. 2010). These observations have produced vociferous debate in the community and more data are required to definitively assess whether Nature's constants vary with time. A positive detection would clearly be one of the most profound physical discoveries in contemporary astrophysics. There is also keen interest in this field amongst Canadian theoretical physicists (e.g. Olive & **Pospelov** 2008). Another example of QALs as cosmological tools is their use as baryometers to test predictions of light element synthesis in the Big Bang. Specifically, the deuterium abundance, which can be measured in both Galactic sightlines and high redshift DLAs (e.g. **Ellison** et al. 2007) is an important determinant of the mass density of baryons in the universe and is one of the few independent metrics other than the cosmic microwave background. Again, Big Bang nucleosynthesis has a following in the Canadian physics community (e.g. **Bird, Koopmans & Pospelov** 2008; Cyburt & **Pospelov** 2009). The IGM is also an important probe of re-ionization; this topic (particularly the use of 21cm observations) is tackled in the white paper by **Pen**.

## 3. SCIENCE DRIVERS IN THE NEXT DECADE

### 3.1. *Atomic gas*

The next decade's study of the ISM/IGM will be characterised by the rendezvous of techniques that are currently largely restricted to certain redshifts. For example, the measurement of the mass of neutral gas in galaxies has been measured with deep, blind HI surveys such as HIPASS out to $z \sim 0.03$, but similarly unbiased HI surveys at higher redshift can only be done with QALs from the ground at $z > 1.7$ (Figure 1). These observations quantify the gas reservoir that is available for star formation as a function of cosmic time and represent important constraints for models of galaxy evolution and feedback processes. Although QAL spectroscopy with UV space telescopes can fill in the 10 billion years that is left unprobed, the extremely time-consuming nature of blind DLA surveys at $z < 1.7$ means that this is a costly venture with HST. Although DLAs have been detected in this range, they are relatively few in number (see the error bars on Figure 1) and they rely on selection by other strong metal lines, which can potentially lead to biases in the selection. A large (> 4-m) UV telescope with moderate resolution spectrograph would be extremely desirable for QAL studies, permitting HI and metals to be traced at $z < 1.7$. Although such a facility is currently not foreseen, the next generation of radio telescopes *will* provide a true revolution.

The Australian SKA pathfinder (ASKAP), in which Canada has a considerable financial, technological and scientific investment will be able to map 21cm in emission out to $z \sim 0.7$. In its final state, the SKA will push this distance out to $z \sim 2.5$ enabling us to determine a full census of the HI interstellar medium over almost the entire Hubble time. In addition to bridging the current redshift gap in our knowledge of the mass of HI gas in galaxies, HI 21cm mapping offers a considerable advantage over QAL spectroscopy in its ability to determine the *spatial* distribution of gas. The ASKAP/SKA will permit imaging of neutral gas flows into galaxies, as well as testing models of gas stripping in different environments. However, perhaps most excitingly, the sensitivity of these telescopes to low column densities of gas will actually be able to image the diffuse intergalactic medium itself, for the first time mapping the cosmic web that is so well known from cosmological simulations (including work by Canadians **e.g. Babul, Martel, Navarro, Thacker, Wadsley**). In order for these simulations to keep pace with the observations, the development of massive parallel supercomputers with thousands of nodes is a must. Such facilities require large consortia, such as the successful C4 collaboration and now the CLUMEQ, developed by Laval, McGill, and the University of Quebec. As more computational resources become available, simulations are able to include ever more sophisticated physics, larger volumes and higher resolution.

Finally, a > 30-m optical telescope will allow absorption line spectroscopy to reach new levels of spatial resolution as individual galaxies become bright enough to use as background sources, permitting 3D topography of the IGM. High resolution spectroscopy of QSOs at $z > 6$ can be used to measure chemical abundances of a variety of elements in the IGM and galaxies (DLAs) alike. This is our most potent opportunity for mapping nucleosynthesis at the highest redshifts. With direct spectroscopic techniques, we will be able to extend ISM studies of Lyman break galaxies from a handful of lensed objects to hundreds of representative galaxies.

### 3.2. *Molecular gas and dust*

Just as the SKA will advance atomic gas studies from the realm of the local to the cosmological, ALMA will do the same for investigations of molecular gas and dust. The negative k-correction of the dust SED compensates for redshift dimming, making millimetre wavelengths ideal for detecting dusty galaxies up to $z \sim 10$. ALMA will actually be able to resolve molecular CO complexes in normal galaxies at $z \sim 3$; again there is synergy with QAL techniques which study $H_2$, but have no spatial information. Many fruitful collaborations could result from this union. Canada is already fully committed to ALMA, so although its importance in the next decade is highlighted here for completeness, it is not included it in the summary of future needs (Section 4).

### 3.3. *The galaxy connection*

One of the past decade's disappointments has been the failure to identify the majority of galaxies associated with the DLA population. Despite a number of concerted imaging campaigns, only a few dozen counterpart galaxies are known, and almost all of them are at $z < 1$ (e.g. **Ellison**, Mallen-Ornelas & **Sawicki** 2005). The main problem is trying to detect a faint galaxy in the glare of a bright QSO. New approaches are clearly needed to connect these studies of the high redshift ISM seen in absorption with global galaxy properties such as mass, luminosity, star formation rate, environment and morphology. Again, the SKA will contribute here, by imaging the galaxies directly at 21cm wavelengths. There are also other possibilities using technology in which Canada excels and can exploit its expertise, such as high resolution AO imaging. Detecting faint galaxies near a bright QSO presents a similar technical challenge to the detection of extra-solar planets, a field in which Canada is leading the world (e.g. **Marois** et al. 2008). Another possibility that circumvents the overwhelming light from the background QSO is attempting to detect the galaxy via its emission lines with IFU spectrographs. This technique has been successfully applied to massive galaxies at $z \sim 2$ (**Forster-Schreiber** et al. 2009) and with a large (30-m or more) optical/NIR telescope the same technique could be applied to fainter absorption galaxies the emission line strengths seem to correlate with the strength of interstellar absorption (**Ménard** et al. 2010). Canada has considerable expertise in the deisgn, construction and use of IFUs (e.g. **Andersen** et al. 2006).

## 4. RESOURCE REQUIREMENTS

In this final section we summarise the facilities that might be expected to make the greatest impact on the field of the extragalactic ISM/IGM

**1. SKA.** The SKA and its pathfinder promises to unite not only the low and high redshift universe, but also these two (currently largely distinct) communities within Canada. This is likely to be the single most important facility for breakthrough science in the next decade and beyond in the study of the neutral ISM/IGM. It will also address a number of issues that bridge the ISM-cosmology field such as measuring 21cm absorption at the epoch or re-ionization and constraining the time evolution of Nature's fundamental constants. It is noteworthy that 23 Canadians are currently involved in ASKAP survey science projects.

**2. Large (>30-m) optical/NIR telescope.** It is imperative that Canada secure access to such a facility, e.g. TMT. This is the cornerstone of all studies of extra-galactic chemical enrichment, using either direct or absorption line spectroscopy.

**3. Medium resolution optical spectroscopy.** A work-horse imaging spectrograph with multi-object capacity is a staple for studies of galaxies at all redshifts. There is still a lot of 8-m science to be done in the ISM/IGM field. Therefore, although access to a large optical telescope is critical, considerable contributions could be made to the field with a rejuvenated program of instruments on Gemini. For a work-horse instrument on a telescope of any size, two design considerations that would make a multi-object imaging spectrograph particularly useful for ISM studies are: 1) wide wavelength coverage in a single setting (e.g., 3500 − 7000 Å at a resolution of $R \sim 2,000$) to facilitate 'direct' abundance studies and 2) blue sensitivity for high redshift work.

**4. High resolution optical/NIR spectroscopy.** A high resolution echelle or echellette ($10,000 < R < 50,000$) is the single most important instrument for measurements of chemical abundances (both in stars and the ISM) and for tracing the IGM. In a field that typically observes fairly isolated objects, detector real estate is best used for wavelength coverage rather than multiple targets. The ideal instrument would function simultaneously from the optical into the IR (such as X-shooter is currently achieving on the VLT). The IR will become increasingly important as we push towards the highest redshifts. Gemini currently lacks a high resolution spectrograph, but would be well served by one. TMT's current instrument possibilities includes HROS as its high resolution instrument.

**5. UV spectroscopy.** Although the SKA will start to close the gap between local and high redshift HI studies, the bridge will be incomplete at $z > 1$ where SKA becomes progressively selective of high HI masses. To fully close the gap, and also to permit follow-up of the chemistry of the ISM/IGM at $z < 1.7$ UV spectroscopy is required. A medium resolution ($2{,}000 < R < 10{,}000$) spectrograph on a > 4-m space telescope is the next step. It is worth noting Canada's growing expertise in UV space astronomy (e.g. **Hutchings, Robert, Drissen, Coté**)

## 5. CLOSING REMARKS

We have aimed to demonstrate that the study of the ISM/IGM is one of the most synergistic fields in astrophysics and that a considerable number of Canadian astronomers have made diverse and important contributions using a range of techniques spanning the UV to the radio and from redshift 0 to 5. The new facilities described here will unite these various groups by allowing them to work on a more common footing. Ultimately, future development will be facility driven and decisions for the next generation of telescopes and instruments will be the midwife for a field that is pregnant with potential.

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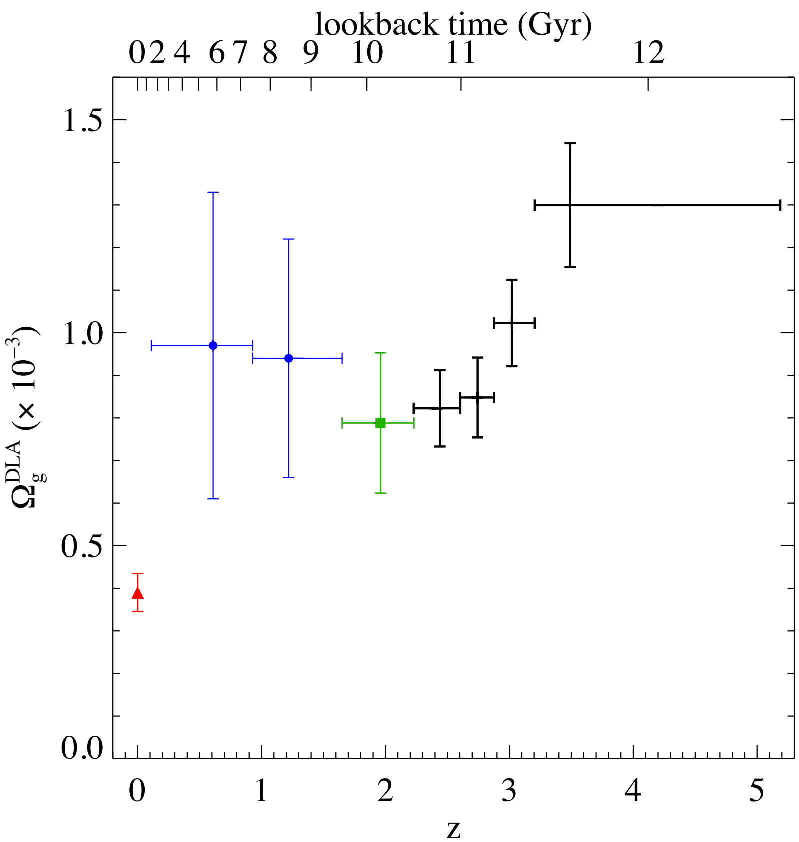


FIG. 1.— The mass density of neutral gas ($\Omega_g$) as a function of redshift, taken from Noterdaeme et al. (2009). Black and green points are from a complete surveys of DLAs, mostly taken from the SDSS DR7. These ground-based surveys for DLAs are cheap and effective and have yielded over 1000 HI selected galaxies at $z > 1.7$. The red triangle is the $z \sim 0$ measurement from the blind HI 21cm emission HIPASS survey (Zwaan et al. 2005). The 10 billion year gap between these data points is currently uniquely the realm of UV QSO absorption line spectroscopy which relies on alternatively (and possibly biased) selection techniques and suffers from much smaller statistics (blue points). The SKA will measure $\Omega_g$ in this intermediate redshift regime.