Previous and Current Research

Katherine A. Kornei

Star Formation and the Interstellar Medium
in High Redshift Galaxies

Understanding the nature of galaxy evolution requires detailed measurements of high redshift objects. With recent advances in both telescope apertures and instrumentation, it is now possible to probe the star-forming properties of high redshift galaxies and make comparisons with local starburst analogs. I use complementary photometric and spectroscopic data sets to study the environment and regulation of star formation in large samples of photometrically-preselected galaxies at 1 < z < 3:

1) In Lyman Break Galaxies at z ∼ 3, I investigate how the strength of the hydrogen recombination line Lyα is correlated with stellar populations (Kornei et al. 2010).

2) At z ∼ 1, I employ diffraction-limited imaging and rest-frame UV spectroscopy to study the properties of galaxies hosting outflowing winds (Kornei et al. 2011a, Kornei et al. 2011b).

Lyα and Star Formation

High-redshift galaxies typically exhibit elevated star-formation rates relative to local galaxies (Reddy et al. 2008). Investigating how spectral signatures of star formation are correlated with stellar populations is important to understanding the physical processes regulating star formation. Objects such as Lyman Break Galaxies (LBGs) and Lyα-emitters (LAEs) – where the former are selected via color cuts around the Lyman limit at 912 Å in the rest-frame (Steidel et al. 1996, Steidel et al. 1999) and the latter are isolated by requiring strong HI Lyα emission at 1216 Å (e.g., Cowie & Hu 1998, Rhoads et al. 2000) – can be efficiently selected in redshift space and consequently form the basis of numerous multiwavelength data sets (e.g., Steidel et al. 2003, Lai et al. 2008). LAEs have been observed to be generally young, low mass, and relatively dust-free (Gawiser et al. 2006) while broadband-selected LBGs typically show a larger spread in stellar populations and include massive, strongly dust-attenuated objects (Shapley et al. 2001). In order to understand if the differences in stellar populations between LBGs and LAEs are related to the strength of Lyα emission, it is necessary to analyze a controlled sample of objects drawn from the same parent UV luminosity distribution.

Within a sample of 321 LBGs at z ∼ 3, I found significant trends between the strength of Lyα emission and stellar populations (Kornei et al. 2010). Specifically, objects exhibiting strong line emission are more likely, on average, to be older, less dusty, and less vigorously forming stars than their counterparts with weaker Lyα emission (or the line in absorption). These observed correlations between Lyα emission and stellar populations (Figure 1) are consistent with the physical picture proposed by Shapley et al. (2001), in which young, dusty LBGs experience vigorous outflows due to supernovae and stellar winds that may decrease the galaxies’ dust and gas covering fractions over several tens of Myr. With lower covering fractions, Lyα photons experience a decreased absorption path length and consequently escape from galaxies more frequently. The Lyα “escape fraction” is therefore a probe of the geometry of gas and dust in a galaxy’s interstellar medium. By comparing the observed Lyα luminosity and the predicted Lyα luminosity (inferred from the star-formation
rate), one can obtain a quantitative measure of the Lyα escape fraction.

At $z \sim 3$, I found that objects consistently had escape fractions less than unity, indicating that Lyα photons appear to experience more attenuation than continuum photons (Kornei et al. 2010). This result is consistent with the physical picture of an interstellar medium composed of well-mixed gas and dust, although it is important to note the systematic uncertainty of slit losses as the observed Lyα luminosity was estimated spectroscopically (Steidel et al. 2011). With a new data set of Lyα narrowband imaging in the SSA22a field centered on a redshift spike at $z = 3.09$, I am currently investigating the Lyα escape fraction for a sample of over one hundred LBGs and LAEs; these imaging data obviate the uncertainty of slit losses and also enable a direct comparison of the spatial extents of Lyα and continuum radiation. With ancillary photometry spanning from the rest-frame ultraviolet to the near-infrared, I will estimate dust extinction and study how the Lyα escape fraction varies with attenuation.

**Galactic Winds**

Other spectral features besides Lyα can also be used to measure the properties of the interstellar medium. In star-forming galaxies at a range of redshifts, interstellar absorption lines – SiII, CII, FeII, MgII, and NaI, for instance – show blueshifts with respect to a systemic frame defined by nebular emission lines (Heckman et al. 2000, Weiner et al. 2009, Rubin et al. 2010, Law et al. 2011). These shifts are the kinematic signature of large-scale outflows of gas attributed to the combined energy of stellar winds and supernovae. Outflows have a significant effect on their host galaxy as winds remove gas that would otherwise be used for the assembly of stars (Binney 2004). Winds also entrain a variety of elements and expel metals into the intergalactic medium (Oppenheimer & Davé 2006). In the distant universe, outflows may have cleared sightlines through galaxies that enabled ionizing photons to escape relatively unimpeded. These photons ionized the surrounding...
intergalactic medium to produce the largely ionized universe that we observe today (Becker et al. 2001). Studying the nature and prevalence of outflows is critical to better understanding the driving forces of galaxy evolution on stellar, galactic, and intergalactic scales.

Given the apparent stellar origin of winds, investigating the star-forming properties of galaxies hosting outflows is important to elucidating the specific thresholds of star formation necessary to drive winds. Higher velocity outflows are seen in systems with larger star-formation rates (Martin 2005, Rubin et al. 2010) and galaxies with higher star-formation rate surface densities also exhibit stronger winds (Chen et al. 2010, Law et al. 2011). However, some authors have found only a weak correlation between outflows and star-formation rate surface density (Rubin et al. 2010, Steidel et al. 2010); the different methods used for parametrizing the relevant galaxy areas corresponding to star formation may explain the disparate results reported by various authors.

Only recently have studies begun to investigate outflows at $0.5 < z < 1.5$, an epoch particularly interesting as it corresponds to the time when the global star-formation rate began declining to its present-day value (Reddy et al. 2008). Weiner et al. (2009) found that outflows – traced by MgII and MgI in the rest-frame UV – are ubiquitous in galaxies at $z \sim 1.4$, irrespective of AGN activity or merger signatures. Rubin et al. 2010 noted a correlation between outflow velocity and star-formation rate in a sample of galaxies at $z \sim 1$ but failed to find a trend between outflows and star-formation rate surface density. Both the Weiner et al. 2009 and Rubin et al. 2010 investigations relied heavily on composite spectra due to the low signal-to-noise ratios of their individual observations.

As part of my thesis, I studied outflows in a sample of 72 objects at $0.7 < z < 1.3$ from the DEEP2 redshift survey (Kornei et al. 2011a, in prep.). These data, in the Extended Groth Strip (EGS), are part of a larger sample of objects for which we obtained Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) spectroscopy (Figure 2, left). We measured the shifts of resonance FeII lines relative to a systemic frame defined by [OII] and other nebular lines on a per-object basis. We found significant outflows in $\sim 40\%$ of the sample, calling into question the ubiquity of outflows in $z \sim 1$ star-forming galaxies. A small fraction of objects exhibit redshifted FeII absorption, perhaps indicative of the cold gas inflows predicted in cosmological simulations (Dekel et al. 2009). Intriguingly, MgII and fine-structure FeII emission are also present in the sample; these features are not seen in local starburst samples (Leitherer et al. 2011). Along with FeII absorption-line measurements, MgII and FeII* are complementary probes of circumgalactic gas (Kornei et al. 2011b, in prep., Rubin et al. 2011, Prochaska et al. 2011). Using ancillary Hubble Space Telescope (HST) imaging available for the EGS, I developed a new technique for estimating galaxy areas corresponding to regions above a physical luminosity threshold. With these areas and GALEX-derived star-formation rates, I found a $3\sigma$ trend between outflow velocity and star-formation rate surface density (Figure 2, right). This trend is significantly stronger than the correlation observed between outflow velocity and star-formation rate, suggestive that the concentration of star formation modulates outflows more than the total number of stars being formed. With galaxy inclinations estimated from axis ratios, I observed that face-on galaxies generally showed more blueshifted FeII features than edge-on systems. The finding is consistent with the theoretical prediction that winds escape along the steepest pressure
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Fig. 2.—Left: Keck LRIS spectrum spanning $\sim 1520-2900$ Å in the rest-frame, showing prominent SiII, CIV, FeII, MgII, and MgI interstellar absorption features (dashed lines). The inset HST thumbnail is the object imaged in the F606W (V-band) filter. Right: Star-formation rate surface density versus outflow velocity, where the velocity of the FeII lines was measured relative to a systemic redshift frame defined by [OII] and Balmer features. I find a correlation between outflow velocity and star-formation rate surface density at the 3σ level after removing two extremely compact objects with uncertain area measurements (not shown). Objects with higher star-formation rate surface densities exhibit more blueshifted interstellar FeII lines, indicative of faster outflows (Kornei et al. 2011a, in prep.).

Related Research

Observations of nearby star-forming regions afford the advantage of spatial scale and serve as a window to high redshift star formation. In the local starburst galaxy NGC 253 ($d \sim 4$ Mpc), intense star formation characterizes a super star cluster near the galactic nucleus. Using near-infrared spectroscopy and diffraction-limited imaging, I studied the mass, dust attenuation, and color of this super star cluster (Kornei & McCrady 2009). Assuming a Kroupa (2001) stellar initial mass function (IMF), I calculated a cluster mass of $1.4 \times 10^7 M_\odot$. Given this cluster’s extremely large mass, I obtained follow-up high-resolution NIRSPEC spectroscopy to kinematically confirm this measurement. Estimates of the cluster’s velocity dispersion, paired with measurements of its half-light radius, enable estimates of the cluster virial mass independent of any IMF assumptions (Kornei et al. 2011c, in prep.). I am investigating if the cluster IMF is deficient in low mass stars, as has been suggested for super star clusters both in the local M82 starburst (McCrady et al. 2003) and in distant submillimeter-selected galaxies (Baugh et al. 2005).

References


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