Starbursts in the Far-Ultraviolet

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Abstract. Starbursts are a significant component of the present-day universe, and offer unique laboratories for studying the processes that have regulated the formation and evolution of galaxies and the intergalactic medium. The combination of large aperture size, medium-to-high spectral resolution, and access to the feature-rich far-ultraviolet band make FUSE a uniquely valuable tool for studying starbursts. In this paper, I summarize several of FUSE’s “greatest hits” for starbursts. FUSE observations of the strong interstellar absorption lines show that powerful starbursts drive bulk outflows of the neutral, warm, and coronal phases of the ISM with velocities of several hundred km/s. These are similar to the outflows seen in Lyman Break Galaxies at high redshift. The weakness of OVI emission associated with these flows implies that radiative cooling by coronal gas is not energetically significant. This increases the likelihood that the flows can eventually escape the galaxies and heat and enrich the intergalactic medium. FUSE observations show that local starburst galaxies are quite opaque below the Lyman edge, with typically no more than ~6% of the ionizing photons escaping (even in starbursts with strong galactic winds). This has potentially important implications for the role of star forming galaxies in the early reionization of the universe. FUSE observations of molecular hydrogen in starbursts show very low molecular gas fractions in the translucent ISM (even in starbursts where mm-wave data show that the ISM is primarily molecular). This implies that the molecular gas is all in dense clouds that are completely opaque in the far-UV. The high far-UV intensity in starbursts photodissociates molecular hydrogen in the diffuse ISM. Finally, FUSE observations of chemical abundances in the neutral ISM in dwarf starburst galaxies suggest that the metallicity in the HI (which dominates the baryonic mass budget) may be systematically lower than in the HII regions. This would have important implications for galactic chemical evolution.

1. Introduction

Starbursts are intense episodes of star formation that dominate their “host” galaxy. Classically, they have been defined in terms of their short duration. That is, given the observed star formation rate, the time it would take to consume the presently available reservoir of interstellar gas and/or the time it would take to produce the present-day stellar mass is much less than the age of the universe. An alternative definition is that a starburst has a high intensity: the star formation rate per unit area is very large compared to normal galaxies. As shown by Kennicutt (1998), these two definitions are functionally equivalent: the gas consumption time is a systematically decreasing function of the star formation rate per unit area. Extreme starbursts have gas consumption times
of only \( \sim 10^8 \) years and star formation rates per unit area thousands of times larger than the disk of the Milky Way.

Starbursts are an important source of light, metals, and high-mass star-formation in the local universe (e.g. Heckman 1998). Their cosmological relevance has been highlighted by their many similarities to star forming galaxies at high-redshift. In particular, local UV-bright starbursts appear to be good analogs to the Lyman Break Galaxies (Meurer et al. 1997; Shapley et al. 2003; Heckman et al. 2005) and so can be used as a “training set” to provide a thorough understanding of rest-frame UV spectral diagnostics that are critical for studying star-formation in the early universe. Starbursts can contain millions of OB stars, and hence they also offer a unique opportunity to test theories of the evolution of massive stars.

The far ultraviolet spectral window is a key one for understanding starbursts. This is where the intrinsic spectral energy distribution of a starburst stellar population peaks. These hot massive stars have photospheric and wind spectral features in the far-UV that provide key information about the starburst age, metallicity, and initial mass function (Robert et al. 2003; Pellerin, this conference). The far-UV region provides powerful (and in some cases, unique) diagnostics of the physical, chemical, and dynamical properties of the interstellar medium from cold molecular through hot coronal phases. Finally, FUSE is well suited to the problem: its LWRS aperture is an excellent match to the angular sizes of the brightest starbursts, and its spectral resolution allows the interstellar lines to be resolved in almost all cases.

In the following, I will describe what we have learned from FUSE about the interstellar medium in starbursts.

2. Dust in Starbursts

While the peak of the intrinsic spectral energy distribution in starbursts peaks in the far-UV band, this output is significantly modified by dust. The high star formation rate per unit area that defines a starburst directly implies a correspondingly high column density of interstellar gas (Kennicutt 1998), and hence a high dust column.

The situation is far from hopeless however! Globally, the volume-averaged emissivity of star forming galaxies in the local universe in the far-IR (IRAS) and vacuum UV (GALEX) implies that \( \sim 1/3 \) of the UV starlight escapes and \( \sim 2/3 \) is absorbed by dust and reradiated in the far-IR (Buat et al. 2005). However, this ratio of UV/far-IR flux varies by about three orders-of-magnitude from galaxy to galaxy, and in a systematic way: the most massive, most metal-rich galaxies with the highest star-formation rates are the dustiest (e.g. Heckman et al. 1998; Martin et al. 2005). Since FUSE is restricted to studying relatively UV-bright starbursts, the observed sample is therefore biased in favor of metal-poor dwarf starburst systems. However, we have taken pains in our FUSE program to broadly sample starburst parameter space.

What is the effect of this dust on the emergent far-UV radiation? Meurer, Heckman, & Calzetti (1999) used a combination of IUE spectra and IRAS data to demonstrate a rather surprising result: starburst galaxies show a correlation between the fraction of the UV radiation that is absorbed and converted to far-IR
and the spectral slope (color) of the emerging vacuum UV radiation. This result is NOT consistent with a simple picture of a homogeneous mix of stars and dust in which the observed UV light arises in thin outer “skin” (photosphere) of the starburst. It is instead consistent with viewing the UV light from the starburst filtered through an ISM filled with dusty clouds (Gordon et al. 1997; Charlot & Fall 2000). This model can also account for the relatively grey starburst extinction curve - or more properly, the “effective attenuation law” (Calzetti 2001). Leitherer et al. (2002) and Buat et al. (2002) have used HUT and FUSE spectra respectively to show that this effective attenuation law can be smoothly extrapolated from the IUE band into the far-UV band.

3. Starburst-Driven Outflows

3.1. Background

By now, it is well-established that galactic-scale outflows of gas are a ubiquitous phenomenon in the most actively star-forming galaxies in the local universe (see Heckman 2002 for a recent review). These outflows are potentially very important in the evolution of galaxies and the intergalactic medium. For example, by selectively blowing metals out of shallow galactic potential wells, they may explain the tight relation between mass and metallicity in galaxies (Larson 1974; Tremonti et al. 2004). This same process would have enriched the intergalactic medium in metals at early times (Adelberger et al. 2003), and could be responsible for the fact that the majority of metals in galaxy clusters are in the intracluster medium (e.g. Loewenstein 2004).

The engine that drives the observed outflows in starbursts is the mechanical energy supplied by massive stars in the form of supernovae and stellar winds (Leitherer & Heckman 1995). The dynamical evolution of a starburst-driven outflow has been extensively discussed (e.g. Suchkov et al. 1994 Tenorio-Tagle & Munzo-Tunon 1998; Strickland & Stevens 2000). Briefly, the deposition of mechanical energy by supernovae and stellar winds results in an over-pressured cavity of hot gas inside the starburst. This hot gas will expand, sweep up ambient material and thus develop a bubble-like structure. If the ambient medium is stratified (like a disk), the superbubble will expand most rapidly in the direction of the vertical pressure gradient. After the superbubble size reaches several disk vertical scale heights, the expansion will accelerate, and it is believed that Raleigh-Taylor instabilities will then lead to the fragmentation of the bubble’s outer wall (e.g. MacLow, McCray, & Norman 1989). This allows the hot gas to “blow out” of the disk and into the galactic halo in the form of a weakly collimated bipolar outflow (i.e. the flow makes a transition from a superbubble to a superwind). The wind will then carry entrained interstellar material out of the galactic disk and into the halo, and will also accelerate ambient halo clouds. These outflowing clouds will give rise to blueshifted interstellar absorption-lines in starbursts.

3.2. The FUSE Perspective

FUSE has contributed to our understanding of these outflows in two ways. First, the interstellar absorption lines in the FUSE band allow us to study the dynamics
of the neutral, warm, and coronal phases of the outflow. Second, observations of OVI line emission with FUSE allows us to assess the energetic importance of radiative cooling by the coronal gas. This has important implications for the dynamical evolution of the wind.

The use of interstellar absorption-lines to study starburst outflows offer several distinct advantages. Since the gas is seen in absorption against the background starlight, there is no possible ambiguity as to the sign (inwards or outwards) of any radial flow that is detected, and the outflow speed can be measured directly. Moreover, the strength of the absorption will be related to the column density of the gas. In contrast, the X-ray or optical surface-brightness of the emitting gas is proportional to the emission-measure. Thus, the absorption-lines more fully probe the whole range of gas densities in the outflow, rather than being strongly weighted in favor of the densest material (which may contain relatively little mass). Finally, the results of these studies can be directly compared to the properties of the outflows seen in the interstellar absorption lines in high-redshift Lyman Break Galaxies (e.g. Shapley et al. 2003).

We (Heckman et al. 2001a; Vasquez et al. 2004) have undertaken FUSE and STIS investigations respectively of the dwarf starburst galaxy NGC 1705. In combination, these serve as a nice case study of the power of absorption line spectroscopy to elucidate the physics of starburst driven outflows. This nearby (D = 6.2 Mpc) dwarf starburst was first investigated in detail by Meurer et al. (1992), who established it as a prototypical example of a dwarf starburst undergoing mass-loss. They were able to delineate a kpc-scale fragmented ellipsoidal shell of emission-line gas that was expanding at roughly 50 km s\(^{-1}\) along our line-of-sight. They also showed that the population of supernovae in the young super star cluster (NGC 1705-1) was energetically-sufficient to drive this flow.

Our analysis of FUSE and STIS echelle mode spectra show that the dynamics of the outflow are quite different in the neutral, warm (photoionized), and coronal (shock-heated) phases. The coronal phase gas (as probed by OVI, CIV, SiIV, and SIV) is flowing out of the starburst at a velocity of ~80 km s\(^{-1}\). However, the mass and kinetic energy in the outflow is dominated by the warm photoionized gas which is also seen through its optical line-emission. The kinematics of this warm gas are compatible with a simple model of the expansion at ~50 km/s of a superbubble driven by the collective effect of the kinetic energy supplied by supernovae in the starburst. However, the observed properties of the OVI absorption in NGC 1705 are not consistent with the simple superbubble model, in which the OVI would arise in a conductive interface inside the superbubble’s outer shell. The relative outflow speed of the OVI is too high and the observed column density is much too large.

We argue that the superbubble has begun to blow out of the ISM of NGC 1705. During this blow-out phase the superbubble shell accelerates and fragments. The resulting hydrodynamical interaction as hot outrushing gas flows between the cool shell fragments will create intermediate-temperature coronal gas that can produce the observed OVI absorption. For the observed flow speed, the observed OVI column density is just what is expected for gas that has been heated and which then cools radiatively (Heckman et al. 2002).
Figure 1. The blueshift of the centroid of the interstellar absorption lines (relative to the galaxy systemic velocity) is plotted as a function of the starburst luminosity (taken as the sum of the far-UV and far-IR luminosity) for a sample of 21 starbursts observed by FUSE. Outflows at velocities of over a hundred km/s are common in powerful starbursts. The seven data points plotted at \( \log v_{\text{out}} = 1.2 \) represent upper limits on outflow speed.

In addition to detailed investigation of favorable cases like NGC 1705, we are also undertaking a comprehensive survey of the dynamics of the ISM in a large sample of starburst galaxies observed to date with FUSE. In a first pass through the data we have identified in each starburst the strongest interstellar lines that are relatively “clean” (not severely blended with foreground Milky Way absorption lines). These are typically lines arising in the neutral or warm-ionized phases (we exclude OVI in this first pass, since it lies in a complex portion of the spectrum). We then have measured the line width and radial velocity relative to the published galaxy systemic velocity. The first results are shown in Figure 1. It is clear that there is a strong trend for the outflow velocity to increase with the
Figure 2. \textit{FUSE} spectra of the OVI1031.9 interstellar absorption-line, tracing outflowing coronal-phase gas. The absorption covers the range from \(v_{\text{sys}}\) to a maximum blueshift of \(\sim 700\) km s\(^{-1}\) in the powerful starburst NGC 3310 (left panel) and \(\sim 140\) km s\(^{-1}\) in the starbursting irregular galaxy NGC 4214 (right panel).

intrinsic UV luminosity of the starburst (which will be proportional to the star formation rate, and hence to the supernova heating rate). For starbursts more luminous than a few \(\times 10^{10} L_\odot\) (SFR \(> 10 M_\odot\) per year), the outflow velocity at line center is several hundred km/s. The lines are very broad, and the maximum outflow speeds approach \(\sim 10^3\) km/s (see Figure 2). This is consistent with a simple model in which the clouds that are initially at rest are accelerated to some terminal velocity by the ram pressure of the wind (see Heckman 2002).

The impact that these outflows have on the evolution of galaxies and the intergalactic medium depend critically upon whether they are able to escape the galaxy potential well and eject material into the intergalactic medium. A necessary condition for the outflow to escape is that radiative losses are not severe enough to drain energy from the wind, causing it to stall (e.g. Wang 1995). The X-ray luminosity of the wind is typically on of-order 1\% of the rate at which supernovae supply kinetic energy. Thus, radiative losses from hot \((T \geq 10^6\) K) gas will not be dynamically significant. \textit{FUSE} observations of OVI emission allow us to measure the importance of cooling by coronal gas. So far, OVI emission has been searched for in four starbursts: M 82 (Hoopes et al. 2003), NGC 1705 (Heckman et al. 2001a), NGC 3079 (Hoopes, this conference), and NGC 4631 (Otte et al. 2003). The line is only detected in the last case, and in all four galaxies the data imply that radiative cooling by the coronal gas is not sufficient to quench the outflow.

4. The Escape of Ionizing Radiation

The intergalactic medium (IGM) contains the bulk of the baryons in the universe (e.g., Fukugita, Hogan, & Peebles 1998). Determining the source and strength of the metagalactic ionizing radiation field and documenting its cosmic evolution is crucial to understanding the fundamental properties of the IGM at both low- and high-redshift. The two prime candidates for producing the background are QSOs and star-forming galaxies. While the contribution to the ionizing background from QSOs can be estimated with reasonable accuracy, considerably less
is known about the contribution from galaxies. QSOs alone appear inadequate to produce the inferred background (e.g., Madau, Haardt, & Rees 1999), especially at $z \geq 3$ where their co-moving space density declines steeply with increasing redshift (Fan et al. 2001). Moreover, there are only rather indirect constraints on the contribution of galaxies to the ionizing background in the low-redshift universe (e.g., Giallongo, Fontana, & Madau 1997; Devriendt et al. 1998; Shull et al. 1999).

The greatest uncertainty in determining the role of star forming galaxies to the reionization of the universe is the value for $f_{esc}$ - the fraction of the ionizing photons that escape and reach the IGM. It seems clear that the leakage of ionizing radiation out of galaxies must be determined by the structure/topology of the ISM. The hope is that investigations of local star forming galaxies will allow us to understand the physical processes that determine $f_{esc}$ so that we can apply these lessons to high redshift galaxies for which our information is less complete.

Leitherer et al. (1995) reported the first direct measurements of $f_{esc}$ using the Hopkins Ultraviolet Telescope to observe below the rest-frame Lyman edge in a sample of four local starbursts, and these data were later reanalyzed by Hurwitz, Jelinsky, & Dixon (1997). The resulting upper limits on $f_{esc}$ were typically 10%. Deharveng et al. (2001) have obtained similar data with FUSE for the starburst galaxy Mrk 54 at $z = 0.0448$. No flux was detected below the Lyman edge in the rest frame. By comparison with the number of ionizing photons derived from the H$\alpha$ line, they set an upper limit to $f_{esc}$ of 6%. Similar types of investigations have been undertaken at high redshift with conflicting results (Steidel et al. 2001; Malkan et al. 2003).

My colleagues and I have used FUSE in a different way to constrain $f_{esc}$ in a sample five of the UV-brightest local starburst galaxies ( Heckman et al. 2001b). We showed that the strong CII$\lambda$1036 interstellar absorption-line is black in its core. Since the photoelectric opacity of the neutral ISM below the Lyman-edge will be significantly larger than in the CII line, we were able to use these data to set a typical upper limit on $f_{esc}$ of 6% in these galaxies. Inclusion of absorption of Lyman continuum photons by dust grains will further decrease $f_{esc}$ (by up to an order of magnitude in some cases). We also assessed the idea that the strong galactic winds discussed above can clear channels through their neutral ISM and increase $f_{esc}$ (e.g. Fujita et al. 2003). We showed empirically that such outflows may be a necessary - but not sufficient - part of the process for creating a relatively porous ISM.

5. Molecular Gas

Molecular hydrogen is the fuel for star formation, so it is natural to expect large amounts of $H_2$ to exist in starbursts. Indeed, millimeter-wave observations using CO as a tracer imply that molecular gas is the dominant phase by mass in typical starbursts (e.g Gao & Solomon 2004). However, observations of some dwarf starburst galaxies reveal little or no CO emission, such as NGC 1705 (Greve et al. 1996) and I Zw 18 (e.g., Gondhalekar et al. 1998). The lack of CO detections is difficult to interpret for metal-poor galaxies because the CO to $H_2$ conversion is metallicity dependent (Wilson 1995). There are numerous transitions
of molecular hydrogen in the far-UV. Furthermore, far-UV absorption studies can probe \( \text{H}_2 \) to column densities much lower than can be studied through CO mm-wave line emission, making it possible to study \( \text{H}_2 \) in the diffuse interstellar medium (ISM). However, unlike radio observations, far-UV measurements are profoundly affected by extinction.

We have used FUSE to search for \( \text{H}_2 \) absorption in five starburst galaxies: NGC 1705, NGC 3310, NGC 4214, M83 (NGC 5236), and NGC 5253 (Hoopes et al. 2004). We tentatively detected weak absorption in M83 and NGC 5253 and set upper limits in the other galaxies. Conservative upper limits on the mass of molecular gas detected with FUSE are many orders of magnitude lower than those inferred from CO mm-wave measurements for the four galaxies in our sample in which CO has been detected.

This indicates that almost all the \( \text{H}_2 \) in starbursts is in the form of clouds with column densities high enough to make them completely opaque to far-UV light. This gas can therefore not be probed with far-UV absorption measurements. The far-UV continuum visible in the FUSE spectra passes through the translucent ISM between the dense molecular clouds, which must then have an areal covering factor less than one. The complex observational biases related to varying extinction across the extended UV emission in the FUSE apertures prevent an unambiguous characterization of the diffuse \( \text{H}_2 \) in these starbursts. However, the evidence suggests that there is a significantly lower molecular fraction in the diffuse interstellar medium compared to similarly reddened sight lines in the Milky Way.

This is consistent with the higher photo-destruction rate of \( \text{H}_2 \) due the greatly elevated intensity of the far-UV radiation field in the diffuse ISM in starbursts compared to the Milky Way (Vidal-Madjar et al. 2000). It is also consistent with qualitatively similar results in the Magellanic Clouds (Tumlinson et al. 2002; Tumlinson, this meeting).

6. The Metallicity of the Neutral Phase

The chemical abundances in galaxies provide a unique probe of the past history of star-formation. For star-forming galaxies essentially all our information about chemical abundances pertains to the bright H II regions associated with recent star-formation. This gas is a very minor fraction of the total ISM mass and may not be representative (since it is potentially subject to self-pollution by the associated massive stars). This problem is especially acute for dwarf galaxies, where the majority of the total baryonic mass (including stars) is in the H I phase of the ISM. In particular, there is considerable debate about whether metal-poor dwarf starbursts are undergoing their first episodes of star-formation, making them local examples of primeval galaxies (e.g., Izotov & Thuan 1999). While the Oxygen abundances in the H II regions are typically of-order 1/10 solar in these galaxies, the abundances in the mass-dominating H I phase could potentially be much lower if self-pollution of the H I phase is important.

FUSE spectra allow these ideas to be tested by providing access to H I and metal absorption lines, which can be used to determine the abundances in the neutral gas outside of star forming regions. This technique has been applied to a handful of dwarf starburst galaxies, with the results described in a series
of papers by several different groups (Aloisi et al. 2003; Cannon et al. 2004; Heckman et al. 2001; Lebouteiller et al. 2003; Lecavelier des Etangs 2003; Thuan et al. 2002). For the most part, these investigations have found that the metal abundances in the neutral gas are significantly lower than those in H II regions (by factors of $\sim 3$ to 10). However, uncertainties associated with optical depth effects and ionization corrections must be borne in mind. These issues have been discussed in more detail in the contributions by Aloisi, Cannon, and Lebouteiller at this meeting.

A robust conclusion is that even if the metal abundances from FUSE are taken as lower limits, they definitely require that substantial previous star formation has occurred, and over time scales long enough for the enrichment of the ISM by intermediate mass stars -in the case of nitrogen- and Type Ia supernovae -in the case of iron (Aloisi et al. 2003). This indicates that these dwarf starbursts are not primeval galaxies undergoing their first significant episode of star formation.

7. Summary and Future Prospects

Starbursts are important components of the present day universe, and wonderful laboratories for studying galaxy evolution, massive stars, and the ISM. The far-UV band is rich with spectral features that provide unique diagnostics of the physical, chemical, and dynamical state of the ISM from its molecular to its coronal phases. The combination of relatively high spectral resolution and a large spectroscopic aperture make FUSE very well suited to the investigation of starbursts. In this review I have summarized some of the highlights of these investigations:

- Powerful starbursts drive bulk outflows of the ISM into their galaxy halo at velocities of several hundred km/s. Similar outflows are seen in Lyman Break Galaxies at high-redshift.
- Radiative cooling/quenching of these outflows by coronal gas is not dynamically significant. This supports the idea that they are the mechanism by which metals were ejected from low mass galaxies and the IGM was metal-enriched.
- Present-day starbursts are quite opaque to their Lyman continuum radiation. This has interesting implications for the possible reionization of the universe by early starbursts.
- The translucent ISM in starbursts has a very low molecular gas fraction (most likely due to a high ambient UV intensity in the ISM).
- The neutral ISM in dwarf starbursts appears to be significantly less metal-enriched than the HII regions. If confirmed, this would have important implications for the chemical evolution of galaxies, since the neutral phase of the ISM dominates the baryonic mass-budget in dwarf galaxies like these.
The future prospects are very bright. The All-sky Imaging Survey of the GALEX mission (Martin et al. 2005) can provide a large sample of starbursts in the local universe that are bright enough for FUSE to obtain very high quality spectra with moderate exposures times. This offers us the opportunity to attack the problems summarized above for a sample large enough to draw statistically robust conclusions across the broad range of fundamental starburst properties (mass, metallicity, star formation rate, etc).

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Starbursts

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