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STARBURST-DRIVEN GALACTIC SUPERWINDS

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Abstract. I provide an observational review of the properties of starburst-driven galactic superwinds, focusing mainly on recent results pertinent to the transport of metals and energy into the IGM. Absorption-line studies are providing rich kinematic information on both neutral and ionized gas in superwinds, with observed mass flow rates similar to the star formation rate and outflow velocities comparable to or greater than the escape velocity. *FUSE* observations of the OVI doublet provide previously unattainable information regarding outflow velocities and radiative cooling rates in hot gas at $T \sim 3 \times 10^5$ K. Emission from gas at temperatures of 10^4 K and $\sim 5 \times 10^6$ K is now being studied with unprecedented spatial resolution using *HST* and *Chandra*, tracing the complex interaction of the still-invisible wind of SN-ejecta with the ambient ISM entrained into these outflows. I discuss the implications of these observations for our understanding of starburst-driven outflows.

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1. INTRODUCTION

Observations of edge-on starburst galaxies show weakly collimated 10 kpc-outflows of gas (Fig. 1), with outflow velocities of several hundred kilometers per second (McCarthy, Heckman, & van Breugel 1987; Heckman, Armus, & Miley 1990; Armus, Heckman, & Miley 1990). Tracers of warm ionized gas such as Hα emission show filaments and arcs of emission extending outward from the nuclear regions of the host galaxy galaxy, which outline the surfaces of bipolar outflow cones of opening angle $\theta \sim 60$deg. The primary observational probes of these outflows have historically been been optical emission lines (Armus et al. 1990), and X-ray emission (Dahlem, Weaver, & Heckman 1998), although all phases of the ISM have been detected (Dahlem 1997). The X-ray emission correlates well spatially with the Hα emission (see Fig. 1), although in many cases the X-ray observations trace these outflows out to larger galactocentric radii ($\gtrsim$ 20 kpc, Read, Ponman, & Strickland 1997) than the Hα observations.

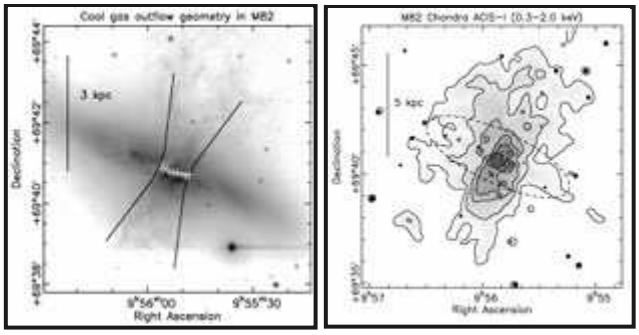

Figure 1. (a) Narrowband Hα+continuum image of the nearby (D = 3.63 Mpc) edge-on starburst galaxy M82, which shows filaments of 10^4 K gas flowing out of the galaxy at ~ 600 km/s along the minor axis. The white crosses mark the positions of ~ 50 young SNRs detected in radio observations of the central 800 × 100 pc starburst region. (b) A soft X-ray *Chandra* ACIS-I image of M82, showing gas with characteristic temperature of a few million degrees.

These outflows result from the energy returned to the ISM by the recently-formed massive stars in the starburst. Core collapse supernovae and massive star stellar winds, from ~ 10^6 O & B stars in galaxies like M82 or NGC 253, return large amounts of kinetic energy along with metal-enriched ejecta to the ISM. Radio observations of local starbursts reveal large numbers of young SNRs within the starburst region (Kronberg, Biermann, & Schwab 1981; Muxlow et al. 1994). Age estimates for the starburst stellar populations (~ 10 Myr for M82, 20 - 30 Myr in NGC 253 [Satyapal et al. 1997; Engelbracht et al. 1998]) agree well with the dynamical ages of the outflows, τ_{dyn} ~ 10 kpc/500 km/s ~ 20 Myr. The kinetic energy of the individual remnants and wind-blown bubbles is thermalized via shocks as SNRs overlap and interact, creating a hot (T ~ 10^8 K), high pressure (P/k ~ 10^7 K cm^{-3}) bubble of metal-enriched gas in the starburst region (Chevalier & Clegg 1985). This "superbubble" expands preferentially along the path of least resistance (i.e. lowest density), breaking out of the disk of the galaxy along the minor axis after a few million years. The hot gas then expands at higher velocity ($v \gtrsim$ 1000 km/s) into the low density halo of the galaxy as a superwind, dragging along clumps and clouds of cool dense entrained ISM at lower velocity (see Suchkov et al. 1994).

Many excellent reviews of both observations and theory of starburst-driven superwinds already exist (Heckman, Lehnert, & Armus 1993; Heckman 1998). In this contribution I highlight recent results related to the issue of mass, metal and energy transport by superwinds out of galaxies and into the IGM.

2. STARBURST GALAXIES IN THE LOCAL UNIVERSE

The average starburst galaxy in the local universe (weighted by FIR luminosity, a convenient estimator of the star-formation rate (SFR) in all but the most metal-poor galaxies) has a FIR luminosity of $L_{FIR} \sim L_*$ (Soifer et al. 1987) and a SFR of a few $M_\odot$ yr^{-1} (Heckman et al. 1993). In general these galaxies are late type spiral galaxies with rotational velocities v_{rot} ~ 200 km/s, local examples being NGC 253, NGC 3628 & NGC 4945. It is these "typical" starbursts that show most clearly evidence for starburst-driven outflows (Armus et al. 1990), and I shall mainly concentrate on discussing this class of galaxies. In terms of overall significance, approximately ~ 25% *of all high mass star-formation in the the local universe is in starburst galaxies* (Heckman 1998), and it is likely that all starbursts drive outflows. This is not a rare or exotic phenomenon.

Although outflows from dwarf galaxies have captured much of the theoretical effort on outflows (e.g. Mac Low & Ferrara 1999), under the assumption that it is easier to drive outflows in low mass systems, it is important to realize that this does not automatically mean that larger galaxies do not drive outflows. I will not discuss outflows from local ultraluminous IR galaxies (ULIRGs) which have SFRs up to ~ 30 times greater than the average starburst galaxy, or the starbursting systems seen at high redshift (see Pettini, this volume), except to note that they appear *at least* as powerful as winds in local starburst galaxies.

3. THE EFFICIENCY OF SUPERNOVA HEATING

The SN rate within a typical local starburst galaxy is ~ 0.05 yr^{-1} (Mattila & Meikle 2001), which implies a total number of SNe exceeding ~ 2 × 10^6 over the lifetime of a starburst event. How much of the kinetic energy from all these SNe is available to drive the wind? This is of particular interest with respect to the possible role SN-driven winds play in imparting additional

heating to the IGM and ICM (see various discussions in this volume).

It is useful to split the problem into two parts, firstly radiative losses within the starburst region, and secondly radiative losses within the larger-scale superwind. The second of these can be assessed relatively straightforwardly with observations of local superwinds, and will be addressed in Section 6. The radiative losses young SNRs suffer within the starburst region are extremely difficult to determine observationally, as these regions are heavily obscured. Consequently arguments about radiative energy losses are based purely on theory and a wide range of opinions exist. I shall present the situation as I see it, and refer the reader to the contribution by Recchi (this volume) for a different point of view.

A single isolated SNR, evolving in a uniform medium of number density ~ 1 cm^{-3} will lose a fraction f ~ 90% of its initial kinetic energy to radiation over ~ 4×10^5 years (Thornton et al. 1998). Adopting the terminology of Chevalier & Clegg (1985), this corresponds to a thermalization efficiency of $\eta_{therm} = 1 - f \sim 10\%$. Cooling depends sensitively on the local density as $\int n^2 \Lambda \, dV$. Many authors assume that because bursts of star formation occur in regions with large amounts of dense gas, virtually all the energy from SNe is lost due to radiation (e.g. Steinmetz 1999). This ignores the multiphase nature of the ISM where the filling factor of dense gas is low, and that the phase structure is determined by the local SN rate (Rosen & Bregman 1995).

In a starburst region such as at the center of M82 or NGC 253 the SN rate per unit volume is a few $\times 10^{-9}$ yr^{-1} pc^{-3}, about 5 orders of magnitude higher than the SN rate/volume in the disk of the MW (~ 4×10^{-14} yr^{-1} pc^{-3}, Slavin & Cox [1993]). The average individual SNR or wind blown bubble in a starburst does not exist long enough to radiate away 90% of its energy before it runs into another remnant or pre-blown low density cavity. Once in a low density medium radiative losses cease to be significant (see Mac Low & McCray 1988). As a consequence the thermalization efficiency in starbursts *must* be considerably higher than the 10% value applicable to "normal" star-forming disks. Numerical simulations investigating thermalization efficiency as a function of SN rate/volume support this argument (Strickland, in preparation). Some SNe may occur molecular cores, and suffer significant radiative losses, but on average SNe in the starburst do not lose a large fraction of their energy. Thermalization efficiencies $\eta_{therm} \gtrsim 50\%$ are quite possible.

In principle, observationally measuring the temperature of the very hot tenuous gas in the starburst region (i.e. the thermalized SN ejecta) can directly provide the thermalization efficiency. Using the rates of mass and energy input from the Starburst99 models (Leitherer et al. 1999), $T_{gas} = 1.2 \times 10^8 \, \eta_{therm} \, \beta^{-1}$ K, where $\beta \geq 1$ is a measure of mass-loading (Suchkov et al. 1996). The faint X-ray emission from this hot gas can, in principle, be detected in nearby starburst galaxies. Unfortunately starburst regions are also host to large numbers of of X-ray binaries, and possible low luminosity AGN, making this measurement extremely difficult. The first believable detection of this very hot gas uses *Chandra*'s high spatial resolution to resolve out the X-ray binaries. Griffiths et al. (2000) claim to detect diffuse emission from a $T \sim 5 \times 10^7$ K gas within M82's starburst region, which if confirmed implies $\eta_{therm} \sim 40 \, \beta^{+1}\%$.

4. WARM NEUTRAL GAS IN SUPERWINDS

Many local starburst galaxies show blue-shifted Na D absorption line profiles (Phillips 1993; Heckman et al. 2000). The sodium D (NaI $\lambda\lambda$ 5890, 5896) lines probe warm neutral gas, at a temperature of a few thousand degrees. In Heckman et al's sample of IR luminous starburst galaxies 19 out of a sample of 33 showed blue shifted absorption, typically extending out to terminal velocities between v_{term} = - 200 to -700 km/s (Fig. 2) in galaxies with rotation velocities between 140 and 330 km/s. Absorption is seen over a wide range in velocity, from the systemic velocity of the galaxy out to v_{term}, suggesting gas with multiple velocity components in the outflow. Those galaxies that show blue-shifted absorption tend to be more face-on than those that do not show absorption.

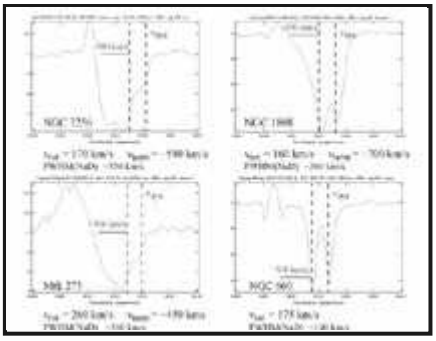

Figure 2. A representative sample of Na D absorption line profiles for four starburst galaxies, adapted from the larger sample shown in Heckman et al. (2000). The dashed vertical lines show the expected centroids of the Na D doublet at the systemic velocity of the galaxy. Horizontal bars represent a blue shift of 500 km/s. Note the strongly blue-shifted Na D absorption in NGC 3526, NGC 1808 and Mrk 273 due to the superwinds in these galaxies.

This is consistent with a model where the blue-shifted absorption features arise in cool ambient gas entrained into a weakly collimated outflow along the minor axis of the galaxy. The gas initially has low velocity, giving rise to absorption near the systemic velocity of the galaxy, but is accelerated to higher velocity by the ram pressure of the SN-ejecta wind.

This cool gas dominates the total mass in the outflow. For a typical starburst in this sample ($L_{\rm FIR} \sim 2 \times 10^{11}\ L_{\odot}$) the mass of warm neutral gas is $M_{\rm NaD} \sim 5 \times 10^{8} M_{\rm sun}$. The mass flow rate in this component significantly exceeds the mass injection rate due to SNe and stellar winds and is comparable to the gas consumption rate due to star formation ($\dot{M}_{\rm NaD} \sim 3 - 10 \times \dot{M}_{\rm SN} \sim \dot{M}_{\rm SF}$). Although not highly metal-enriched, this component is significant in terms of total mass of metals transported out of the disk of the galaxy.

Does this gas escape the galaxy and pollute the IGM? The observed terminal velocities are typically several times the rotational velocity of the galaxy, comparable to or greater than the galactic escape velocity assuming $v_{\rm esc} \sim 3 \times v_{\rm rot}$. It should be stressed that even if $v < v_{\rm esc}$, this does not automatically imply that the gas is retained by the galaxy. The motion of this cool gas is not simply ballistic, as the clouds are carried along by the wind. The long term fate of this gas is unknown, and depends more on on hydrodynamic forces (wind ram pressure, retardation by halo gas) than the gravitational potential of the galaxy.

5. WARM IONIZED GAS

A large literature exists using optical emission lines to study warm ionized gas at $T \sim 10^4$ K in superwinds (see Heckman et al. 1993 and references therein). Given this, I will only briefly mention some of the important wind diagnostics provided by these studies, before discussing what I believe to be an important observation affecting numerical estimates of mass loss from superwinds.

Balmer lines, primarily Hα emission, provide kinematic information along with morphological information regarding the structure of the outflow. Spatially resolved kinematic studies (McKeith et al. 1995; Shopbell & Bland-Hawthorn 1998; Cecil et al. 2001) provide information on the entrainment and acceleration of cool gas. The [SII] doublet ($\lambda\lambda$6717, 6731) can be used as a density diagnostic. This has been used to derive densities and pressures in the warm clouds in superwinds (McCarthy et al. 1987; Armus et al. 1990). Line ratios also provide ionization source diagnostics. The gas near the starburst region is primarily photoionized by the intense UV radiation from the massive stars, but at larger distances the Hα emitting gas shows line ratios indicative of shock heating (Martin 1997). In the future we may hope to apply the detailed shock diagnostics used in studies of local SNRs to superwinds.

One particularly noteworthy recent development is high resolution studies with *HST* of the optical emission line filaments in NGC 3079 's superwind (Cecil et al. 2001) and M82 's superwind (Shopbell et al, in preparation). At high resolution the filaments and arcs of warm gas break up into very small clumps or clouds. The largest clumps or clouds in NGC 3079 are ~ 30 pc in diameter, although many are unresolved even by HST. Most of the mass in a superwind is in these cool, very compact

clouds. Accurately treating the entrainment and acceleration of such clouds by the wind requires that the model resolves the wind/cloud interaction. Klein, McKee, & Colella (1994) argue that this requires at least 100 cells across across a cloud diameter, implying cell sizes of << 1 pc in simulations that must cover 2-or-3-dimensional volumes 10's of kpc on a side (preferably ~ 200 kpc on a side, see Aguirre and Pettini in this volume). No current simulations achieve this level of resolution, and therefore these models may significantly underestimate mass loss in superwinds.

6. UV ABSORPTION PROBES OF CORONAL GAS

The launch of NASA's Far Ultraviolet Spectral Explorer (*FUSE*) mission in 1999 has finally allowed absorption from the O VI $\lambda\lambda$ 1032, 1038 doublet to be detected in local starburst galaxies. These lines probe collisionally ionized gas at $T \sim 3 \times 10^5$ K. These observations provide us with kinematic information on gas ~ 30 times hotter than probed by optical emission lines.

A theoretical prediction of both analytical and numerical models of superwinds is that hotter gas has higher outflow velocities than the cool gas. The maximum velocities are achieved by the very energetic SN-ejecta, while cooler denser ambient ISM is swept up and accelerated to a terminal velocity dependent on the column density of the clump or cloud (Chevalier & Clegg 1985). If true, hot gas might escape these galaxies even if outflow velocities in the cool phases are well below escape velocity.

If superwinds are to be stopped before reaching the IGM, it is necessary to radiate away the majority of their energy. Observations place strong limits on the radiative power loss in the X-ray band at ~ 1% or so of the SN energy injection rate $\dot{E}_{SN}$, while optical emission lines account for a few to ~ 10% of $\dot{E}_{SN}$. The only waveband where appreciable energy could be emerging that has not previously been explored is the far UV.

Blue-shifted absorption from O VI is seen in a variety of of starbursts of different mass and star-formation intensity, from starbursting dwarf galaxies like NGC 4214 (Martin et al, in preparation) through to typical starbursts like NGC 3310. Heckman et al. (2001) present a detailed case study of one the archetypal starbursting dwarf galaxies, NGC 1705, which shows a complicated optical morphology suggesting that hot gas is in the process of "blowing-out" of a ~ 2 kpc diameter Hα bubble. The *FUSE* observations reveal that the hot gas responsible for the O VI absorption has a higher outflow velocity than the warm ionized medium, which in turn has a higher outflow velocity than warm neutral gas (v_{OVI} = - 77 ± 10 km/s, v_{WIM} = - 53 ± 10 km/s, v_{WNM} = - 32 ± 11 km/s). These observations are inconsistent with the standard superbubble model (Castor, Weaver, & McCray 1975; Mac Low & McCray 1988), but agree with the predictions gas entrainment and acceleration as hot gas flows out through holes in a fragmented superbubble shell to form a superwind. FUV radiative losses in NGC 1705 appear minimal, only ~ 5% of $\dot{E}_{SN}$, so superwinds appear to be inefficient radiators at any wavelength.

7. THERMAL X-RAY EMISSION FROM SUPERWINDS

The motivation for studying X-ray emission from superwinds has always been the hope that the observed thermal X-ray emission provides a direct probe of the hot, metal-enriched, gas that drives these outflows. The 10-kpc-scale diffuse X-ray emission in superwinds seen by *Einstein*, *ROSAT* & *ASCA* had characteristic temperatures of a few million degrees. This is much cooler than the ~ 10^8 K expected for raw SN-ejecta within the starburst region, but as the wind expands cooling processes such as adiabatic expansion or mass-loading (Suchkov et al. 1996) might reconcile the observed temperatures with an interpretation of the X-ray emission coming from a volume-filling wind of SN-ejecta. The alternative model is that X-ray emission comes from an interaction between the hot, high velocity wind, and cooler denser ISM along the walls of the outflow or in clouds embedded within the wind (Chevalier & Clegg 1985; Suchkov et al. 1994; Strickland & Stevens 2000). A fraction of the cool dense ISM is shock-or-conductively heated to million degree temperatures.

Distinguishing between these two competing models has awaited high spatial resolution X-ray imaging. If the X-ray emission comes from a volume-filling wind, then the X-ray emission should smoothly fill the interior of the cone or lobes outlined by Hα emission. In the wind/ISM interaction model the X-ray emission should be concentrated in regions with dense cool gas, and it should appear as filamentary and limb-brightened as the Hα emission. The spatial resolution and sensitivity of X-ray instruments prior to *Chandra* was not high enough to make an exact comparison between X-ray and Hα emission in even the nearest superwinds, although a general correlation between the two has long been noted (Watson et al. 1984; McCarthy et al. 1987).

Chandra's $\lesssim$ 1" spatial resolution corresponds to ~ 12 pc at the distance of nearby superwinds - the same physical scales as the Hα emitting clouds. We now have unambiguous evidence (Fig. 3) for a 1-to-1 relationship between the spatial distribution of the soft thermal X-ray emission and the Hα emission in the inner kpc of several superwinds (Strickland et al. 2000; 2001 in preparation). Over the larger 10 kpc scales of the winds the X-ray emission still appears filamentary and arc-like, and is associated with nearby filaments or arcs of Hα emission. Low-volume filling factor gas dominates the X-ray emission from

superwinds, and the the gas that actually drives the outflow remains invisible.

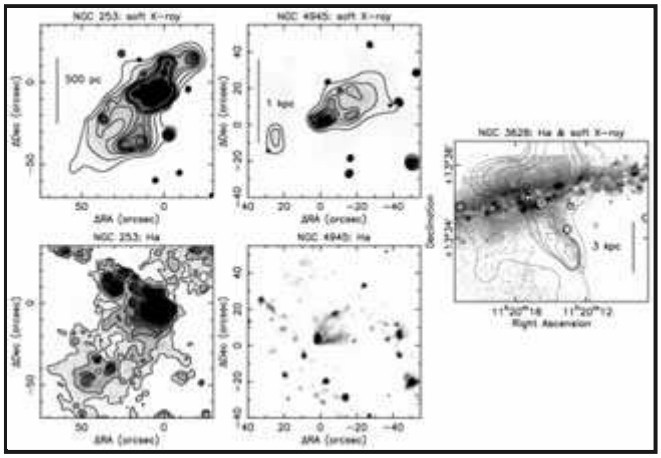

Figure 3. Soft X-ray and Hα emission in several edge-on starburst galaxies, showing the spatial similarities between the two phases. NGC 253 & NGC 4945 have kpc-scale limb-brightened nuclear outflow cones (the opposite outflow cone is obscured in both cases) with a close match between X-ray & Hα emission. In NGC 3628 a 5 kpc-long Hα arc on the eastern limb of the wind is matched by an offset X-ray filament.

8. SUMMARY AND CONCLUSIONS

Typical starburst galaxies ($L_{\rm FIR} \sim L_{*}$) show high velocity (200-700 km/s) multi-phase outflows. The observed mass flow rates in the wind are comparable to the gas consumption rate due to star formation ($\dot{M}_{\rm wind} \gtrsim \dot{M}_{*}$), and are dominated by relatively cool ambient gas ($T \sim$ few thousand K) that has been swept-up and accelerated by the ram pressure of the hotter wind of SN-ejecta.

Outflow velocities are typically comparable or greater than estimates of the galactic escape velocity, but caution should be exercised in making claims about mass loss rates. The gas motions are not ballistic, making it impossible to give quantitative observational *mass loss* rates. Observations of gas at much larger galactocentric radii ($\gtrsim$100 kpc) are needed to directly observe mass loss. Nevertheless, the observed *mass flow* rates are considerable, and does seem likely that some significant fraction of even the coolest phases may well escape even moderately massive starburst galaxies. Speaking as a practitioner of hydrodynamical simulations of superwinds, I am not convinced that we know mass-loss rates theoretically. Existing models have yet to be meaningfully tested against observations. The lack of sub-parsec numerical resolution in current simulations prejudices the ability of these models to treat mass transport in winds.

FUSE observations of OVI absorption provide vital information of the kinematics and radiative losses of coronal gas at $T \sim 3 \times 10^5$ K. In the dwarf starburst NGC 1705 the *FUSE* observations support the theoretical prediction of superwind models that the hotter phases in superwinds have higher outflow velocities than the cooler phases. This suggests that the even hotter material holding the metals is more likely to escape than the warm neutral and ionized gas. Radiative energy losses within the wind appear minimal compared to the energy injection rate from SNe, even within the FUV and X-ray wave-bands.

With the sub-arcsecond spatial resolution provided by *Chandra* it is now clear that the soft thermal X-ray emission seen in superwinds is due to some form of interaction between the (still invisible) high velocity hot wind and cooler denser ambient gas swept-up or overrun by the flow. This is unfortunate in the sense that X-ray observations do not provide a direct probe of the energetic metal-enriched gas driving these winds. Nevertheless the data from *Chandra* allow us to obtain more accurate estimates of the physical properties of the X-ray emitting gas than ever before, and provide deeper insight into the conditions within these winds.

Starburst-driven winds are difficult objects to study, due to the range of different gas phases involved and the faintness of the emission. Nevertheless, very significant progress is being made, most notably due to the new observational capabilities provided by *FUSE* & *Chandra*. The wealth of multi-wavelength data will place extremely strong constraints upon numerical models of superwinds. This is an exciting time to study superwinds, and there is no prospect of an end to new discoveries about these fascinating and important objects.

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