

Winds from nuclear Starbursts: Old truths and recent progress on superwinds

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Abstract. I will discuss a few select aspects of the most common and best understood galactic-scale outflow – starburst-driven superwinds, focusing on winds from nuclear starburst galaxies. I will show that modern observations, in particular in the soft and hard X-ray bands, complement and reinforce the existing paradigm of superwinds as flows collectively driven by multiple SNe. The properties of the diffuse X-ray emission from dwarf starburst galaxies, $L_{\text{BOL}} \sim L_{\star}$ starburst in spiral galaxies, and ULIRGS, are all consistent with superwind activity. Where appropriate, I contrast the physics of starburst-driven winds with poorly collimated winds from AGN, and discuss what we know of the role of LLAGN and Seyfert nuclei in starburst superwind galaxies.

1. Introduction

It has long been appreciated that outflows from galaxies can have a major effect on galaxy formation and evolution, influencing such basic galactic properties such as the mean metal abundance (Larson 1974; Garnett 2002) or even the survival of low mass galaxies (Dekel & Silk 1986). More recent discoveries have reinvigorated interest in the role of galactic outflows, e.g.: The presence of metals in the true inter-galactic medium at low and high redshifts (Songaila 1997; Tripp et al. 2000); that a sizable fraction of all metals ever created now reside outside galaxies (Pagel 2002); and direct observational evidence for ubiquitous outflows from, and 100 kpc-scale cavities around, the Lyman break galaxies (Adelberger et al. 2003).

By the far the best-studied, best-understood, and arguably most common form of galactic outflow capable of polluting the IGM are superwinds (Heckman et al. 1990; Dahlem 1997). These are loosely-collimated multi-phase outflows from actively-star forming galaxies, i.e. starburst galaxies. Within the local universe starbursts account for $\sim 25\%$ of all massive star formation (and hence metal production), and starburst activity becomes progressively more important at higher redshifts (Heckman 1998). As all local starburst galaxies appear to have superwinds (Lehnert & Heckman 1996), it is clear that starburst-driven winds are of major importance.

Over the last 5 years new observations of superwinds, in particular satellite-based observations in the EUV and soft and hard X-ray bands, have substantially added to our understanding of the physics behind superwinds. I will discuss how these new observations support the long-standing conceptual picture of how superwinds work, specifically (a) how superwinds are driven by the collective mechanical power of multiple supernovae (SNe) occurring within the disks (in particular the nuclei) of starburst galaxies, and (b) X-ray emission from superwinds. Where appropriate I will contrast superwinds with AGN winds (i.e. loosely collimated outflows, and not large-scale jets).

2. Distributed energy and mass injection in starburst nuclei

The basic conceptual picture of how starburst-driven winds work was established nearly two decades ago. In the Chevalier & Clegg (1985, henceforth CC) model, the very high rate per unit volume of core collapse SNe in starburst regions leads to young SNRs colliding before they have time to lose energy radiatively. Shocks in these collisions thermalize the kinetic energy of the ejecta, creating a very hot ($T \sim 10^8$ K), high pressure ($P/k \sim 10^7$ K cm $^{-3}$) and low density gas that fills the volume of the starburst region. In the analytical CC model the multiple individual SN events are treated as a time-averaged, spatially-uniform injection of mass and energy. The merged SN-ejecta expands adiabatically, becoming supersonic at the edge of the starburst region and rapidly reaching terminal velocity of $\sqrt{(2\dot{E}/\dot{M})} \sim 3000$ km s $^{-1}$. Numerical simulations show that this wind expands preferentially along the minor axis of any disk-like galaxy forming a bipolar flow, sweeping up cooler, denser, ambient disk or halo gas, and stripping ambient gas from the walls of the cavity (e.g. Tomisaka & Ikeuchi 1988; Suchkov et al. 1994; Strickland & Stevens 2000). The ram pressure of the merged SN-ejecta accelerates this entrained gas to velocities of a few $\times 100$ to 1000 km s $^{-1}$. The multiple cool, warm and hot gas phases observed in superwinds (e.g. Dahlem 1997) are all entrained ambient gas.

Is this simple scenario realistic, given what we have learned about starbursts in the last 20 years? Before the *Chandra* observations of Griffiths et al. (2000) there had been no believable detection of the very hot gas predicted by the CC model in any starburst region (the very hot gas that in theory drives superwinds), so why was this model accepted in the first place? In fact, convincing observational evidence for the SN-driven nature of superwinds, and the quantitative accuracy of the CC model, appeared soon after its publication. Modern observations continue to validate its most basic concepts.

The classic starburst M82 is a particularly convenient laboratory for investigating starbursts and superwinds, given that it is one of the closest powerful starburst galaxies ($D=3.6$ Mpc), and that all current SF occurs within a 400 pc radius of the nucleus. Its FIR luminosity, dominated by the starburst activity, indicates a SN rate of ~ 0.1 per year. In terms of SF rate per unit area M82 lies close to the upper limit found in starbursts at both low and high redshift (Meurer et al. 1997). Radio observations show ~ 40 compact, but spatially resolved, SNR remnants (Muxlow et al. 1994), that outline the starburst region as seen at other wavelengths. These are not the same SNe that drive the wind, but are a subset of the SN population that occur in dense gaseous environments, although the total fraction of the starburst region filled with such dense gas must be < 0.1 (Chevalier & Fransson 2001). Optical, near and mid-IR observations show large numbers of massive star clusters ($4 < \log M_{\text{cluster}} < 6$) within the starburst region (O'Connell et al. 1995; McCrady et al. 2003; Lipsy & Plavchan 2004). Note that the fraction of massive stars (and hence eventual SNe) within such massive clusters is only $\sim 20\%$ of the total, consistent with the value observed in many starburst galaxies (Meurer et al. 1995). Thus, to first order, energy and mass injection from SNe is distributed over the volume of the entire starburst region, in accord with the CC model.

McCarthy et al. (1987), and later Heckman et al. (1990) and Lehnert & Heckman (1996), used optical spectroscopy to map the pressure in warm ionized gas in central regions of M82 and other starburst galaxies with superwinds. Essentially this uses the low filling factor H α -emitting gas clouds as tracers of the much hotter gas they are embedded in. At large radii the pressure drops rapidly with distance, as expected for a free radial wind. Within a certain radius r_P the pressure is approximately constant, indicating that energy and mass injection is distributed within this region. The radial shape and normalization of these pressure profiles are consistent with the CC model.

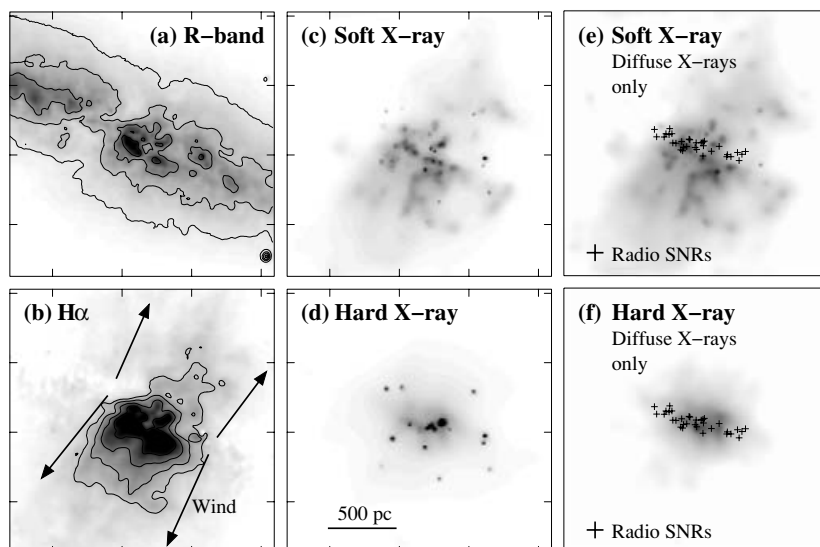


Figure 1. The center of M82 in (a) the optical R-band, (b) $H\alpha$ emission from $\log T \sim 4$ gas, (c) Soft X-ray emission ($E=0.3\text{--}2.0$ keV), (d) Hard X-ray emission ($E=2.0\text{--}8.0$ keV), (e) Diffuse soft X-ray emission from $\log T \sim 6.5$ gas only, X-ray point sources have been removed, (f) Diffuse hard X-ray emission, including some contribution from $\log T \sim 7.5\text{--}8$ gas. Each image is 2 kpc on a side, centered on the dynamical center of the galaxy. X-ray images are from *Chandra* ACIS observations. The location of the ~ 40 compact radio SNRs that mark the starburst region are plotted on panels e and f. The base of the superwind matches the size of the starburst region. Adapted from Strickland et al. (2004a).

Heckman et al. (1990) demonstrated for many galaxies with superwinds that r_P is the same as the size of starburst r_* .

Note that if AGN drove these winds r_P would not equal r_* , even in models where energy injection is distributed over large regions due to diverted or halted jets (Colbert 1997). A thermal AGN wind driven from the vicinity of the accretion disk (e.g. Schiano 1985) would further differ from a starburst-driven wind, even if having initially similar total mass and energy injection rates. The CC model assumes radiative losses from the thermalized gas are negligible, which is true if energy and mass injection occurs over a volume similar to the size of an entire starburst region. Silich et al. (2003) have pointed out that if the injection region is much smaller than this, the increased density of the thermalized gas leads to significant radiative losses. Their model is essentially of flows from very massive ($\log M > 6$) super star clusters, but I wish to point out that it would also apply to centrally-driven AGN winds. Strong radiative losses in AGN winds would thus alter the physical properties observed on the larger galactic scales from those in starburst-driven superwinds.

Recent X-ray observations of superwinds have validated the use of warm gas as a tracer of the hot merged SN-ejecta, as well as detecting the very hot plasma predicted by the CC model. It is only with the *Chandra* X-ray Observatory's arcsecond spatial resolution that emission from the multiple X-ray binaries formed in the starburst can be cleanly separated from the diffuse X-ray emission associated with the superwind (see Fig. 1). This is especially true in the hard X-ray band ($E = 2$ to 8 keV) where *faint* diffuse bremsstrahlung and line emission from $T \sim 10^8$ K gas would be expected to be seen. Griffiths et al. (2000) were the first to robustly detect diffuse hard X-ray emission in a starburst region, once again in the archetype M82. The spatial extent of this emission in

the plane of the galaxy exactly matches that of the 40''-diameter starburst region, and matches the base of the superwind as seen at other wavelengths. More recent, higher spectral-resolution, *Chandra* observations (Strickland et al. in preparation) show that the diffuse hard X-ray emission is not purely thermal, but do confirm the presence of a $E \approx 6.7$ keV Fe K-shell emission that must come from a $\log T > 7.5$ K plasma. In general such diffuse hard emission has not been detected in other nearby starbursts, even with *Chandra*, as other starburst nuclei are more distant, and have smaller angular scales, than that in M82. Weaver et al. (2002) detected diffuse hard X-ray emission within the central $\sim 10''$ of the nuclear starburst NGC 253, but argue that the properties of this emission are more consistent with gas photoionized by that galaxy's LLAGN.

3. Soft X-ray emission from superwinds: theory vs observation

Diffuse soft X-ray emission in superwinds is considerably easier to observe than diffuse hard X-ray emission, by virtue of being orders of magnitude more luminous and spatially extended. Nevertheless *Chandra* has also revolutionized our understanding of the origin and properties of soft diffuse X-ray emission in starbursts. The majority of starburst activity in the local universe occurs in galaxies with $\log L_{\text{BOL}}(L_{\odot}) \sim 10.5$, e.g. classic starbursts M82, NGC 253, or NGC 3628. Thus edge-on starburst galaxies such as these objects, at distances of $\lesssim 20$ Mpc, provide the best observational data on superwinds.

Models such as Starburst99 (Leitherer et al. 1999) predict that the ratio of mechanical energy released by SNe and stellar winds to the bolometric radiated power from a starburst is $L_{\text{W}}/L_{\text{BOL}} \approx 0.01$ to 0.015, where L_{BOL} is proportional to the star formation rate. The fraction of the superwind mechanical power expected to emerge as soft X-ray emission is rather more uncertain. There are a variety of different theoretical models for the origin of the soft X-ray emitting gas. The merged SN ejecta driving the wind is too tenuous to provide significant X-ray emission, unless its density has been significantly increased by mass-loading (e.g. Suchkov et al. 1996). In our multi-dimensional hydrodynamical simulations of superwinds (Strickland & Stevens 2000), where the emission is primarily due to shock heating of ambient disk and halo gas, we found $L_{\text{X}}/L_{\text{W}} \sim 0.03$, (with higher values associated with mass-loaded models). Similar values can be found if the Weaver et al. (1977) wind-blown bubble model is applied to superwinds (e.g. Strickland et al. 2004b), where the soft X-ray emission is primarily from conductively-heated ambient gas at the wall of the bubble. Combining these models, and including the scatter, theoretical models of starburst-driven winds predict $\log L_{\text{X}}/L_{\text{BOL}} \approx -3.5 \pm 0.6$.

Chandra observations of many classic starbursts have now demonstrated that the soft thermal X-ray emission from the superwinds is highly-structured and spatially correlated with H α emission, as expected if the X-ray emission is generated by the interaction of the superwind with cool ambient gas. In many cases both the X-ray and H α emission is strongly limb-brightened, indicating that the emission comes predominantly from the walls of the cavity carved by the superwind into the disk and halo medium of the host galaxy (Strickland et al. 2000, 2002, 2004a). The fraction of the wind volume occupied by soft X-ray emitting gas is relatively low, with upper limits of $< 20\%$ of the soft X-ray emission coming from any volume-filling mass-loaded wind (Strickland et al. 2000, 2003). Both the total diffuse soft X-ray luminosity $L_{\text{X,TOT}}$ and the superwind emission at heights $z > 2$ kpc from the disk $L_{\text{X,HALO}}$, scale in direct proportion to the the host galaxies bolometric luminosity, $\log L_{\text{X,TOT}}/L_{\text{BOL}} \approx -3.6 \pm 0.2$ and $\log L_{\text{X,HALO}}/L_{\text{BOL}} \approx -4.4 \pm 0.2$ (Strickland et al. 2004b), remarkably tight correlations.

Chandra and XMM-Newton observations of many dwarf starbursts ($L_{\text{BOL}} \lesssim 9$) and ULIRGs ($\log L_{\text{BOL}} \gtrsim 12$) are now available (Martin et al. 2002; Ott et al. 2003; Ptak et al.

2003; Summers et al. 2003, 2004; Hartwell et al. 2004). The characteristics of the diffuse X-ray emission in these objects are essentially the same as those of the classic starbursts, with similar spectral properties (e.g. relative α -to-Fe abundances) and L_X/L_{BOL} ratios (Grimes *et al.*, in preparation).

4. Outflows from galaxies with both starburst and AGN activity

The soft X-ray properties of many actively star-forming galaxies with spatially-extended soft X-ray emission are in accord with models of supernova-driven winds. But what of starburst galaxies that also host AGN? In general the outflows from classic starburst galaxies that also host LLAGN (e.g. NGC 253, NGC 3079) do not differ from winds from pure starbursts (e.g. M82, NGC 3628, see Strickland et al. 2004a). The one “classic” starburst that does appear unusual is NGC 4945, which is also the host of a very peculiar X-ray-luminous AGN that is probably heavily obscured along all lines of sight (Marconi et al. 2000; Levenson et al. 2002). Although it has a X-ray and H α nuclear outflow cone similar to NGC 253, it is lacking in diffuse X-ray or H α emission when compared to a starburst of the same *total* galactic bolometric luminosity, $\log L_{X,\text{TOT}}/L_{\text{BOL}} = -4.25$ (Strickland et al. 2004a). However, the AGN may dominate L_{BOL} . If we assume that the diffuse X-ray emission is due to a starburst-driven wind alone, then the starburst must only account for $\lesssim 20\%$ of L_{BOL} . In general, the large-scale soft X-ray emission in Seyfert/Starburst composite galaxies is consistent with a purely-starburst origin (Levenson et al. 2001a,b, 2004). Thus, for a given total bolometric luminosity it appears that SNe are more effective at driving galactic-scale winds than AGN. This does not imply that AGN-driven galactic winds do not exist. There clearly are galaxies with AGN but lacking starbursts that have galactic-scale (i.e. ~ 10 kpc) outflows (Colbert et al. 1996, 1998), but their local space density is lower than typical starburst superwind galaxies.

5. Final remarks

Many questions remain to be solved regarding the physics within superwinds, and their larger cosmological impact on galaxies and the IGM. Nevertheless, we have a good physical understanding of how SNe within starbursts drive galactic-scale superwinds. The standard superwind conceptual model is almost two decades old, but modern observations validate it far more often than not. Future research in this area, in particular the transition between starburst activity (with superwinds) and “normal” galaxies (with or without galactic fountains), will strengthen our understanding of the interplay between SF, stars, and the ISM in regulating galaxy assembly, structure and evolution.

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References

- Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
- Chevalier, R. A., & Clegg, A. W. 1985, Nature, 317, 44
- Chevalier, R. A., & Fransson, C. 2001, ApJ, 558, L27
- Colbert, E. J. M. 1997, Ph.D. thesis, University of Maryland
- Colbert, E. J. M., et al. 1996, ApJS, 105, 75

- Colbert, E. J. M., Baum, S. A., O'Dea, C. P., & Veilleux, S. 1998, *ApJ*, 496, 786
- Dahlem, M. 1997, *PASP*, 109, 1298
- Dekel, A., & Silk, J. 1986, *ApJ*, 303, 39
- Garnett, D. R. 2002, *ApJ*, 581, 1019
- Griffiths, R. E., et al. 2000, *Science*, 290, 1325
- Hartwell, J. M., Stevens, I. R., Strickland, D. K., Heckman, T. M., & Summers, L. K. 2004, *MNRAS*, 348, 406
- Heckman, T. M. 1998, in *ASP Conf. Ser. 148, Origins*, (ed. C. E. Woodward, J. M. Shull, & H. A. Thronson) San Francisco: ASP, 127
- Heckman, T. M., Armus, L., & Miley, G. K. 1990, *ApJS*, 74, 833
- Larson, R. B. 1974, *MNRAS*, 169, 229
- Lehnert, M. D., & Heckman, T. M. 1996, *ApJ*, 462, 651
- Leitherer, C., et al. 1999, *ApJS*, 123, 3
- Levenson, N. A., Krolik, J. H., Życki, P. T., Heckman, T. M., Weaver, K. A., Awaki, H., & Terashima, Y. 2002, *ApJ*, 573, L81
- Levenson, N. A., Weaver, K. A., & Heckman, T. M. 2001a, *ApJS*, 133, 269
- 2001b, *ApJ*, 550, 230
- Levenson, N. A., Weaver, K. A., Heckman, T. M., Awaki, H., & Terashima, Y. 2004, *ApJ*, 602, 135
- Lipscy, S. J. & Plavchan, P. 2004, *ApJ*, 603, 82
- Marconi, A., Oliva, E., van der Werf, P. P., Maiolino, R., Schreier, E. J., Macchetto, F., & Moorwood, A. F. M. 2000, *A&A*, 357, 24
- Martin, C. L., Kobulnicky, H. A., & Heckman, T. M. 2002, *ApJ*, 574, 663
- McCarthy, P. J., Heckman, T., & van Breugel, W. 1987, *AJ*, 93, 264
- McCraday, N., Gilbert, A. M., & Graham, J. R. 2003, *ApJ*, 596, 240
- Meurer, G. R., Heckman, T. M., Lehnert, M. D., Leitherer, C., & Lowenthal, J. 1997, *AJ*, 114, 54
- Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, *AJ*, 110, 2665
- Muxlow, T. W. B., Pedlar, A., Wilkinson, P. N., Axon, D. J., Sanders, E. M., & de Bruyn, A. G. 1994, *MNRAS*, 266, 455
- O'Connell, R. W., Gallagher, J. S., Hunter, D. A., & Colley, W. N. 1995, *ApJ*, 446, L1
- Ott, J., Martin, C. L., & Walter, F. 2003, *ApJ*, 594, 776
- Pagel, B. E. J. 2002, in *ASP Conf. Ser. 253: Chemical Enrichment of Intracluster and Inter-galactic Medium*, (eds. R. Fusco-Femiano & F. Matteucci), San Francisco: ASP, 489
- Ptak, A., Heckman, T., Levenson, N. A., Weaver, K., & Strickland, D. 2003, *ApJ*, 592, 782
- Schiano, A. V. R. 1985, *ApJ*, 299, 24
- Silich, S., Tenorio-Tagle, G., & Muñoz-Tuñón, C. 2003, *ApJ*, 590, 791
- Songaila, A. 1997, *ApJ*, 490, L1
- Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2003, in *IAU Symposium 212: A Massive Star Odyssey: From Main Sequence to Supernova*, (eds. K. van der Hucht, A. Herrero, & C. Esteban), San Francisco: ASP, 612
- Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004a, *ApJS*, 151, 193
- 2004b, *ApJ*, 606, 829
- Strickland, D. K., Heckman, T. M., Weaver, K. A., & Dahlem, M. 2000, *AJ*, 120, 2965
- Strickland, D. K., Heckman, T. M., Weaver, K. A., Hoopes, C. G., & Dahlem, M. 2002, *ApJ*, 568, 689
- Strickland, D. K. & Stevens, I. R. 2000, *MNRAS*, 314, 511
- Suchkov, A. A., Balsara, D. S., Heckman, T. M., & Leitherer, C. 1994, *ApJ*, 430, 511
- Suchkov, A. A., Berman, V. G., Heckman, T. M., & Balsara, D. S. 1996, *ApJ*, 463, 528
- Summers, L. K., Stevens, I. R., Strickland, D. K., & Heckman, T. M. 2003, *MNRAS*, 342, 690
- 2004, *MNRAS*, in press
- Tomisaka, K. & Ikeuchi, S. 1988, *ApJ*, 330, 695
- Tripp, T. M., Savage, B. D., & Jenkins, E. B. 2000, *ApJ*, 534, L1
- Weaver, K. A., Heckman, T. M., Strickland, D. K., & Dahlem, M. 2002, *ApJ*, 576, L19
- Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, *ApJ*, 218, 377