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STARBURST-DRIVEN OUTFLOWS IN GALAXIES

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RESUMEN

Se describen las observaciones de flujos de gas, a escalas galácticas (superburbujas y supervientos), generadas por brotes de formación estelar. Se ilustran los procesos físicos y la fenomenología con tres casos específicos, que tienen los mejores datos: NGC 1569, una galaxia enana, M82, un caso poco usual de galaxia temprana de baja masa, y NGC 253, una galaxia barrada de tipo tardío.

ABSTRACT

I review observations of galactic-scale outflows (superbubbles and superwinds) driven by starbursts, with an emphasis on X-ray and optical data. I consider 3 specific cases with the best data as illustrative of the physics and phenomenology of these outflows: NGC 1569, a dwarf galaxy undergoing a starburst of modest luminosity, M82, a somewhat unusual example of a low mass early-type galaxy with a powerful nuclear starburst, and NGC 253, a late-type barred spiral. Both its starburst and host galaxy are typical of the members of *IRAS*-selected samples. I conclude with a brief summary of the relevance of starburst-driven outflows to some current issues in cosmogony.

Key words: **GALAXIES: INDIVIDUAL: M82, NGC 253, NGC 1569 — GALAXIES: JETS — HYDRODYNAMICS**

1. INTRODUCTION

The complex gas flows in and around starburst galaxies arise from a time-dependent, non-axisymmetric gravitational potential (bars, oval distortions, and companion galaxies) and from the hydrodynamical consequences of the enormous rate of mechanical energy deposition inside the starburst (SB). The former is related to the causes of SBs, while the latter is an effect of the SB. Both processes causally connect the SB with regions that are one or two orders of magnitude larger than the SB itself. Understanding these gas flows is then central not only to understanding the SB phenomenon, but for relating it to broader issues of cosmogony.

In this review, I focus on the gas-dynamical effects of SBs on their environments. Such 'feedback' is crucial to our understanding of star formation and the physical and dynamical state of the interstellar medium (ISM) of our own and nearby galaxies. More globally, feedback from massive stars can profoundly influence the structure, evolution, and even the formation of galaxies. The most spectacular manifestations of feedback are the galaxy-scale gas outflows driven by the collective effect of the SN, winds, and possibly radiation pressure in SBs. These have sometimes been called "superbubbles" or "superwinds", with the latter loosely referring to the largest-scale flows and/or to the cases in which the outflow has apparently burst out of the ISM. In addition to their importance in galaxy evolution, superwinds may have chemically-enriched and heated the intergalactic medium (IGM).

2. THE CONCEPTUAL FRAMEWORK

The 'engine' that drives the observed outflows is the mechanical energy supplied by massive stars in the form of SN and winds (cf., Leitherer & Heckman 1995). For typical SB parameters, the rate of supply of this energy is of-order 1% of the bolometric luminosity of the SB and typically 10 to 30% of the Lyman continuum luminosity. Some fraction of the energy may be radiated away by dense shock-heated material inside the SB. However, observations imply that a significant fraction is available to drive the outflow (see below). Radiation pressure acting on dust grains may also play a role in driving the observed outflows. The evolution of a SB-driven outflow has been extensively discussed (cf., Tenorio-Tagle & Bodenheimer 1988). Briefly, the deposition

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of mechanical energy by SN and winds results in an over-pressured cavity of hot gas inside the SB. This hot cavity will expand, sweep up ambient material and thus develop a bubble-like structure. If the ambient medium is stratified (like a disk), the bubble will expand most rapidly in the direction of the vertical pressure gradient. After the bubble 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. 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 observational manifestations of SB-driven outflows involve both the outflowing hot gas and its interaction with the ambient ISM. The latter (both the material in the outer superbubble wall and overtaken clouds inside the superbubble or superwind) can be photoionized by the SB and shock-heated by the outflow. This material can produce soft X-rays and optical/UV emission and absorption lines. The hot gas that drives the expansion of the superbubble/superwind may itself be an detectable source of X-rays, especially if a significant amount of 'mass-loading' of the outflow occurs in or around the SB (cf., Suchkov et al 1996). Finally, cosmic ray electrons and magnetic field may be advected out of the SB by the flow and produce a radio synchrotron halo and possibly an X-ray halo via inverse Compton scattering of soft photons from the SB (cf., Seaquist & Odegard 1991).

3. WELL-STUDIED EXAMPLES OF STARBURST-DRIVEN OUTFLOWS

3.1. NGC 1569 - A Dwarf Starburst

NGC 1569 is a nearby (D = 2.2 Mpc) dwarf galaxy that has been extensively studied (cf., Israel 1988; Waller 1991). It has $M_B = -17$ (about 6% L_*). However, its small rotation speed ($v_{rot} = 33$ km s^{-1}), together with the Tully-Fisher relation, suggests that it would have $M_B \sim -14$ to -15 in the absence of the SB (Krismer et al. 1995). The central SB has $L_{bol} \sim 2 \times 10^9$ $L_\odot$, and appears to be in a late evolutionary phase some 10^7 yr after the peak of the burst. Recently, we (Heckman et al. 1995; Della Ceca et al. 1996) have analysed *ROSAT* and ASCA X-ray data and optical long-slit spectroscopy on this galaxy. The famous system of Hα filaments extends out to a radius of about 1.5 kpc (Fig. 1), preferentially oriented along the optical minor axis in the NNE/SSW direction. These filaments seem to bound and circumscribe the X-ray halo (which the ASCA data show to be thermal emission from hot gas with T $\sim 8 \times 10^6$ K). The kinematics of the Hα filaments are consistent with a system of hollow structures expanding at about 100 km s^{-1} (de Vaucouleurs et al. 1974; Heckman et al. 1995). A similar-sized nonthermal radio halo is also present (Israel & de Bruyn 1988). The Hα, X-ray, and radio halos lie just within the H I envelope of the galaxy —at least in projection (Israel & van Driel 1990).

Overall, the data are consistent with the conceptual framework outlined above. The dynamical age of the expansion is about 10 Myr, similar to the age of the SB. The radius and expansion speed of the filament system are consistent with an energy-conserving bubble blown by the SB (Heckman et al 1995). The morphology of the X-ray and optical emission suggests that the outflow is in the superbubble phase, and has not yet blown out of the H I envelope that surrounds the SB. The thermal energy content of the hot gas is a few times 10^{54} ergs, which is about 10% of the estimated amount of mechanical energy injected by the SB over the last 10 Myr. The properties of the nonthermal radio halo are consistent with a model in which cosmic rays and magnetic flux are advected out of the SB (Israel & de Bruyn 1988). The new X-ray data allow us to address the fate of the hot outflowing gas in NGC 1569: will this gas escape and carry the newly synthesized metals into the IGM, or will the gas remain bound and return as a galactic fountain? The 'escape temperature' for hot gas in a galaxy potential with an escape velocity v_{es} is given by (Wang et al. 1995)

$$T_{es} = 10^5 (v_{es}/84\ \mathrm{km\,s^{-1}})^2 K \quad , \tag{1}$$

The H I rotation curve peaks at 33 km s^{-1} (Reakes 1980). If NGC 1569 does not have a dark matter halo, the estimated escape temperature at a radius of 1.7 kpc (the radius of the optical filament system) is about 3×10^4 K. If NGC 1569 has an isothermal dark halo that extends out to 20 times the optical Holmberg radius (out to $\sim$ 20 kpc), the corresponding escape temperature is about 10^5 K. Comparing these to the measured temperature of the hot gas ($\sim 10^7$ K), we conclude that the observed gas can easily escape unless it suffers strong radiative cooling. This possibility seems unlikely in this case: the cooling time is an order-of-magnitude longer than the gas dynamical timescale and the observed X-ray luminosity is about 300 times smaller than the mechanical luminosity of the SB. Moreover, the size of the superbubble system is only slightly less than that of the H I envelope, so that blow-out should soon occur.

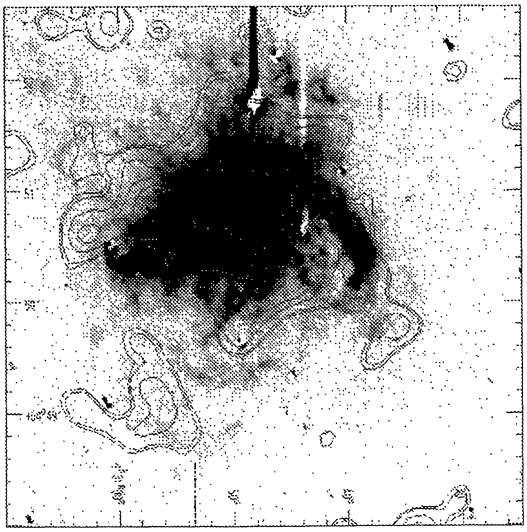

Fig. 1. Overlay of an archival *ROSAT* PSPC X-ray image of NGC 1569 on a narrow-band Hα image kindly provided by Dr. Deidre Hunter. The field displayed is roughly 4.7 arcmin or 3.0 kpc on a side.

3.2. NGC 253 - A Typical IRAS-Selected Starburst

The galaxy NGC 253 contains —along with M82— the nearest (3.4 Mpc) and best-studied example of a nuclear SB. The burst is quite compact, with a size of only a few hundred pc (cf., Pina et al. 1992; Forbes et al. 1993). Its luminosity is near the characteristic 'knee' in the IR galaxy luminosity function ($L_{bol} \sim 3x10^{10}$ $L_{\odot}$; cf., Soifer et al. 1987). NGC 253 is a typical late-type barred (SAB(s)c) galaxy with an absolute magnitude that is near the fiducial Schecter L_* value ($M_B = -20.3$) and a rotation speed $v_{rot} = 180$ km s^{-1}. Its nearly edge-on orientation is ideal for studying the outflow. As first seen by Fabbiano & Trinchieri (1984), there is a 'fan' of X-ray emission to the south-east of the SB, along the galaxy minor axis. The *ROSAT* PSPC data imply a gas temperature of about $7{\times}10^6$ K and an unabsorbed luminosity of about 4×10^{39} erg s^{-1} (Dahlem et al. 1996). This can be compared to the estimated mechanical luminosity of the SB, $\sim 10^{42}$ erg s^{-1}. A system of minor-axis Hα filaments seem to lie along the sides of the X-ray source, suggesting that the optical emission arises in material that is being compressed and accelerated by the hot outflowing material visible in X-rays (McCarthy et al. 1987). This is confirmed by optical spectroscopy, which shows that the emission-line gas here exhibits the 'line-splitting' characteristic of a hollow structure that is expanding at a velocity of several hundred km s^{-1} (Ulrich 1978; Heckman et al. 1990). A counterpart of the outflow can be seen in the X-ray and Hα images on the opposite (north-west) side of the SB. This north-west region is fainter, presumably because it is absorbed by the galaxy disk. A molecular manifestation of this back-side outflow to the north-west was discovered by Turner (1985).

In addition to this kpc-scale 'nuclear' outflow, NGC 253 has a larger X-ray halo (Fig. 2a; see also Pietsch 1993), roughly 25 by 12 kpc, with its long axis aligned with the galaxy minor axis. Absorption of the soft X-rays by the near-side of the disk can be seen on the north-west side. In PSPC maps the halo appears filamentary, with an overall 'X' shape (Pietsch 1993). The X-ray halo is quite soft, and is much less conspicuous at energies above 0.5 keV (Pietsch 1993; Dahlem et al. 1996). The implied temperature is a few million K, and the unabsorbed luminosity of the halo component in the *ROSAT* band is about 10^{40} erg s^{-1}. Interestingly, the rotation speed for NGC 253 and eq. (1) implies that the escape temperature from NGC 253 at radius of 10 kpc will be 2 to 3 million K if it has an isothermal dark matter halo extending out to a radius of $\sim$ 50 kpc (cf., Puche & Carignan 1991). Thus, the observed hot halo gas is close to the escape temperature, and its fate is unclear. Observations at 0.33 GHz, by Carilli et al. (1992) show that NGC 253 is also one of the few known galaxies with a radio halo. The radio and X-ray halos are similar in size, but the radio halo is more nearly spherical and does not show the limb-brightened 'X' shape seen in the *ROSAT* data. The relationship of the SB and its kpc-scale outflow to the galaxy-scale X-ray and radio halos is a matter of debate. On morphological grounds, Carilli et al., suggest that the radio halo may be powered by an outflow from the inner part of the 'normal' star-forming disk of NGC 253, rather than from the nuclear SB. Indeed the inner disk is riddled with giant H II regions, and Carilli et al., note that a radio 'spur' seems to connect to a region of bright Hα emission located

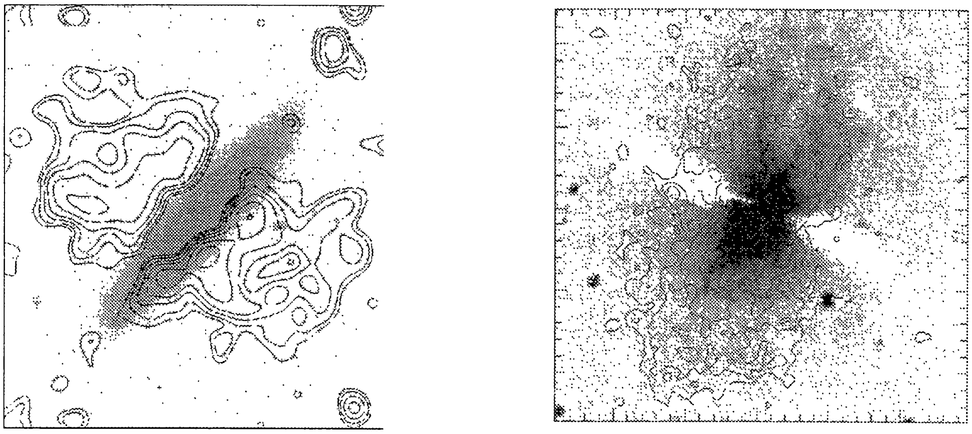

Fig. 2. *a)* An overlay of the *ROSAT* PSPC X-ray image of NGC 253 in the 0.25 keV band (in contour form) on an optical continuum image (greyscale). The displayed field size is 30 arcmin (30 kpc) on a side. The *ROSAT* image has been processed by first digitally subtracting the point-like sources (including the nucleus) and then heavily smoothing the residual map to bring up diffuse, low-surface-brightness emission (see Dahlem et al. 1996). *b)* An overlay of the archival *ROSAT* HRI X-ray image (contours) and an optical image (greyscale) of the Hα (dark) and red stellar continuum (light) of the central 5 arcmin (5 kpc) of M82. The optical image was kindly provided by Dr. Eric Smith.

several kpc from the nucleus in the disk. *ROSAT* data also show that the inner disk (with a radius similar to the lateral extent of the X-ray halo) is a soft X-ray source. This could represent hot gas flowing out of the disk and into the halo. Nevertheless, the rarity of X-ray halos in normal spiral galaxies on the one hand (cf., Vogler et al. 1996) and their ubiquity in galaxies with powerful central SBs (Dahlem et al. 1996) suggests to me at least that the X-ray halo in NGC 253 is primarily powered by the SB. I would therefore propose the following possible interpretation, which is based in part on the numerical simulations presented by Suchkov et al. (1994; 1996).

Gas with a temperature of about 10^7 K is created in the SB and flows out along the galaxy minor axis. The outflowing gas produces the kpc-scale X-ray source (cf., Bregman et al. 1995; Suchkov et al. 1996), while swept-up, shocked-heated disk gas produces Hα emission along the walls of the outflow. As the outflow propagates into the halo, its X-ray emissivity drops dramatically due to the steep drop in its density and to adiabatic cooling. However, the outflow creates a high-pressure piston of gas that drives a shock into the pre-existing halo gas at a velocity of about 400 km s^{-1}, heating the halo gas to several million K, and producing a limb-brightened X-ray source (Suchkov et al. 1994). The fact that this halo source is 'X'-shaped rather than '8'- shaped suggests that the outflow has recently 'blown-out' of the galactic halo (cf., MacLow & MacCray 1988). The size of the halo and the inferred shock speed would imply a dynamical age of a few times 10^7 yr —similar to the estimated SB age.

3.3. M82 - A Powerful Starburst in a Low-Mass Galaxy

The overall properties (size, luminosity, edge-on orientation) of the M82 and NGC 253 SBs are quite similar. However, they occur in very different galaxies. Based on its dust-riddled morphology, M82 is classified as an Amorphous galaxy in the *Revised Shapley-Ames Catalog* and an I0 galaxy in the *Third Reference Catalog of Bright Galaxies*. It is smaller and less massive than NGC 253, with $M_B = -18.6$ and a rotation speed of about 110 km s^{-1}. These properties are rather atypical of SBs with comparable IR luminosities (Lehnert & Heckman 1996a,b). The presence of an outflow in M82's famous Hα filament system has been debated for many years, and the history of this was nicely summarized by Bland & Tully (1988). While scattering of SB light by dust in the halo of M82 clearly plays a role in what we see (cf., Scarrott et al. 1991), there is now no doubt that an outflow is also occurring. The kinematic signature of expanding superbubbles or a hollow biconic outflow was first noted by Axon & Taylor (1978). Bland & Tully (1988) later published optical Fabry-Perot data that showed the presence of a bipolar outflow (superwind) along the optical minor axis (see Heckman et al. 1990). The outflow interpretation was also bolstered by X-ray observations by Watson et al. (1984), Fabbiano (1988), and Bregman et al. (1995) showing diffuse X-ray emission co-extensive with the Hα filaments (Fig. 2b). The X-ray morphology of the M82 outflow is different from that in NGC 253. In M82, the entire 10-kpc-scale X-ray nebula resembles the small nuclear outflow in NGC 253. Note the laterally limb-brightened morphology of the Hα filament system (particularly to the North). This is suggestive of a 'blow-out' of hot gas into the halo, with the Hα emission produced by a sheath of shocked and entrained disk gas with a ruptured top (see Section 2 above). In support of this interpretation, the X-ray emission can be detected out to about a factor of two larger radius than the Hα emission (~5 kpc vs. ~2.5 kpc). Moran & Lehnert (1996) have analysed *ROSAT* PSPC and ASCA data and they conclude that the hot gas in M82 has a temperature of about 7×10^6 K in and near the SB, declining to 4×10^6 K in the halo. The unabsorbed X-ray luminosity of these two components is about 10^{41} erg s^{-1}, which can be compared to the estimated mechanical luminosity of the SB ($\sim 10^{42}$ erg s^{-1}). The rotation speed and eq. (1) implies that the escape temperature from M82 at a radius of 5 kpc will be about 10^6 K, even if this small galaxy has an isothermal dark matter halo extending out to a radius of $\sim$ 50 kpc. Since the halo gas is about four times times hotter than this, it may well be escaping from M82.

Like NGC 253, M82 also has a radio-synchrotron halo extending out to a radius of at least 8 kpc (Seaquist & Odegard 1991). As in the case of NGC 253, this radio halo is more nearly spherical than the X-ray nebula. The spectrum of the radio emission in M82 steepens with increasing radius, which Seaquist & Odegard attribute to the more rapid cooling of the most energetic electrons by inverse Compton scattering of the SB IR photons. They then derive an outflow speed for the relativistic plasma of about 2000 km s^{-1} ($>> v_{esc}$). They also estimate that relativistic particles comprise only a few percent of the energy content of the M82 outflow. This ratio is similar to that observed in SN remnants, as expected in the superwind model. To summarize, the outflow in M82 is similar to that in NGC 253 but differs in some important respects. The outer (25-kpc-scale) limb-brightened X-ray halo in NGC 253 is produced as the superwind drives a shock into a pre-existing gaseous halo surrounding NGC 253 (cf., Suchkov et al. 1994). Perhaps a dwarf galaxy like M82 lacks such a halo (as Steidel 1993 suggests may be generally true based on his identifications of galaxies responsible for Mg II absorption in quasar spectra). On the other hand, the X-ray outflow in M82 is considerably brighter than the inner (kpc-scale) X-ray outflow in NGC 253. This may imply that there is a larger amount of mass-loading of the outflow in M82 than in NGC 253 (Bregman et al. 1995; Suchkov et al. 1996). Suchkov et al show that for a given SB energy injection rate, the X-ray luminosity of the outflow is proportional to roughly the cube of the mass outflow rate: a factor of two increase in the mass outflow rate leads to nearly an order-of-magnitude increase in L_X.

4. SOME IMPLICATIONS OF STARBURST-DRIVEN OUTFLOWS

I conclude by briefly summarizing several key astrophysical topics where SB-driven outflows are quite likely to be relevant.

The Chemical Enrichment of the Intergalactic Medium: It has long been known that the mass of metals contained in the intra-cluster medium in galaxy clusters is similar to the mass of the metals locked up in the stars inside the cluster galaxies. Theories to explain this have invoked ram pressure stripping, 'late' galactic winds driven by type Ia SN and 'early' winds driven by type II SN associated with a SB/formative phase of an early type galaxy. The recent discovery with ASCA (Loewenstein & Mushotzky 1996) that the abundances of α-peak (e.g., O, Si, Ne) elements relative to Fe are several times the solar value implicates type II SN and supports the 'early wind' (SB-driven outflow) scenario. If galaxies inside clusters can eject as much metals as they retain, why wouldn't this be true globally (e.g., in the field)? While a truly diffuse IGM has not been detected in X-rays, recent spectroscopic investigations of the Lyman-α 'forest' (the cloudy component of the IGM at high redshift) shows that this material is also enriched with metals (cf., Cowie et al 1995). It is tempting to speculate that SB-driven outflows in the early universe polluted the IGM with metals.

The Evolution of Galaxies: In the SBs studied to date, the temperature of the hot outflowing gas is always in the range of a few million to ten million K. This temperature is presumably set by thermal and gas dynamical processes in the ISM of the SB, independent of the depth of the gravitational potential provided by the host galaxy. Inspection of equation 1 above implies that the observed temperature range corresponds roughly to the 'escape temperature' for a L_* galaxy. This then implies that SB-driven outflows can escape much more readily from low-mass galaxies (and in so-doing, carry away the newly synthesized metals). Such a mechanism provides a physical basis for the mass-metallicity relation among galaxies and the radial metallicity gradients within galaxies (cf., Lynden-Bell 1992; Franx & Illingworth 1990). Objects like NGC 1569 provide us with dramatic examples of low-mass galaxies undergoing highly episodic bursts of star-formation with a subsequent loss of the resulting metals. Do such events dominate the evolution (chemical and otherwise) of such galaxies? These ideas are highly popular with theorists (especially in the context of explaining the population of 'faint blue galaxies'). For example, Babul & Ferguson (1996) propose that a strong SB associated with the formation of a dwarf galaxy blows away the remaining ISM thereby shutting off further star-formation and allowing the population of faint blue galaxies to fade and redden to become a presently inconspicuous population of dwarf elliptical or dwarf spheroidal galaxies. Skillman (this volume) argues that there may be more to this story, at least in the case of dwarf Irregular and related galaxies.

Many people have worked with me over the past decade on various aspects of the work described above. I am particularly grateful to my Ph.D. students past and present (L. Armus, M. Lehnert, A. Marlowe, and J. Wang) and to Drs. M. Dahlem, R. Della-Ceca, and K. Weaver who have taken the lead on the analysis of the X-ray data. My research on superwinds and superbubbles has been supported in large part by NASA grants NAGW- 4025 and NAG5-1991, and by NSF grant AST-90-20381.

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