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OBSERVATION AND MODELING OF STARBURST-DRIVEN GALACTIC WINDS: A REVIEW IN HONOR OF JOHN DYSON

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RESUMEN

Las galaxias con brote de formación estelar están generalmente asociadas a los halos extendidos de rayos-X y emisión radio, lo cual da una indicación clara de un flujo de gas y partículas relativistas del disco hacia el halo. Los agentes impulsores son, como es de esperarse, las regiones de formación estelar activa y las ondas de choque de las superburbujas. La dinámica del flujo y la evolución térmica del plasma están fuertemente acopladas y por lo tanto se require un modelo autoconsistente para una descripción adecuada. Debido a que la temperatura del plasma se encuentra entre uno y unos pocos millones de grados Kelvin, el halo es más conspicuo en rayos-X suaves. Se demostrará que los datos de rayos-X recientemente obtenidos con el *XMM-Newton* EPIC pn tienen características espectrales claras que están en fuerte desacuerdo con la idea de un halo isotérmico en equilibrio de ionización colisional (EIC). En su lugar, se observa una estructura de temperatura en los halos de rayos-X. Se demostrará que un modelo de un flujo de viento galáctico en donde se calcula de manera autoconsistente la estructura de ionización fuera de equilibrio puede dar una explicación satisfactoria y física de las características espectrales de los rayos-X, por ejemplo, en el caso de la galaxia local con brote de formación estelar NGC 3079. En particular, se demuestra que las altas abundancias subsolares que se reportaron de las observaciones de rayos-X en algunos casos son artefactos de los modelos de ajuste de espectros EIC. Se encuentra que los modelos espectrales están fuertemente restringidos por la presencia de líneas diagnósticas tales como O VII y O VIII además de los complejos de líneas Fe L. Por lo tanto, un modelo espectral de rayos-X detallado ayudará a proporcionar parámetros importantes del viento galáctico tales como la tasa de pérdida de masa y el perfil de velocidad, lo cual será util también como una valiosa aportación a los flujos galácticos en el universo temprano.

ABSTRACT

Starburst galaxies are generally associated with extended X-ray and radio halos, giving a clear hint of an outflow of gas and relativistic particles from the disk into the halo. The driving agents are, not surprisingly, active star-forming regions, injecting hot gas and cosmic rays generated by supernova remnant and superbubble shock waves. The dynamics of the outflow and the thermal evolution of the plasma are strongly coupled, and therefore a self-consistent model is necessary for a satisfactory description. Since the plasma temperature is between one and a few million Kelvin, the halo is most conspicuous in soft X-rays. It will be shown that X-ray data obtained recently with *XMM-Newton* EPIC pn bear clear spectral signatures that are in strong disagreement with an isothermal halo in collisional ionization equilibrium (CIE). Instead, a temperature structure in X-ray halos is observed. It will be demonstrated that a galactic wind outflow model, in which the non-equilibrium ionization structure is calculated self-consistently, can give a satisfactory and physical explanation for the X-ray spectral characteristics, e.g., in the case of the local starburst galaxy NGC 3079. In particular, high sub-Solar abundances, which have been reported from X-ray observations in some cases, are shown to be artefacts of CIE spectral-fit models. It is found that spectral models are strongly constrained by the presence of diagnostic lines such as O VII and O VIII as well as Fe L line complexes. Thus, a detailed spectral X-ray model will help to provide important galactic wind parameters, such as mass-loss rate and velocity profile, which may also serve as valuable input for galactic outflows in the early universe.

Key Words: **HYDRODYNAMICS — GALAXIES: HALOS — GALAXIES: STARBURST — X-RAYS: GALAXIES**

1. INTRODUCTION

The observation of optically selected late-type galaxies led to the conclusion that the bluest objects could not all be young, but more likely are in a state of enhanced star formation (Searle, Sargent, & Bagnuolo 1973). These so-called starbursts are intermittent during galaxy evolution with a duration of typically 10^8 yr. It has been argued that the total rate of high-mass star formation within these short (with respect to a Hubble time) periods is comparable in the local universe to the rate in spirals during the whole time of quiescent star formation (Heckman

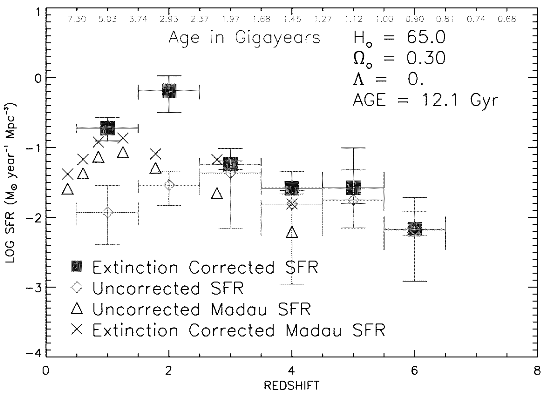

Fig. 1. Star-formation rate as a function of redshift in a comoving volume including also extinction (Thompson et al. 2001).

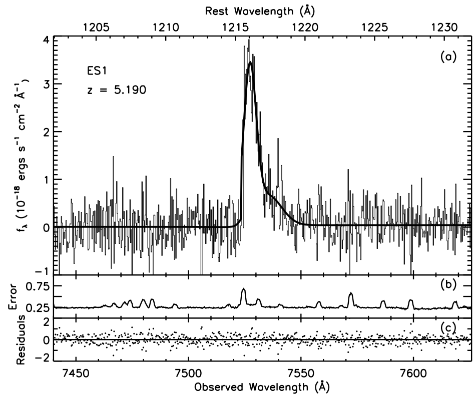

Fig. 2. Lyα emission line from the outflow of the star-forming galaxy J 123649.2+621539 (Dawson et al. 2002). The fitted line profile could be modeled by 3 components: a large amplitude narrow Gaussian for the recombination of H^+, a small amplitude broad Gaussian (redshifted by $320\,\mathrm{km\,s^{-1}}$) for backscattered red-wing emission of far-side Lyα photons of the expanding wind, and a broad Voigt absorption profile (blueshifted by $360\,\mathrm{km\,s^{-1}}$) to model the blue decrement due to near-side absorption of photons.

1998). Undoubtedly, the effects of a starburst on the ISM are dramatic. A high supernova rate disturbs and eventually disrupts the gaseous disk, and supernova remnant (SNR) heated gas and accelerated energetic particles (cosmic rays) are injected into the base of the galactic halo.

It has been shown theoretically that the combined pressure gradients of gas, cosmic rays (CRs), and MHD waves are able to drive a galactic wind even in cases of moderate star formation, like in our own Galaxy (Breitschwerdt, McKenzie, & Völk 1991). A necessary condition is that there is a dynamical coupling between the plasma and the CRs. Such a coupling can be provided by strong resonant scattering off self-excited MHD waves, which are generated by a large-scale CR gradient pointing away from the galaxy, and thus induce a so-called streaming instability (e.g., Kulsrud & Pearce 1969). On the other hand, the overpressure in superbubbles generated by rich OB clusters is sufficient to drive a largely thermal outflow. In the case of starburst galaxies the conditions are even more extreme, and in galaxies like M 82 the galactic wind (or superwind, as it is sometimes called) is purely thermally driven (Chevalier & Clegg 1985; Völk, Aharonian, & Breitschwerdt 1996).

In recent years the study of starburst phenomena and galactic winds has received a tremendous boost. This was largely driven by observations, notably the availability of 8 m-class telescopes such as the VLT and Keck with superb instrumentation, as well as the *Hubble Space Telescope* (*HST*). Selecting galaxy samples by color and measurement of the UV flux of galaxies indicated a peak in the star-formation rate (SFR) near redshift $z \sim 1.5$ (Madau et al. 1996), while in more recent observations it was argued for a near constancy between $z = 1.5$ to 4 (Steidel et al. 1999). A major uncertainty in these studies was the amount of extinction in the UV. Therefore, both extinction and redshift should be included in the SFR analysis. A detailed study of the northern Hubble Deep Field with *HST* NICMOS, in which both the SFR was determined individually for galaxies from the 1500 Å UV flux and a spectral energy distribution template fitting method was applied to determine redshift as well as extinction, yielded the result (Thompson, Weymann, & Storrie-Lombardi 2001) of an increase in SFR between $z = 1$ to 2, then a fall-off from $z = 2$ to 3 and a plateau region between $z = 3$ to 5 (see Figure 1); as a clear result, the SFR was higher up to redshifts of ~ 5 than at present.

Naturally, an enhanced SFR implies an enhanced starburst activity during the infancy of galaxy evolution and galactic winds are expected to have been fairly common at that time. Such an assumption is indeed confirmed by observation. A recent serendipitous discovery of a galactic wind at $z = 5.19$ by Dawson et al. (2002) revealed a strong asymmetric Lyα emission line (see Figure 2). The best-fit model line profile resulted in a red- and blueshifted wing, indicating an outflow velocity of 320 to $360\,\mathrm{km\,s^{-1}}$. As will be shown below, such velocities are entirely consistent with wind speeds derived from modeling the X-ray emission of *local* starburst galaxies. An important consequence of winds is the pollution of the intergalactic medium (IGM) with chemically enriched material. In addition to metals, entropy is also added to the IGM.

This may be an explanation for the so-called "entropy floor" postulated by comparing the X-ray luminosity versus temperature relationship. Going from massive clusters of galaxies to poor groups there is a deviation from a power law towards the low-mass end. This has been interpreted in terms of an "entropy floor" that dominates the gravitational heating of the poor clusters and groups as the potential wells become shallower (Ponman, Cannon, & Navarro 1999). Thus, the preheating of the IGM by starburst-driven galactic winds starts to dominate the release of gravitational energy. Also, the fairly high abundances of $Z \sim 0.3\,Z_{\odot}$ (e.g., Molendi et al. 1999) found in the intra-cluster gas may be explained by ejection of metals from galaxies by massive winds during initial starburst phases.

In the local universe, evidence for galactic winds mainly stems from observations of starburst galaxies, such as M 82 or NGC 253. In these more evolved objects, starbursts are thought to be triggered by a substantial disturbance of the gravitational potential, e.g., by interaction with a companion. Nevertheless, as it has been pointed out, local starbursts are similar in origin, evolution, duration, and its effects on the IGM to those at high redshifts (e.g., Pettini et al. 2000). If one accepts these findings as a working hypothesis, nearby starburst galaxies would serve as ideal laboratories for studying the effects of starbursts on the early evolution of galaxies and the interaction with the IGM. Since the starburst-driven outflows are mostly thermal, they are best observed in soft X-rays.

2. OBSERVATIONS OF LOCAL STARBURST GALAXIES

Direct evidence for supernova (SN) heated galactic halos stems from imaging and spectroscopy of diffuse soft X-ray emission. This has been impressively demonstrated by a recent *XMM-Newton* observation of NGC 253 (Pietsch et al. 2001). From Figure 3 it can be clearly inferred that (i) the diffuse emission is soft (cf. 0.2 to 0.5 keV band color-coded in red), and (ii) that the outflow is extended and distributed over the whole disk rather than being constrained solely to the nuclear region. The nearby (distance 17 kpc), edge-on (inclination to the line of sight about 85°) spiral galaxy NGC 3079 has been observed with *XMM-Newton* for a total of 25 ksec. The galaxy is classified as an SBc LINER with distinct nuclear activity. The object is an ideal target for analyzing the diffuse X-ray emission in the

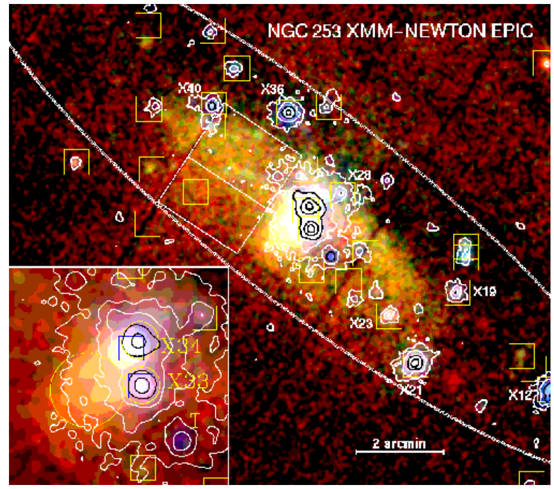

Fig. 3. The extended soft X-ray emission of the nearby edge-on starburst galaxy NGC 253, as observed by the EPIC pn and MOS cameras onboard *XMM-Newton* in a three-color image (red: 0.2 to 0.5 keV, green: 0.5 to 0.9 keV, blue: 0.9 to 2.0 keV; overlayed contours represent the 2.0 to 10.0 keV band; Pietsch et al. 2001). For reference the D_{25} ellipse is plotted to show the optical extension of the gas disk. The inlay is a zoom-in of the nuclear region, with *ROSAT* detected sources marked by squares. NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

disk and the surrounding galactic halo, since galactic foreground absorption is low (column density $N_{\rm H} < 10^{20}\,{\rm cm}^{-2}$). The target was chosen to investigate both the problem of starburst-AGN connection, and to see if there was widespread extranuclear X-ray emission, for which we wanted to derive the spectral properties. The observation was carried out as part of the *XMM* SSC Guaranteed Time Program. Rejection of high background times led to an overall useable integration time of 16.4 ksec. We detected a huge soft (0.2 to 1.0 keV) X-ray halo (see Figure 4) extending perpendicular to the galaxy disk to about 17.5 kpc (Breitschwerdt et al. 2003). The emission is therefore expected to be dominated by thermal lines, which are abundant in the soft band. The spectrum of a conspicuous emission region indeed proves this point. Moreover, it clearly shows that the galactic starburst must drive a thermal outflow, since we have strong indications for collisionally excited oxygen and iron L line complexes in the spectrum (see Figure 5). A further argument for a halo connected to star-forming regions in the underlying gaseous disk, rather than to AGN activity, is the softness of the halo, which completely disappears in the higher energy band (1.0 to 2.0 keV). The morphology

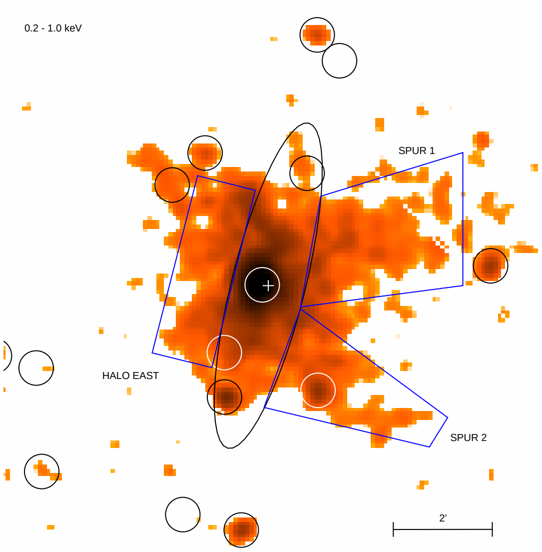

Fig. 4. The extended soft X-ray halo of the nearby edge-on starburst galaxy NGC 3079, as observed by the EPIC pn camera onboard *XMM-Newton* in the 0.2 to 1.0 keV energy band (Breitschwerdt et al. 2003). Point sources are shown by circles. For reference the D_{25} ellipse is indicated to show the optical extension of the underlying gas disk.

of the halo also shows extranuclear spurs supporting the starburst connection.

3. SELF-CONSISTENT DYNAMICAL AND THERMAL MODELING OF OUTFLOWS

The injection of SN-heated gas into the base of the halo generates a huge pressure gradient with respect to the ambient IGM. Consequently, the hot plasma can escape the gravitational potential well and expand to infinity, provided that the external pressure is sufficiently low. Otherwise, the expanding hot gas will become thermally unstable and rain down in the form of intermediate-velocity clouds on the galactic disk (galactic fountain). This is to be expected if the radiative cooling timescale, $\tau_{\rm cool} \simeq 3n\Lambda(T)/(k_{\rm B}T)$, is much less than the dynamical flow timescale, $\tau_{\rm f}(z) = \int_{z0}^{z} dz'/u(z')$; in a steady-state flow this condition has to hold at least at the sonic point. Further out the flow is supersonic and cannot be influenced by the source region; mass loss is then inevitable. In a starburst-driven flow this is certainly fulfilled as our calculations show. The model as applied to an edge-on galaxy is sketched in Figure 6.

We have tested the hypothesis of a thermally driven superwind by modeling the outflow with our galactic wind hydrocode, in which the radiative cooling and X-ray emission is treated self-consistently

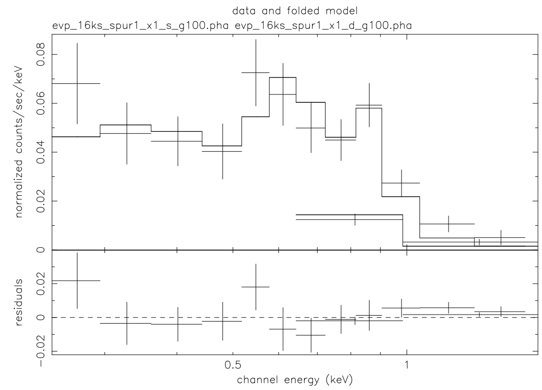

Fig. 5. Fit ($\chi^2 = 1.2$) of the Epic pn observed spectrum (crosses = error bars) of the soft X-ray halo emission of NGC 3079 between 0.2 and 2 keV obtained with a self-consistent non-equilibrium emission outflow model (solid line; Breitschwerdt et al. 2003).

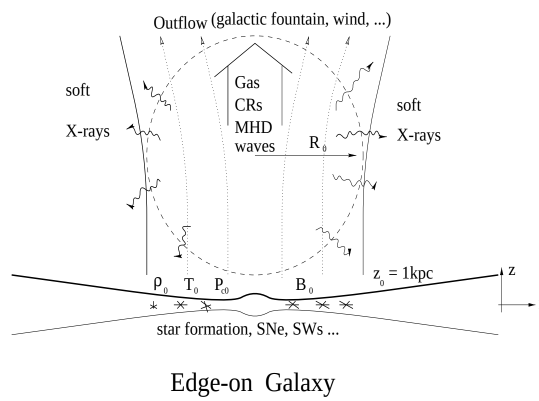

Fig. 6. Sketch of the galactic outflow model. The wind is mainly driven by thermal pressure, but cosmic rays and MHD waves may also assist and are included self-consistently.

with the dynamics in full non-equilibrium (NEI). In essence this means that we follow the time-dependent ionization structure of the outflow instead of using the usual assumption of collisional ionization equilibrium (CIE). The necessity in doing so has been been extensively discussed in Breitschwerdt & Schmutzler (1999). For brevity we just repeat here the main arguments. Firstly, the assumption of CIE is strictly never fulfilled. A detailed balancing of the collisional ionization rate by the recombination rate would require three-body collisions (one electron recombining with an ion, another one carrying away the excess energy), which are extremely rare in an optically thin and dilute plasma. Therefore, collisional de-excitation is negligible and the coronal approximation holds. Instead, radiative cooling, by which the excess energy is removed by a pho-

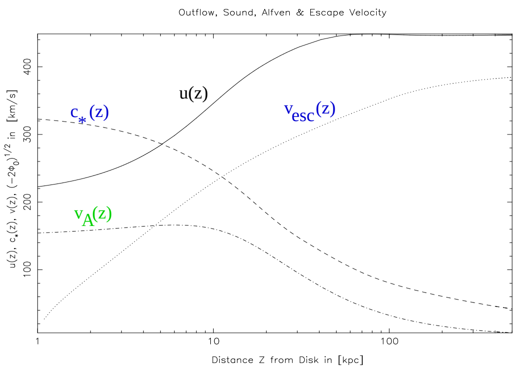

Fig. 7. Dynamically and thermally self-consistent outflow model of the starburst-driven galactic wind of NGC 3079 (Breitschwerdt et al. 2003). The solid line is the outflow velocity $u(z)$, $v_{\rm A}(z)$ is the Alfvén velocity (dash-dotted line), $c_*(z)$ is the generalized speed of sound (dashed line) and $v_{\rm esc}(z)$ (dotted line) is the escape speed from the gravitational potential of the galaxy.

ton, dominates by far. Except for resonant processes, the absorption probability of these photons is very low and they escape. But this means that both collisional ionization and radiative recombination are *cooling processes* for the plasma, which will hence be driven out of equilibrium (Shapiro & Moore 1976; Schmutzler & Tscharnuter 1993). CIE can therefore only hold as an approximation during a limited period or due to some form of heat input. Secondly, it has been shown that if the plasma is in a dynamical state (e.g., expansion), the dynamical timescale can be shorter than any atomic timescale, and the plasma is characterized by a state of *delayed recombination* (Breitschwerdt & Schmutzler 1994). Thirdly, there exists a feedback mechanism between thermal and dynamical evolution. The latter changes the density, pressure, etc. of the flow, which in turn changes the time-dependent ionization structure and thereby the radiative energy losses, which crucially determine the dynamics again. An approximate and efficient way of solving the hydrodynamics *self-consistently* along with the non-equilibrium ionization (NEI) structure is to calculate the temporal evolution separately and couple them by a *time-dependent cooling rate* $\mathcal{L}[n(t), T(t); Z]$, where n, T and Z are the density, temperature and chemical abundances, respectively (Breitschwerdt & Schmutzler 1999). This iterative procedure converges fairly rapidly. The NEI code treats the time-dependent atomic processes (collisional ionization, recombination, autoionization, dielectronic recombination, to name just a few; for details see Schmutzler & Tscharnuter 1993) of the ten most abundant elements and their respective ionization stages, and includes at present 1155 lines. The hydrocode has been described in detail by Breitschwerdt et al. (1991). It entails a realistic gravitational potential of the galaxy, and the flow is calculated in steady state in a flux-tube geometry, which is a fair representation of the transition from plane-parallel flow close to the disk to spherical divergence far away. We expect that steady state is justified *during* the starburst and as long as there are no dramatic changes at the inner boundary conditions. Fully time-dependent simulations, using the STARBURST99 code, are underway (Dorfi & Breitschwerdt 2003), and confirm this by and large, but also show that abrupt changes in the SN rate lead to propagation of shocks, reheating of the halo, and particle acceleration up to energies well in excess of the 10^{15} eV reached in individual SNRs. This has to be borne in mind when interpreting the spectra.

In order to compare the simulated spectra directly with the observations, we have folded them through the EPIC pn instrumental response. Taking the instrumental field of view of $\sim 30' \times 30'$, we have projected the outflow cone at the galaxy's distance (see Fig. 6) onto it. Thus, we do not only reproduce the form of the spectrum, but also the absolute count rate. We even went one step further, and instead of comparing the observed and synthetic spectra by eye, we have used the latter as input for XSPEC to actually *fit* the observed spectrum. The result shows (see Figure 7) that the halo indeed exhibits a "multi-temperature structure", fully consistent with an NEI outflow, in which supernova-heated gas is injected into the halo at temperatures of 3.6×10^6 K and density $5 \times 10^{-3}\,{\rm cm}^{-3}$ at an initial velocity of about $220\,{\rm km\,s}^{-1}$ (see Fig. 7) to give a satisfactory fit with $\chi^2_{\rm red} \approx 1.2$. A closer inspection of Fig. 5 reveals two distinct humps at 0.6 keV and 0.9 keV, caused by the O VII, O VIII and Fe L line complexes, respectively.

We emphasize that a single temperature CIE model, as e.g., by Raymond & Smith (1977) or a so-called MEKAL model, are not able to reproduce the spectrum in a statistically acceptable way. The reason is, because CIE models are extremely temperature sensitive, each hump in our spectrum would require a different CIE temperature. In an attempt to achieve a fit, although not a very good one, a common error is to decrease the element abundances to extremely low values (e.g., a few percent Solar, has been advocated in some publications) in order to get rid of prominent lines that would enforce a specific excitation temperature. We consider this to be a pure *artefact* of the fit procedure, and, moreover, as *unphysical*, because an outflow that is mass loaded by chemically enriched material from the starburst region should have high rather than low metallicities.

4. CONCLUSIONS

Star formation is a highly nonlinear process, and it has been known for some time that, for example, it can be triggered by nearby SN explosions. On the other hand, the rate cannot increase indefinitely because the exhaustion of gas fuel renders it more and more inefficient, thereby forcing it into a self-regulating cycle. The highest rates known to date are realized by galaxy-galaxy interactions (with mergers as an extreme form), and starbursts as a common manifestation. In particular, in the early universe, when the average distance between galaxies was much smaller, starbursts could dominate their integrated luminosity. Both local and distant starburst galaxies show that the enhanced star-formation rate is accompanied by a thermally driven outflow, which can be traced out to large distances in soft X-rays. Although only a few percent of the energy released is radiated in this wavelength range, the presence of lines of highly ionized and abundant species, such as oxygen and iron, in the spectrum serves as a clear fingerprint for the generation of a hot plasma and its dynamical evolution as a galactic wind. Therefore, spectral modeling of outflows provides important quantitative information of mass-loss rates, chemical enrichment of the IGM, and, possibly, a contribution to the WHIM (warm hot intergalactic medium) that has been invoked to explain the so-called missing baryon problem (Cen & Ostriker 1999). Last but not least, the effect of a starburst-induced superwind on the further evolution of the host galaxy should not be underrated. Venting hot material away removes a lot of entropy, thus ensuring a continuation of star formation in a more quiescent fashion in the disk.

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