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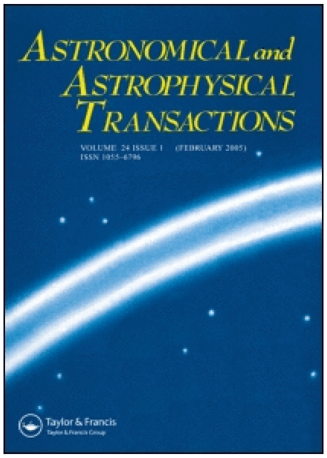

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CHEMICAL COMPOSITION AND X-RAY EMISSION FROM STARBURST BLOWN SUPERBUBBLES

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Recent observational results related to the X-ray emission from SB galaxies are reviewed. The results of calculations of the superbubble inner hot gas metallicity are presented. It is shown that supernova metal ejection leads to a high overabundance of the hot bubble interior, that allows for up to an order of magnitude higher X-ray luminosities compared with the standard model predictions.

KEY WORDS Interstellar medium, galaxies, Starbursts, X-ray emission

1 INTRODUCTION

It has recently been recognized that the star formation activity in many galaxies is highly non monotonic and can vary dramatically with time. Starbursts (SB), short ($\leq 10^8$ Myrs) episodes of violent star formation, are now considered to play a crucial role in the general galaxy evolution. The powerful energy deposition during a SB life time provides dramatic changes in the host galaxy interstellar medium (ISM), initiates a large scale shock wave formation and gas outflow (a galactic superwind) out of the SB region. These gas outflows are observed in the non-thermal, optical and soft X-ray emissions in many nearby galaxies. This defines the cosmological interest of the starburst phenomenon as a potential mechanism which is able to provoke effective transport of interstellar matter and newly processed metals out of the parental galaxies and provide pollution of the intra-cluster gas by SN produced metals Dekel and Silk (1986), De Young and Heckman (1994).

An alternative approach, however, predicts that currently observed perturbations of the ISM by supernova explosions play only a minor role in gas and metal ejection from the galaxies, while the galaxy mergings (Gnedin, 1998) or mass ejection from the low mass pre-galactic systems in the early galaxy formation epoch (Madau *et al.*, 2000) dominate the intergalactic medium pollution by heavy elements.

The chemical abundances of the SB disturbed regions can provide strong constraints on the proposed models. At the same time, the hot gas chemical composition is one of the key parameters which defines the X-ray emission itself. However, neither the hydrodynamical properties (the dynamics, location and filling factor of the X-ray emitting plasma) nor the physical processes which define the hot gas chemical composition are yet clear.

Here I review some recent observational results related to the X-ray emission from the SB galaxies and describe our (Silich *et al.*, 2001a) new approach to the problem, which is based on time dependent calculations of the chemical composition of SB produced hot gas.

2 X-RAY EMISSION FROM STARBURST GALAXIES

The energy deposition in the starburst regions exceeds that of the rest of the galaxy $L_{SB} \gg L_{gal}$ and is concentrated in the few luminous H_α knots as observed in NGC 5253 (Strickland and Stevens, 1999), NGC 4214 (MacKenty *et al.*, 2000) or VII Zw403 (Fourniol, 1997) galaxies. These patches of violent star formation are usually embedded in the extended (up to tens of kiloparsecs) regions of the diffuse soft X-ray emission. A careful analysis of the usual scheme for the X-ray data reduction and fitting procedure (Strickland and Stevens, 1998) shows that a multiple rather than a single temperature component model has to be used to derive realistic properties of the X-ray emitting plasma. However, it is not yet clear whether all these components would be thermal or not. Essential progress in this field is expected with the launch of the Chandra and XMM missions.

Here I summarize some of the known X-ray properties of SB galaxies using for illustration the well-studied galaxies NGC 5253, 1569, 253 and VII Zw403. Note that an X-ray survey of the seven far-infrared nearby edge-on SB galaxies (NGC 253, 3079, 3628, 4631, 4666, 55 and M82) was recently undertaken by Dahlem *et al.* (1998). All of them with exception of NGC 55 show evidence for the presence of hot X-ray emitting gas in their haloes. In NGC 55, hot gas was found only in the vicinity of the most intensive star forming region, which also can be traced in the H_α emission.

NGC 5253 is one of the nearest (4.1 Mpc) and the youngest known starbursts. The gaseous component of the galaxy shows an almost round morphology with star formation located within a central region. WR stars identified in two of the five central massive star clusters constrain their ages to 3–5 Myr only. A soft X-ray emission with $L_x \approx 6.5 \times 10^{38}$ ergs s^{-1} from the central $\sim$ 200 pc region of the galaxy was revealed by Martin and Kennicutt (1995). They also found that the simple superbubble model under-predicts the NGC 5253 X-ray luminosity by a factor of 16. Strickland and Stevens (1999), however, within the central 500×600 pc region, instead of a single superbubble revealed a system of at least five sources of X-ray emission, three of which are clearly connected with the young massive star clusters. The X-ray luminosities of the individual components range between $(2\text{–}7)\times10^{37}$ erg s^{-1} which is in better agreement with the model predictions. The comparison of the observed X-ray emission radial distribution with the five component model seems to suggest an excess of the diffuse X-ray emission out to the 1 kpc radius.

VII Zw403 is the nearest blue compact dwarf (BCD) galaxy, in recent years considered in many discussions to be related to star formation histories and the possible impact of dwarf systems on the surrounding intergalactic medium. It is an isolated system with a total mass of $2 \times 10^8 M_\odot$, a neutral hydrogen mass of $7 \times 10^7 M_\odot$, and a low interstellar gas metallicity $Z = 0.06 Z_\odot$. It was considered to be a member of the M81 group. However, recent HST observations (Lynds *et al.*, 1998) moved it 1.5 kpc farther away, to a 4.5 Mpc distance. The intense H_α emission ($L_{H_\alpha} \approx 1.8\times10^{39}$ ergs s^{-1} from the central star clusters gives an indication of continuous star formation, which lasts to the present epoch (Silich *et al.*, 2001b). Observations by Papaderos *et al.* (1994) and Fourniol (1997) added more interest to the system, as they revealed an extended kpc-scale region of diffuse X-ray emission with a total X-ray luminosity of $L_x \approx 2.3 \times 10^{38}$ergs s^{-1}. Our estimates (Silich *et al.*, 2001b) show that this value is more than an order of magnitude above that predicted by the model.

NGC 1569. The ASCA 0.5-6 keV broad-band observations showed extended X-ray emission. The total X-ray luminosity was estimated to be $L_x \approx 3.1 \times 10^{38}$ergs s^{-1} and may be best fitted with two spectral components. The soft component is best described by a hot plasma model with a temperature $T = (0.6\text{–}0.8)$ keV that provides around 60% of the total X-ray emission. It is clearly extended and associated with the system of H_α filaments. About 40% of this emission comes from the unresolved central region, whereas the rest comes from the extended diffuse component.

NGC 253 is one of the three nearest galaxies with prominent superwind features. It presents an extended X-ray region 9 kpc along the galaxy minor axis, and also shows a large number of X-ray point sources both in the midplane of the galaxy and its vicinity. The ASCA (Ptak *et al.*, 1997) and BeppoSAX (Persic *et al.*, 1998) observations revealed soft (0.5–2.0)keV and hard (2.0–10.0)keV emission with luminosities $L_x \approx 7.7 \times 10^{39}$ergs s^{-1} and $L_x \approx 1.6 \times 10^{40}$ergs s^{-1} respectively. Chandra observations (Strickland *et al.*, 2000) give a unique possibility to investigate the NGC 253 central kpc-scale region with an unprecedented resolution down to ~ 20 pc scale. These observations reveal the X-ray emission to be well-collimated, strongly limb-brightened and perfectly coinciding with the well known H_α cone. This provides direct evidence for the first time that the majority of the X-ray emission comes from a thin (with the volume filling factor between 4 and 40 per cent) layer, which is probably dominated by the mass evaporation from the cold outer shell.

3 THE OBSERVED SUPERBUBBLE METALLICITIES

The standard bubble model (Weaver *et al.*, 1977) includes four zones: (a) a freely expanding wind; (b) a hot shocked wind; (c) a dense shell; and d) an external ISM. For a moderate energy deposition the outer bubble shell cools during the early evolution, and the X-ray emission comes mainly from the hot shocked wind (zone (b)). This region contains a mixture of the SN ejected matter with the gas evaporated from the cold outer shell and pre-existing interstellar clouds. Therefore, X-ray observations provide a direct diagnostic of the metal production rate and, ultimately, the SB chemical evolution.

On the other hand, examination of the hot gas chemical composition is extremely important for modeling the superbubble X-ray emissions. Indeed, the interpretation of the observed X-ray emission is based on a fitting procedure, which includes some assumptions of both gas temperature and metallicity distributions.

The early ROSAT and ASCA studies of the SB galaxies reported extremely low metal abundances (Ptak *et al.*, 1997). However, later on it was realized that these low metal abundances may be an artifact, coming from the oversimplified model for the emitting gas temperature and metallicity structure (Dahlem *et al.*, 1998; Strickland and Stevens, 1998).

Despite the high degree of uncertainty, the present day determinations of the superbubble hot gas metallicities show that X-ray data are consistent with the near solar abundances, and therefore the extremely low metallicities as derived from the ROSAT and ASCA data are no longer required (Weaver *et al.*, 2000). For example, the NGC 253 hot gas absolute abundances were best estimated to be $Z_{\mathrm{Fe}} = 0.25Z_{\odot}$ for iron, and $Z_{\alpha} = 1.7\mathrm{Z}_{\odot}$ for α-elements. The relative abundances are more definite and confirm an obvious overabundance of the α-elements.

That is, ***the metals ejected by sequential SNe are to be found in the hot bubble interior, causing drastic changes to its metallicity.*** The later is important because the main contribution to the soft X-ray band comes from the emission lines of oxygen and other α-elements, and thus the gas metallicity strongly affects the derived parameters of the X-ray plasma. This, in turn, leads to a wrong estimate of the emitting gas density, hot gas mass, and the total ejected energy.

In an effort to address these issues we (Silich *et al.*, 2001a) have examined the time evolution of the SB produced hot gas average metallicity, and its relation to the predicted bubble X-ray luminosity.

4 MODIFICATION OF THE STANDARD BUBBLE MODEL

The bubble X-ray luminosity depends strongly both on the bubble dynamics and the inner hot gas X-ray emissivity Λ_x. We use for the calculations our (Bisnovatyi-Kogan and Silich, 1995; Silich and Tenorio-Tagle, 1998) 3D Lagrangian numerical code based on the thin layer approximation. The program includes interstellar medium inhomogeneity, galactic disk rotation, star and dark matter gravity, cooling, and shell destruction via Rayleigh–Taylor instabilities at the acceleration phase. For a homogeneous spherical density distribution our numerical results are in an excellent agreement with the analytic predictions of Weaver *et al.* (1977) for the bubble outer shell radius and expansion velocity:

$$R_s = \left(\frac{125}{154\pi}\right)^{1/5} \left(\frac{L_{\rm SB}}{\rho_{\rm ISM}}\right)^{1/5} t^{3/5} \approx 267 \left(\frac{L_{38} t_7^3}{n_{\rm ISM}}\right)^{1/5} \text{pc} \qquad (1)$$

$$V_s = \frac{3}{5}\frac{R_s}{t} \approx 15.7 \left(\frac{L_{38}}{n_{\rm ISM}}\right)^{1/5} t_7^{-2/5} \,\text{km s}^{-1}, \qquad (2)$$

where L_{38} is the starburst energy input rate $L_{\rm SB}$ in 10^{38} erg s^{-1} units, t_7 is the evolutionary time in 10^7 year units, $\rho_{\rm ISM}$ and $n_{\rm ISM}$ are the interstellar gas mass and particle number densities.

We assume the bubble interior density is dominated by the cold outer shell evaporation and use the approximate similarity solution of Weaver *et al.* (1977) for the interior hot gas density and temperature distributions:

$$n(r) = n_c(1 - r/R_s)^{-2/5}, \qquad (3)$$

$$T(r) = T_c(1 - r/R_s)^{2/5}, \qquad (4)$$

where n_c and T_c are the central bubble density and temperature.

The bubble X-ray luminosity can be calculated now by integration over the bubble volume:

$$L_x = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \sin\theta \mathrm{d}\theta \int_0^{R_s} Z_{\rm ev} n^2(r) \Lambda_x r^2 \mathrm{d}r. \qquad (5)$$

In the standard bubble model the inner gas metallicity $Z_{\rm ev}$ is assumed to be constant and equal to the ISM gas metallicity $Z_{\rm ISM}$. We relax this simplification and assume that all the newly synthesized heavy elements are well mixed with the SN ejected and shell evaporated material. That is, the mean hot gas metallicity $Z_{\rm ev}$ is function of time. We further assume that massive stars lose all their mass as they explode as SNe. Then for a power law initial mass function (IMF) the total ejected mass as a function of the cluster age t is,

$$M_{\rm ej}(t) = M_{\rm SB}\frac{M_*(t)^{2-\alpha} - M_{\rm up}^{2-\alpha}}{M_{\rm low}^{2-\alpha} - M_{\rm up}^{2-\alpha}}, \qquad (6)$$

where $M_{\rm up}$ and $M_{\rm low}$ are the upper and lower cut-off masses, $M_{\rm SB}$ is the total star cluster mass, and α is the slope index. The mass loss rate from the shell, is defined by classical evaporation theory and reads as (Mac Low and McCray, 1988)

$$\dot{M}_{\rm ev} = \frac{16\pi\mu}{25k} C T_c^{5/2} R_s, \qquad (7)$$

where k is the Boltzmann constant, μ is the mean mass per particle, and $C = 6 \times 10^{-7}$ ergs s^{-1} cm^{-1} $K^{-7/2}$, is the thermal conductivity coefficient. Because

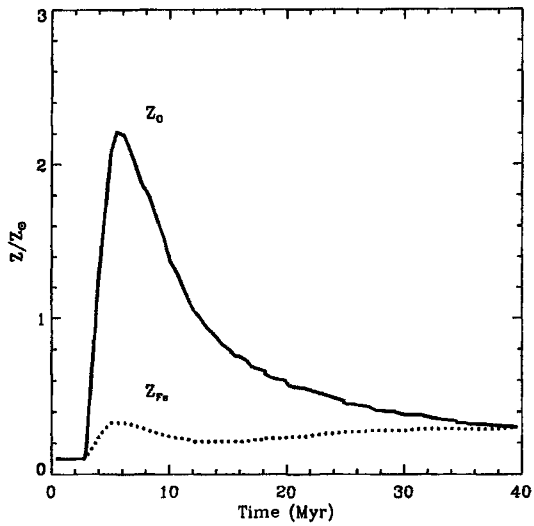

Figure 1 The hot bubble interior oxygen metallicity as function of time.

emissivity in the soft (0.1–2.0 keV) X-ray band is dominated by the α element lines, we use the mean oxygen metallicity as a tracer of the hot gas chemical composition

$$Z_{\rm ev} = Z_O = \frac{M_{{\rm ej},O}/Z_\odot(O) + Z_{\rm ISM}M_{\rm ev}}{M_{\rm ev} + M_{\rm ej}}. \tag{8}$$

The oxygen mass $M_{{\rm ej},O}$, which was produced by supernovae and ejected from an SB region before a given time t, is defined by the oxygen yield Y_O and the initial star cluster mass function. It reads as

$$M_{{\rm ej},O} = \frac{(\alpha-2)M_{\rm SB}}{M_{\rm low}^{2-\alpha} - M_{\rm up}^{2-\alpha}} \int\limits_{M_*(t)}^{M_{\rm up}} Y_O(m)m^{-\alpha}{\rm d}m. \tag{9}$$

We use the Pilyugin and Edmunds (1996) approximation for Maeder (1992) and Woosley *et al.* (1993) oxygen yields for the stellar mass range $10.5M_\odot \le M_\star \le 25M_\odot$, and assume a constant yield out of this mass interval. That is, we use Maeder (1992) and Woosley *et al.* (1993) stellar evolution models which account for the stellar wind mass loss rate.

The results of the calculation for the $10^6 M_\odot$ starburst and ISM gas metallicity $Z_{\rm ISM} = 0.1$ are presented in Figures 1 and 2.

Figure 1 shows the evolution of the hot gas oxygen metallicity (which is compared with the iron one) with time. It reaches $Z_O \sim 2Z_\odot$ after 6 Myr of evolution that is 20 times of the assumed ISM gas metallicity, and slowly drops to an ISM gas metallicity 0.1 $Z_\odot$ at the end of the calculation. This consequently leads to the larger X-ray luminosity, which is shown in Figure 2. The dotted line represents the

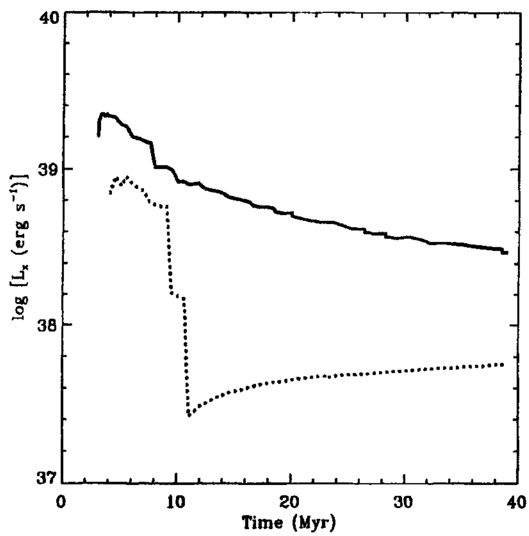

Figure 2 The calculated bubble X-ray luminosity (solid line) compared with the standard bubble model (dashed line).

standard model with a fixed gas metallicity $Z = 0.1Z_{\odot}$. It first reaches rather a high value of about 10^{39}ergs s^{-1}. However, at this stage the main contribution to a total X-ray emission comes from the adiabatic shell rather than from the hot bubble interior. As soon as the shock speed slows down to several hundreds of km s^{-1} the shell contribution becomes rapidly less important because the shell cools below the X-ray cut-off temperature ($\sim 5\times10^5$). Later on, the main contribution to the bubble X-ray emission comes from the hot bubble interior. At this stage our results (solid line) are remarkably different from the standard model predictions (dotted line). In our calculations the X-ray luminosity after 10 Myrs reaches approximately an order of magnitude larger value than predicted by the standard model and remains within the range of 10^{39} - 5 $\times$ 10^{38} erg s^{-1} throughout the evolution. This difference is caused mainly by an enhanced inner gas metallicity.

5 CONCLUSIONS

The results presented here imply that starburst driven superbubble mean metallicities are highly time dependent. They can easy exceed the solar value even if the host galaxy ISM metallicity is well below the solar one. Therefore, the extremely low hot gas metallicities as have been derived in the earlier studies are no longer required. The effects of metal injection into the superbubble interior are most noticeable during the first 10 Myr of the bubble evolution. The important implication of the approach described here is the obvious increase of the predicted values with respect to the standard (with a constant gas metallicity) model predictions for starburst driven superbubble X-ray luminosity.

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