RevMexAA (Serie de Conferencias), **9**, 279–282 (2000)

X-RAY OBSERVATIONS OF SUPERBUBBLES IN DWARF GALAXIES

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RESUMEN

Existen indicaciones claras, basadas en observaciones de hidrógeno neutro, que el medio interestelar es violento y está dominado por burbujas llenas de plasma caliente. Sin embargo, excepto por objetos en la Vía Láctea, carecemos de observaciones directas de la emisión térmica en rayos-X de estas burbujas en otras galaxias. Presentamos observaciones del satélite *ROSAT* de las galaxias enanas IC 2574 y Holmberg II con algunos resultados muy alentadores. Sin embargo, tendremos que esperar a los satélites *Chandra* y *XMM* para respuestas más definitivas.

ABSTRACT

There is plenty of evidence from neutral hydrogen observations for a violent interstellar medium, dominated by hot-plasma filled superbubbles. However, there are few direct observations of their thermal X-ray emission from galaxies other than our own. We discuss pointed *ROSAT* observations of the dwarf irregular (dIrr) galaxies IC 2574 and Holmberg II which provide some tantalizing results. However, for definitive answers we will have to await *Chandra* and *XMM*.

Key Words: **GALAXIES: DWARF — GALAXIES: INDIVIDUAL (HOLMBERG II, IC 2574) — ISM: BUBBLES — X-RAYS: GALAXIES — X-RAYS: ISM**

1. INTRODUCTION

The more we learn about the Interstellar Medium (ISM) of galaxies, the more we come to realize that its structure, and the physics describing it, is highly complex. A fundamental contribution to the understanding of the ISM was provided by the 3-phase model of McKee & Ostriker (1977). Building upon their pioneering work, it has become clear that there are at least five components to the ISM: the cold molecular phase (characterized by self-gravitating individual clouds), the cool and warm neutral phase (CNM and WNM) which make up some 60% by mass of the ISM and which can be traced through the 21 cm line of neutral hydrogen (H I), a warm ionised phase (WIM; also sometimes referred to as the Diffuse Ionized Gas or DIG), traced by Hα emission, and a hot coronal phase (Hot Ionized Medium or HIM), which is detectable in soft X-ray emission and UV absorption lines (see e.g., van der Hulst 1996 for a summary of the mass and volume filling factors of these components). Most of the WIM is maintained by the ionizing radiation of O-stars; the HIM in turn is a result of stars which are more massive than 8 $M_\odot$ and which explode as supernovae, leaving behind tenuous, hot gas.

As this meeting is on Astrophysical Plasmas, we will ignore for the rest of this paper the molecular component. The other constituents are not perfectly mixed, of course. As young stars tend to form in groups, or OB associations, massive amounts of energy are dumped within a relatively small volume with radius typically a

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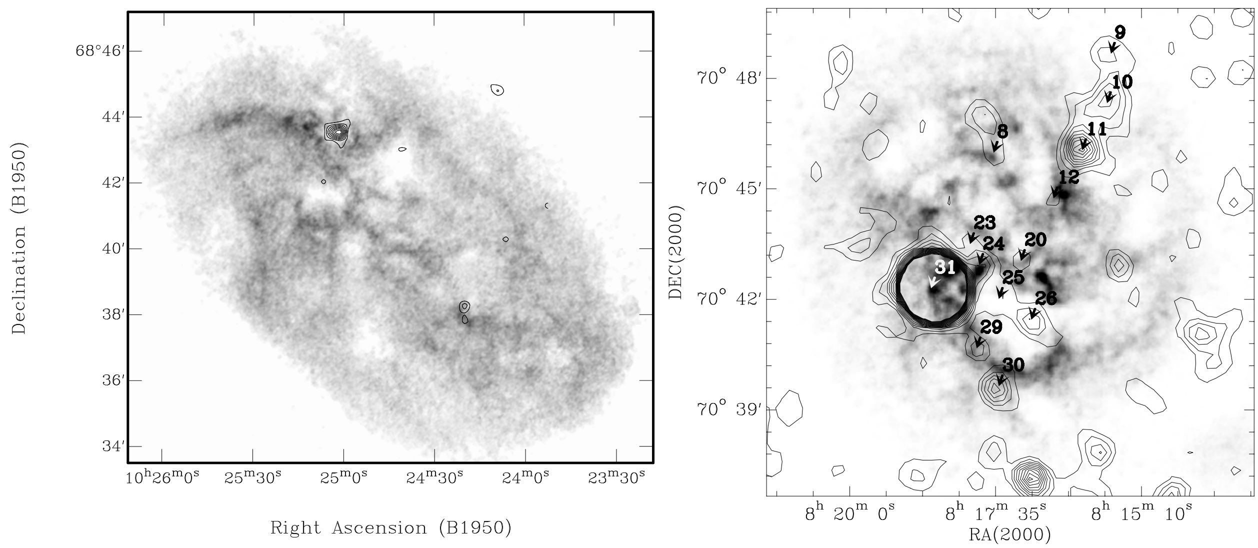

Fig. 1. H I image of IC 2574 (left) and Holmberg II (right), in halftone, with contours of the *ROSAT* PSPC X-ray emission. Both images are on approximately the same linear scale ($1'' = 15.5\,\mathrm{pc}$). Notice the huge, kiloparsec size H I holes in both galaxies which delineate superbubbles that are supposedly filled with hot, X-ray emitting plasma. The X-ray source coinciding with a prominent H I hole in IC 2574 (left) is the feature to the northeast. In the image of Ho II (right), the numbers indicate discrete X-ray sources which were catalogued by us (Kerp et al., in preparation).

few 10–100 pc. In the standard picture, the surrounding material is pushed outward, forming a supershell of warm and cool material surrounding a superbubble filled with hot ($T > 10^6\,\mathrm{K}$) gas.

H I has proven to be a remarkably useful tool in tracing the cool *and* hot gas, albeit indirectly in the case of the latter. As H I measures the bulk of the material between the stars it neatly delineates the volumes which are supposedly filled with hot gas. Neutral hydrogen is easily observed these days, at resolutions of order $5''$ and velocity resolutions of a few $\mathrm{km\ s^{-1}}$.

H I superbubbles were first described by Heiles (1979) in our Galaxy and subsequently by Brinks & Bajaja (1986) in M31 and Deul & den Hartog (1990) in M33. In recent years it has been shown that, somewhat counterintuitively, superbubbles can grow larger in dwarf irregular (dIrr) galaxies, and can persist longer. There are several reasons for this. Briefly, dwarf galaxies have a lower gravitational potential which causes an increase of the scaleheight of their gas, to several times that of more massive spiral galaxies (500 pc, typically, against 100 pc). And, because they are dominated by solid-body rotation and lack spiral density waves, the holes do not get destroyed as quickly. Some stunning examples of galaxies whose ISM is totally dominated by superbubbles are two dwarf companions of M81, Holmberg II (Puche et al. 1992) and IC 2574 (Walter & Brinks 1999), and the Small (Staveley-Smith et al. 1997; Stanimirovic et al. 1999) and Large Magellanic Clouds (Kim et al. 1998; Kim et al. 1999; see Brinks & Walter (1998) for a review).

2. X-RAY EMISSION FROM SUPERBUBBLES

In the Milky Way several examples of hot-plasma filled H I cavities are known. Most prominent is the local cavity which encloses the Sun (Sfeir et al. 1999). Its X-ray emission is very soft ($\log(T[\mathrm{K}]) \leq 6.0$) and faint. Its pressure of $P_{\mathrm{local}} \simeq 1 \times 10^4 \mathrm{K\,cm^{-3}}$ is, however, a factor of 2 to 5 higher than that of the neutral clouds located within the cavity. Recent models consider the local cavity as a low-volume density region produced by several supernova events. The latest supernova event dates back to $1\text{–}2{\times}10^6$ years. Another interesting feature is the X-ray bright supershell known as Loop I or North Polar Spur (Egger & Aschenbach 1995). Loop I has a diameter of about $\sim 300\,\mathrm{pc}$. Its temperature is $\log(T_{\mathrm{LoopI}}[\mathrm{K}]) = 6.7$, much higher than that of the local X-ray

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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plasma. It is highly overpressured ($P_{\rm Loop\,I} = 2.5 \times 10^4\,{\rm K\,cm^{-3}}$) and still expanding.

Observed from an external galaxy, both X-ray features would have remained undetected using an X-ray telescope like *ROSAT*, because the photoelectric absorption of the enclosing thin neutral shell with $N_{\rm HI} \sim 3\times10^{20}{\rm cm^{-2}}$ is sufficiently high for the X-ray photons originating within the interior of the shell to be absorbed. The only extragalactic detections of hot gas in superbubbles claimed thus far are restricted to dwarf galaxies. Examples are the supergiant shell LMC 4 (Bomans, Dennerl, & Kürster 1994), the superbubbles N 44 (Chu et al. 1993) and N 11 (Mac Low et al. 1998), all three situated in the LMC, the supergiant shell SGS 2 in NGC 4449 (Bomans, Chu, & Hopp 1997) and the possible supershell near Holmberg IX (Miller 1995).

Recently we detected X-ray emission coinciding with a supergiant shell in IC 2574 (Walter et al. 1998). A pointed *ROSAT* observation towards this object revealed marginally extended soft X-ray emission, the resolution being limited to that offered by the *ROSAT* PSPC detector, filling a 500×1000 pc H I hole (see Fig. 1). We find an X-ray luminosity, assuming a distance of 3.2 Mpc, of $1.6 \pm 0.5 \times 10^{38}$ erg s^{-1}. Assuming, as usual, a Raymond-Smith model (Raymond & Smith 1977) we derive a plasma temperature of $\log(T[{\rm K}]) = 6.8 \pm 0.3$ and an internal density of $n_{\rm e} = (0.03 \pm 0.01)\,{\rm cm^{-3}}$. The internal pressure of $P \approx 4 \times 10^5\,{\rm K\,cm^{-3}}$ is much higher than the pressure of the ambient warm ionized medium ($P \approx 10^3 - 10^4\,{\rm K\,cm^{-3}}$) suggesting that it is probably this hot gas which is still driving the expansion of the shell (see e.g., Weaver et al. 1977).

3. DISCUSSION

There is a fly in the ointment, though. If this emission is indeed due to coronal gas, why do we detect X-rays from only a few superbubbles? A recent re-analysis of a deep, pointed *ROSAT* PSPC observation (Zezas, Georgantopoulos, & Ward 1999) by us of Ho II shows *no* extended X-ray emission which can be unambiguously associated with the hot interiors of superbubbles (Kerp et al., in preparation), at least down to the *ROSAT* detection limit. A casual inspection of Figure 1 shows that most H I holes have no X-ray counterpart. The bright object in Ho II marked #31 does not coincide with any of the H I holes and was found by Zezas et al. (1999) to be unresolved by the *ROSAT* HRI and variable. It could be an X-ray binary although the spectrum, which is well approximated by a thermal spectrum with low metallicity and a temperature of ~ 0.8 keV, suggests rather a black hole origin, or contamination by thermal emission from hot gas.

That no emission is seen from the majority of superbubbles agrees, in fact, with what was expected. Chu & Mac Low (1990), Chu et al. (1995), Mac Low et al. (1998) and Mac Low (these proceedings) at various occasions pointed out that the X-ray luminosity of the thermal gas expected to fill the superbubbles is well below the *ROSAT* detection limit. The expected X-ray luminosity can be written as (Martin & Kennicutt 1995):

$$L_X = 2.12 \times 10^{36}\ L_{38}^{33/35} n_0^{17/35} t_6^{19/35} \kappa_0^{4/7}\,{\rm erg\,s^{-1}}\ , \tag{1}$$

where L_{38} is the mechanical energy expressed in units of 10^{38} erg s^{-1}, n_0 the ambient density in atom cm^{-3}, t_6 the age of the superbubble in Myr and κ_0 a dimensionless scaling factor for the classical conductivity (≤ 1). This leads to predicted values for $L_{\rm X} \approx 10^{36} - 10^{37}$ erg s^{-1}.

What does this imply? Simply put, the vast majority of superbubbles are far too weak to have been detected by *ROSAT*. Those which have been are the "pathological" cases. Besides, there remains the possibility that these cases are associated with X-ray binaries rather than plasma filled superbubbles. For example, in the case of IC 2574, due to the limited angular resolution of the *ROSAT* PSPC, we cannot rule out confusion (or rather contamination) by X-ray binaries. These sources do have the same luminosities, of order 10^{38} erg s^{-1}, as supershells. Alternatively, we could be dealing with a supernova developing in a dense environment, such as SN1988Z which reportedly reached an X-ray luminosity of 10^{41} erg s^{-1} (Fabian & Terlevich 1996). On the other hand, the X-ray source in IC 2574 is extended (and oriented perpendicular to the wobble direction of the spacecraft). Moreover, the X-ray hardness ratio of the emission corresponds better to a thermal than to a power-law spectrum which lends some support to the source being at least in part related to hot X-ray gas. One method to boost the X-ray luminosity, and increase the X-ray emitting lifetime, would be to invoke mass loading (Arthur & Henney 1996).

In a similar vein, there could be a conspiracy at work. Perhaps only (super)bubbles in the making, which are still actively being powered and hence overpressured, would be sufficiently bright to have been seen by *ROSAT*. However, these objects tend to be fairly small, young, and surrounded by a dense H I shell which would absorb the X-rays, especially the softer ones. Once a bubble has reached its final size, after some 10^8 yr, the interior has cooled down to below 10^6 K and no X-rays will be detected. So, the superbubble in IC 2574 would be special in the sense that it is one of the few large bubbles which are still being heated by SNe. This is corroborated by the fact that we still see a stellar cluster within the boundary of the H I shell (Walter 1999). The age as determined on the basis of the H I data of the expanding shell is of order 14 Myr whereas the life expectancy of the lowest mass stars of this cluster which will go off as supernovae is of order 50 Myr.

Luckily, we won't have to wait until very long before we can hope to find an answer to this puzzle. We managed to obtain observing time on the *Chandra* and *XMM* satellites on this and some other targets which should, if all goes well, allow us to resolve this issue.

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