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The Violent Interstellar Medium of Nearby Dwarf Galaxies

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Abstract: High resolution HI observations of nearby dwarf galaxies (most of which are situated in the M 81 group at a distance of about 3·2 Mpc) reveal that their neutral interstellar medium (ISM) is dominated by hole-like features most of which are expanding. A comparison of the physical properties of these holes with the ones found in more massive spiral galaxies (such as M 31 and M 33) shows that they tend to reach much larger sizes in dwarf galaxies. This can be understood in terms of the galaxy's gravitational potential. The origin of these features is still a matter of debate. In general, young star forming regions (OB-associations) are held responsible for their formation. This picture, however, is not without its critics and other mechanisms such as the infall of high velocity clouds, turbulent motions or even gamma ray bursters have been recently proposed. Here I will present one example of a supergiant shell in IC 2574 which corroborates the picture that OB associations are indeed creating these structures. This particular supergiant shell is currently the most promising case to study the effects of the combined effects of stellar winds and supernova explosions which shape the neutral interstellar medium of (dwarf) galaxies.

Keywords: galaxies: individual (IC 2574, Holmberg II, DDO 47, NGC 3077) — ISM: kinematic and dynamics — ISM: structure radio lines — ISM: X-rays

1 On Holes and Shells in Galaxies

Since the discovery by Heiles (1979, 1984) of huge, shell-like structures in the HI distribution of our Galaxy similar such structures have been found in several nearby galaxies, such as in M 31 (Brinks & Bajaja 1986), M 33 (Deul & den Hartog 1990), Holmberg II (Puche et al. 1992) and the Small Magellanic Cloud (Staveley-Smith et al. 1997). These discoveries have been made possible by the advent of powerful aperture synthesis radio telescopes such as the Very Large Array (VLA), the Westerbork Synthesis Radio Telescope (WSRT) and the Australia Telescope Compact Array (ATCA). One of the most stunning examples of what is possible these days is without doubt the latest ATCA image of the LMC (Kim et al. 1998*b*).

All these observations indicate that the interstellar medium (ISM) of medium- to late-type galaxies is dominated by features, which have variously been described as shells, rings, holes, loops, bubbles or cavities [the 'cosmic bubble bath' (Brand & Zealey 1975) or 'violent interstellar medium']. Until recently, most authors concentrated on large spiral systems. However, there are several advantages in using dwarf galaxies to study the structure of the ISM: dwarfs are slow rotators, generally show solid body rotation, and lack density waves. This implies that once features like shells have formed, they will not be deformed by galactic shear and therefore tend to be long lived. Moreover, the overall gravitational potential of a dwarf is much smaller than that of a normal spiral, hence expanding structures can more easily reach large sizes.

Figure 1 (top left) shows an HI map of Holmberg II, a member of the M 81 group (at a distance of about 3·2 Mpc) by Puche et al. (1992). This was the first high resolution, high sensitivity HI image of a nearby dwarf galaxy ever obtained and shows that the presence of HI holes clearly dominates its overall appearance (in total, 51 HI holes were catalogued by Puche et al.). This result prompted several questions such as: Is Holmberg II a special case? Do other dwarf galaxies show the same structures in their ISM?

Figure 1 (top right) presents a VLA HI surface brightness map of the dwarf galaxy IC 2574, also a member of the M 81 group (taken from Walter & Brinks 1999). As can be seen from this map, the ISM of IC 2574 is clearly shaped by HI holes and shells—a total of 48 were catalogued by Walter & Brinks. Figure 1 (bottom left) shows the distribution of neutral hydrogen in DDO 47 (Walter & Brinks 1998) which is a dwarf galaxy situated at an assumed distance of 4 Mpc. Again, many holes and shells are visible in this galaxy—in fact, DDO 47 closely resembles Holmberg II. So far, about 20 HI holes have been catalogued in this galaxy, most of which are expanding (Walter & Brinks, in prep.).

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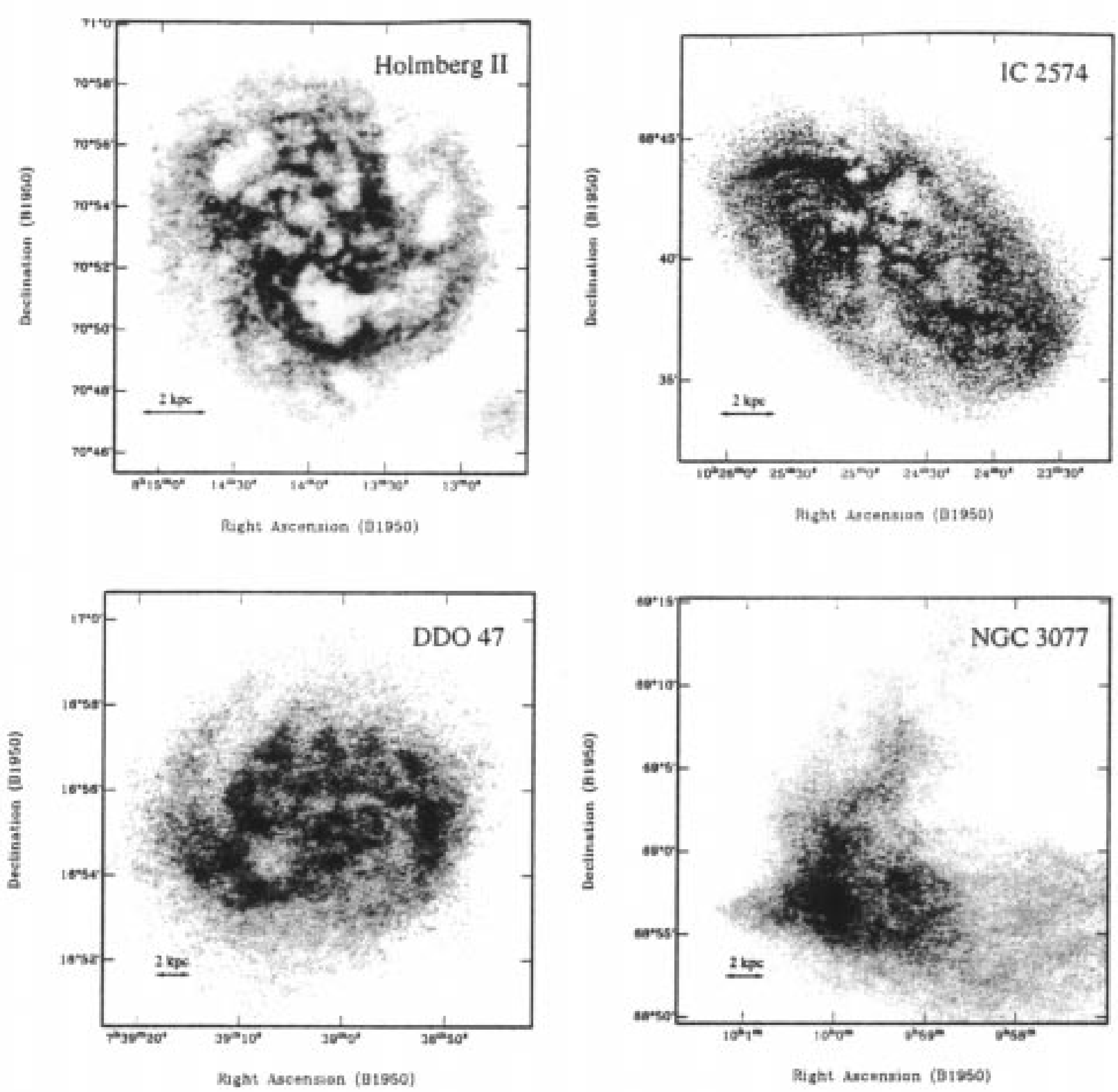

Figure 1—*Top left:* HI surface brightness map of Holmberg II (Puche et al. 1992). In total, 51 HI holes were catalogued by Puche et al. *Top right:* HI surface brightness map of IC 2574 (Walter & Brinks 1999). We find a total of 48 HI holes in this galaxy, most of which are expanding. *Bottom left:* HI surface brightness map of DDO 47. A companion galaxy (not visible) has been discovered somewhat south–east of the main galaxy (see Walter & Brinks 1998). *Bottom right:* HI surface brightness map of NGC 3077 (Walter et al., in prep.). The map has not been corrected for primary beam attenuation. The two prominent tidal arms connect this galaxy to M 81 and M 82 (see Yun, Ho & Lo 1994).

So do all nearby dwarf galaxies show similar structures? To answer this question, studies of other dwarf galaxies are needed. Here I will briefly discuss NGC 3077, another member of the M 81 group. The distribution of the neutral hydrogen in this galaxy is presented in Figure 1 (bottom right). Like all the other maps presented here, this map was obtained with the VLA after combining observations in three different configurations (B-, C- and D-array). An analysis of the data rather surprisingly showed that no expanding hole-like features are visible in this particular galaxy (Walter et al., in prep.). Note, however, that NGC 3077 is a special case since it is strongly interacting with its high-mass neighbours M 81 and M 82—it may therefore very well be that structures like holes and shells are destroyed prematurely due to the strong tidal forces.

2 Holes in Dwarfs versus Holes in Spirals

Having convinced ourselves that the most distinctive features of the ISM in dwarf irregular galaxies are HI holes and shells, at least provided they are not participating in strong interactions, the question is

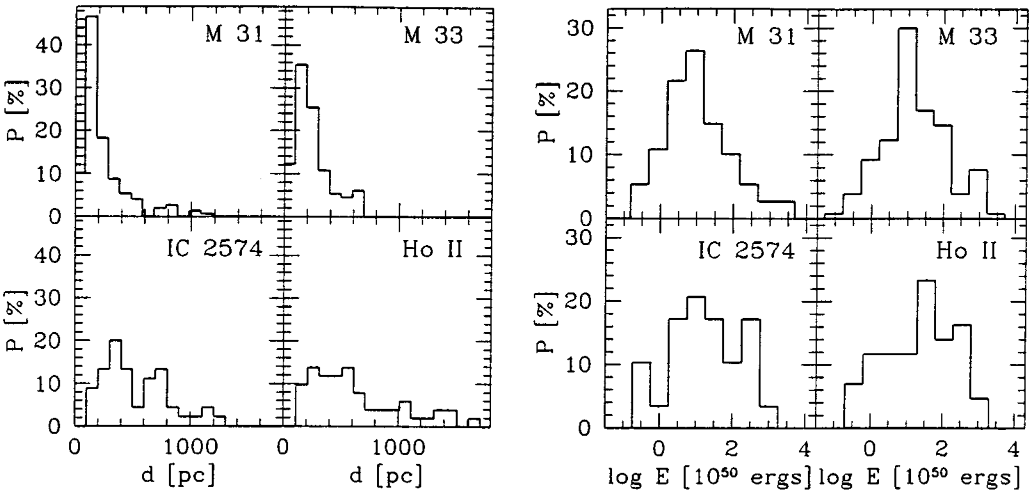

Figure 2—*Left:* Comparison of the relative distribution (%) of the diameters of the HI holes in IC 2574, M 31, M 33 and Ho II. *Right:* Comparison of the relative distribution (%) of the energies required to produce the HI holes in IC 2574, M 31, M 33 and Ho II.

now how their physical properties compare to the holes found in more massive, spiral galaxies. A detailed comparison has been performed by Brinks & Walter (1998) and only the main results are highlighted here. In what follows we compare the observed HI hole properties of M 31 (Brinks & Bajaja 1986), an example of a massive spiral galaxy similar to our own; M 33 (Deul & den Hartog 1990), a less massive spiral; IC 2574 (Walter & Brinks 1999) and Ho II (Puche et al. 1992), two dwarf galaxies in the M 81 group of galaxies (note that Ho II is four times less massive than IC 2574). In other words, the sequence M 31 – M 33 – IC 2574 – Ho II spans a large range of different Hubble types from massive spirals to low-mass dwarfs.

Despite the fact that a similar study, and at considerably higher sensitivity, is now available for the SMC (Staveley-Smith et al. 1997), we have decided not to include these results, the main reason being that the linear scales (or spatial frequencies) sampled by the ATCA only just overlap with those observed in the galaxies listed above. The linear resolution, at 28 pc, is almost four times higher than, for example, the VLA maps of IC 2574. At the other end of the spectrum, because of the lack of short spacing information, structures larger than a few hundred parsec will have been missed. Moreover, the SMC is a very disturbed system, being torn apart by tidal forces due to interactions with the LMC and the Galaxy. An additional argument for leaving out the SMC is that Staveley-Smith et al. used a different approach in searching and identifying the holes which makes a direct comparison difficult.

Other objects with catalogued HI holes, such as DDO 47 (Walter & Brinks 1998) and IC 10 (Wilcots & Miller 1998) have so few holes that a statistical analysis is not warranted. Limiting the comparison to the four galaxies listed above has some further advantages. The linear resolutions are very similar, as are the velocity resolutions with which they have been observed (see Walter & Brinks 1999 for details). In addition, all four galaxies were examined in more or less the same fashion, one of the authors (E. Brinks) having taken part in the analysis of three of the four objects. The results for the four galaxies suffer partially from low statistics and incompleteness due to personal bias and observational constraints (such as the beamsize). However, these effects, to first order, affect a comparison in a similar way and it is valid to try to find global trends as a function of Hubble type. In order to remove the human factor, it would be interesting to apply an automated object recognition package such as that developed by Thilker, Brown & Walterbos (1998) to all galaxies with sufficiently detailed observations.

Figure 2 (left) shows an overlay of the relative size distribution of the holes found in the four galaxies. In this plot the bins are on a linear scale. Note that there is a clear sequence with Hubble type! The size distribution for holes in M 31 and M 33 cuts off sharply near 600 pc. In contrast, holes in IC 2574 and Ho II reach sizes of 1200 to 1500 pc, respectively. The lack of holes with sizes smaller than ~ 100 pc is due to our resolution limit. As explained in the previous section, holes are larger for 'later' Hubble types because these smaller galaxies have lower masses and hence a lower mass surface density. So, for the same amount of energy deposited, an HI shell can grow much larger, both because of a lower gravitational potential and a lower ambient density. Because the HI layer is much thicker in dwarfs as well (Puche et al. 1992; Walter & Brinks 1998, 1999), shells take longer to break out of the disk.

From the observed hole properties such as the expansion velocities and diameters, one can try to

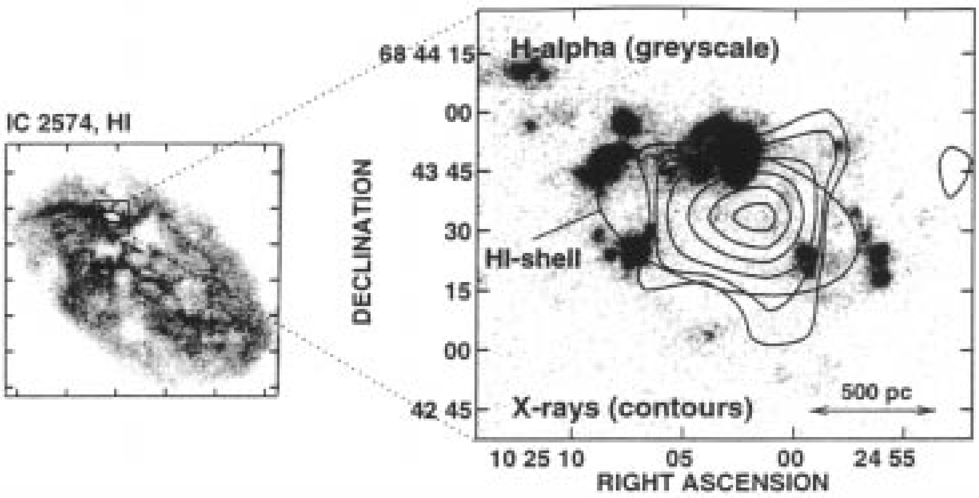

Figure 3—*Left*: IC 2574 in the 21 cm line of neutral hydrogen (HI). *Right*: Blowup of the supergiant shell in IC 2574. The ellipses plotted in both maps indicate the size of the expanding HI shell (linear size ≈ 1000 × 500 pc). The greyscale is a representation of the Hα emission coming from the rim of this shell. The contours represent the X-ray emission coming from the inside of the shell as observed with the ROSAT PSPC camera (for details see Walter et al. 1998). Coordinates are given for B1950·0.

estimate the amount of energy which was needed to produce the holes, based on numerical simulations. Here we use the numerical model developed by Chevalier (1974) to calculate the total mechanical energy needed to create the holes. Note that many assumptions enter the calculations and that the results should only be taken to be order of magnitude estimates. A plot of the results of this analysis is shown in Figure 2 (right). Gratifyingly, the energies needed to produce the holes are the same for all galaxies—this suggests that, whatever the underlying physical mechanism for the creation of the holes is, it seems to be the same in all galaxies, at least to first order.

In addition to the objects listed in the introduction and the maps shown here, several more dwarf galaxies have been observed. Walter & Brinks are working on data on Holmberg I and M 81 dwarf A. Van Dyk, Puche & Wong (1998) present data for Sextans A. Wilcots and collaborators have data on three more galaxies, IC 1613, IC 10 and NGC 4449, the former object being completely dominated by HI holes and shells, much like IC 2574 and Ho II. Hence, within the coming year, a lot more material should thus become public, allowing for better comparative studies to be performed.

3 So, what created the Holes?

Until not too long ago, the origin of these structures was generally thought to lie in the combined effects of stellar winds and supernova explosions produced by young stellar associations—for review articles see Tenorio-Tagle & Bodenheimer (1988) and van der Hulst (1996, and references therein). However, several authors have pointed out that this model is not without its flaws. One of the potential problems with the hypothesis that the HI holes are the result of an evolving OB association in which the most massive stars, through their winds and supernovae, create the observed supershells is the following. Using reasonable assumptions one still expects a substantial population of A and F main sequence stars to be present. However, searches by Radice, Salzer & Westpfahl (1995) and Rhode, Salzer & Westpfahl (1997) in galaxies like Ho II have not led to the expected result. A possible alternative explanation has been proposed by Efremov, Elmegreen & Hodge (1998) who suggested that Gamma Ray Bursters, which recently have been conclusively associated with objects at cosmological distances, might provide the required energy, and occur frequently enough, to explain the observed HI supershells.

Another objection to the standard model is that in the case of the largest observed shells, the energy requirements seem to exceed the output of stellar winds and supernovae. To explain those structures an alternative mechanism was proposed: the infall of gas clouds. Tenorio-Tagle et al. (1987) presented a numerical simulation and van der Hulst & Sancisi (1988) provided what is probably the best observational evidence for infall, the case of one of the largest holes in M 101.

One should also consider the possibility that we are tricked by nature and that the holes that we see to be expanding are actually the result of turbulent motions. A search for their powering sources would then be completely futile. To investigate this possibility we examined turbulence cubes calculated by Mac-Low et al. (1998*b*) in the very same fashion as was done in our search for HI holes in galaxies (Walter & Brinks 1999). The result was that only a few percent of the smaller holes may be due to turbulence. However, in the case of the larger holes (> 100 pc), turbulence is not able to produce coherent features which seem to be expanding. We therefore feel confident that the structures we observe are indeed due to expanding HI shells.

Obviously, to investigate the sources which created the holes, a multi-wavelength approach is needed. In this approach, 21 cm observations are needed for the identification of the holes as well as for the determination of their kinematics. Optical observations are indispensable to check the stellar distribution and populations within the shells. Narrow band Hα observations are important to trace the regions of current star formation. Quite often, Hα emission is found to be located close to or on the rim of the holes, as defined by the HI observations. Finally, X-ray observations are important to check whether the cavities of the HI holes are filled by hot X-ray emitting gas or not. A hot-gas interior is one of the main predictions of theories which state that the holes are created by young OB associations (see also the discussion below).

So far, only a few shells have been found where such an approach is possible. Examples are the supergiant shell LMC 4 (Bomans, Dennerl & Kürster 1994), the superbubbles N 44 (Kim et al. 1998*a*) and N 11 (Mac Low et al. 1998*a*), 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). In the following section, the detection of a supergiant shell in the nearby dwarf galaxy IC 2574 is presented which is probably the most prominent supergiant shell known to date. This region has proved to be an ideal laboratory to study the physical nature of supergiant shells in general and is expected to provide conclusive proof as regards to the source lying at its origin.

4 Case of the Supergiant Shell in IC 2574

The supergiant shell in IC 2574 was first seen in high resolution VLA HI observations [Walter & Brinks 1999; see also Figure 3, left panel, which is a scaled-down version of Figure 1 (top right)]. The shell has a linear size of about 1000 pc × 500 pc ($60'' \times 30''$) and is expanding at $\sim$25 km s^{-1}. It is therefore an ideal target to study expansion models since despite its size it has not stalled yet (as most of the supergiant shells in the LMC have). The elliptical shape of the HI shell is indicated in Figures 3 and 4. The kinematic age based on the observed size and expansion velocity is estimated at 14 Myr.

Deep narrow-band Hα imaging revealed that current star formation (SF) regions within IC 2574 are predominantly situated on the rim of the HI shell (Figure 3, right panel, greyscale). This suggests that we are witnessing triggered star formation on the rim due to the expansion of the HI shell (see e.g. Elmegreen 1994). Follow-up radio continuum observations showed that these starforming regions are the main source of the radio continuum emission (see the contours in Figure 4 for a map of the λ6cm emission).

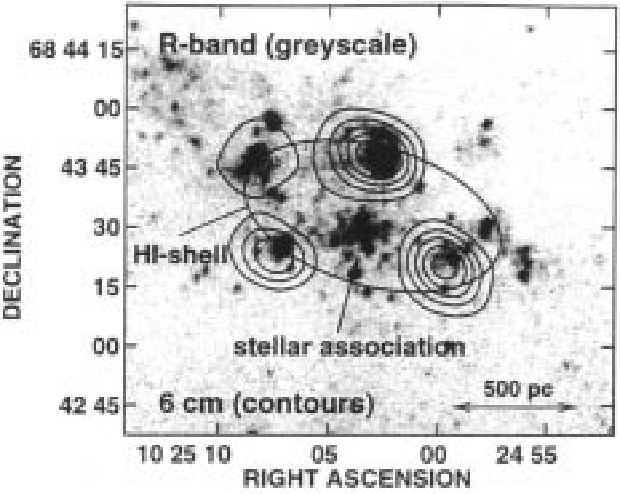

Figure 4—Supergiant shell in IC 2574, showing the same region as in Figure 3 (right panel). The plotted ellipse again indicates the size of the expanding HI shell. The greyscale is a representation of our deep R-band image showing the central stellar association. The superimposed contours represent λ6cm radio continuum emission.

Various theories on the creation and formation of supergiant shells (SGSs) predict that the cavity within the shell should be filled with hot gas (see e.g. Cox & Smith 1974; Weaver et al. 1977; Chu et al. 1995). A pointed ROSAT observation towards IC 2574 (Walter et al. 1998) revealed that the supergiant shell is indeed filled with extended hot X-ray gas (see the contours in Figure 3). This makes the supergiant shell in IC 2574 a truly unique region and suggests that we have caught this SGS at an auspicious moment. Assuming a Raymond–Smith (1977) plasma temperature of $\log(T[\mathrm{K}]) = 6\cdot8 \pm 0\cdot3$ and an internal density of $(0\cdot03 \pm 0\cdot01)$ cm^{-3} we derive an internal pressure of $P \approx 4 \times 10^5$ K cm^{-3}. This pressure is much higher than the pressure of the ambient warm ionised medium ($P \approx 10^3 - 10^4$ 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).

We have just been granted observing time during Cycle 1 with the Advanced X-ray Astrophysics Facility (AXAF), so we will soon be able to derive the spatial extent and the temperature of the X-ray gas to a much higher accuracy. The AXAF observations will also allow us to determine the contribution to the X-ray flux by point sources (e.g. X-ray binaries and supernovae). Note that the X-ray source is resolved in the ROSAT observations, indicating that at least a significant fraction of the X-ray emission is extended.

From ground based R-band imaging, a giant stellar association is readily visible within the IC 2574 SGS (see Figure 4, greyscale). We speculate that this stellar association is in fact responsible for the formation and expansion of the shell as well as for the heating of the X-ray gas. Unfortunately, the evidence is still largely circumstantial.

The wealth of observations which is available for this supergiant shell suggests that this central stellar association is the powering source for the formation and expansion of the shell as well as for the heating of the X-ray gas. Based on our HI observations and using the models of Chevalier (1974), we estimate that the energy required to produce the shell must be of order 10^{53} erg or the equivalent of about 100 Type II SNe. This would mean that the least massive stars that go off as SN are most probably still present in the central stellar association since their lifetimes (~50 Myr) are somewhat longer then the dynamical age of the hole (~14 Myr, as derived from the HI observations).

5 Conclusions

HI observations of sufficient angular and velocity resolution as well as sensitivity of dwarf irregular galaxies are now becoming available in the literature. Because dwarfs have several advantages over spiral galaxies (the absence of density waves, the absence of differential rotation and hence shear) one can expect a lot of progress to be made in our understanding of the structure of the ISM. In addition, multi-wavelength studies of the most prominent shells will reveal which physical processes are the cause of the HI holes in general. The prominent supershell in IC 2574 is a nice example of what can be done in that respect. In summary:

(1) Dwarf galaxies show a stunning amount of detail in the form of shells and holes in their neutral interstellar medium. These features are similar to those found in large systems like our Galaxy, M 31, M 33, M 101 and NGC 6946. Often, the HI shells completely dominate the morphology of a dwarf galaxy, such as in the case of IC 2574 or Ho II.

(2) The shells can grow to large dimensions because of several conditions which are favourable in dwarf galaxies. The volume density in the plane is low, which facilitates expansion. In the direction perpendicular to the disk, the gravitational pull is smaller than in a massive spiral. Also, because of the thick HI layer, shells are easily contained and unlikely to break out into the halo. Lastly, solid body rotation and a lack of spiral density waves prevent holes from being rapidly destroyed.

(3) A comparison of IC 2574 with other galaxies spanning a range of Hubble types and studied in similar detail so far (M 31, M 33 and Ho II) shows that the size distribution of HI holes found in a galaxy is related to its Hubble type in the following way. The size of the largest HI shells is inversely proportional to the global gravitational potential (and hence mass surface density). The energies needed to create these structures, though, are found to be of the same order for all types of galaxies. Hence, whatever physical mechanism lies at their origin, it is not related to the host galaxy, at least to first order.

(4) In order to determine the source(s) which created the observed structures a multi-wavelength approach is needed. So far, a few theories have been invoked to explain the presence of the holes: (1) young OB associations which drive the expansion of the shell by strong stellar winds and supernova explosions, (2) gamma ray bursters and (3), for the largest holes, the infall of high velocity clouds. The scenario regarding the creation due to strong stellar winds and subsequent supernova explosions still has some problems. Detailed studies of single HI holes are needed to distinguish between the various theories.

(5) The supergiant shell in IC 2574 seems to be an ideal target to shed light on this problem. This supergiant shell is clearly defined in HI observations and is surrounded by massive star formation. A pointed ROSAT observation has revealed that the cavity enclosed by the supergiant shell is filled with hot, X-ray emitting gas. A prominent stellar association in the centre of this SGS is thought to be the powering source for the formation and expansion of the shell as well as for the heating of the interior X-ray emitting gas. Future investigations, especially regarding the central stellar association, are needed to understand fully what created this fascinating region.

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