Galactic Outflows and Winds in Dwarf Galaxies*

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Abstract

Dwarf galaxies provide a special environment due to their low mass, small size and generally low metal content. The natural result of the spatially concentrated energy output from stellar winds and supernovae of an OB association is an expanding bubble. These bubbles can grow to kpc-size and become the dominant driver of the chemical and dynamical evolution of dwarf galaxies. In such low mass systems, bubbles have an enhanced probability of breaking out of the gaseous disk into the halo of the host galaxy. This may lead to venting metal enriched hot gas to large distances from the sites of creation. Several aspects of the observation and interpretation of such outflows are critically reviewed in this paper.

1 Introduction

Dwarf galaxies, by definition of their class, are galaxies of low mass and size. This directly implies that they have a much weaker gravitational potential well than typical spiral galaxies and fill a smaller volume with gas and stars. All dwarf galaxies, even very low mass systems, show quite complicated star formation histories (e.g. Mateo 1998). From the color-magnitude diagrams one derives the presence of some low level star formation activity over most of the lifetime, sometimes interrupted by short intervals of strongly enhanced star formation rate. These results and the presence of blue compact dwarf galaxies, where the current star formation rate is so high that these dwarf galaxies appear as isolated giant H II regions, tells us that bursts of star formation are indeed a natural process in dwarf galaxies. The spatially and temporally correlated energy input from massive stars and supernova explosions inside physically small systems should lead to a strong response of the gas in the host galaxy.

Analytical and numerical modeling of the reaction of the gas to the energy input from stellar winds and supernovae is an active topic since the papers of Castor et al. (1975) and Weaver et al. (1977). Recent examples are Freyer & Hensler (2000), Strickland & Stevens (2000), Mac Low & Ferrara (1999), and Tomisaka (1998). For a review of the basic ideas, see Tenorio-Tagle & Bodenheimer (1988). The result of the energy input into the interstellar medium (ISM) is basically an expanding bubble of hot gas inside the substrate of cool gas of the host galaxy. The hot bubble is enclosed by a dense cool shell, which has ionized gas at the inner boundary layer between the hot gas and the shell. If the bubble grows to a linear diameter comparable to the neutral gas scale height of the galaxy, the expansion speeds along the z-axis (e.g. Mac Low & McCray 1988) and the shell expands into the lower halo of the host galaxy while starting to deform and break due to Rayleigh-Taylor instabilities (e.g. Mac Low et al. 1989). Since massive stars and supernova explosions are the dominant source of heavy elements, the newly processed material is located inside

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the shells. Whether and to which degree it is moved upward out of a galaxy and what happens to this gas in the lower halo, is of crucial importance for the understanding of the chemical evolution of dwarf galaxies (e.g. Hensler & Rieschick 1999). In the work of Mac Low & Ferrara (1999) for the first time a set of hydrodynamical simulations incorporating a relatively detailed model of the dwarf galaxy potential (including dark matter) was used and the simulations for a whole dwarf galaxy was run for more that 100 Myr. Still, the authors had to compromise e.g. by relatively basic treatment of the cooling processes and ignoring magnetic fields.

The hot gas inside the bubbles is predicted to be in the temperature range of 10^5 and 10^7 K (e.g. Weaver et al. 1977), which implies that the plasma will radiate in the extreme UV and soft X-ray regime. The ionized gas at the boundary layer between the hot interior and the cool shell wall should be visible in optical and UV emission lines, while the cool shell itself can be observed in 21cm emission. The (more abundant) small bubbles do not break out of the disk of a galaxy. These bubbles do still structure the interstellar medium and should lead to ionized filaments, as observed in the Magellanic Clouds (e.g. Kennicutt et al. 1995) and the Milky Way (Haffner et al. 1999). They also lead to large regions of hot gas observed in the LMC (e.g. Chu & Mac Low 1990, Bomans et al. 1994) and the Milky Way (e.g. Snowden et al. 2000).

The observation of warm and hot gas in dwarf galaxies allows to study the mechanism shaping the topology and phase structure of the ISM as well as the processes responsible for the chemical and (at least partly) the dynamical evolution of the host galaxy. Dwarf galaxies are supremely suited for this task. They present the most extreme environment for feedback of massive stars on the interstellar medium due to their shallow potential wells, their small sizes, and the absence of complicating other factors like density waves.

2 Hot Diffuse Gas

2.1 Diffuse gas and outflows

The number of dwarf galaxies, which had their X-ray properties investigated is still relatively small and a quite inhomogeneous data set. For a review of the X-ray observations of dwarf galaxies see Bomans (2001). All objects emitting relatively soft (low energy) X-rays, like the diffuse hot gas in dwarf galaxies, share an observational problem. The low energies are strongly absorbed by the galactic N_{H}, which implies, that studies of the soft diffuse emission is only possible in dwarf galaxies with sufficiently low foreground N_{H}. This imposes a strong and unavoidable selection bias on the X-ray properties of dwarf galaxies. For example, the dwarf galaxy NGC 1569 does not show a very soft X-ray emission (e.g. Heckman et al. 1995), while NGC 4449 does (Bomans et al. 1997; Vogler & Pietsch 1997). The difference may be intrinsic to the galaxies, but since the foreground N_{H} of NGC 1569 is much higher, it is equally possible that all soft X-ray emission of NGC 1569 is just absorbed.

The natural results of some locally increased star formation rate is a superbubble, which expands in the neutral interstellar medium of the host galaxy. Due to the small size of the dwarf galaxy, a big association takes up a significant part of the host galaxy. Additionally dwarf galaxies tend to have larger OB associations than spiral galaxies when scaled to the galaxy sizes (Elmegreen et al. 1994). The bubble, which has to develop will not be sheared in the solid-body rotation field of the dwarf galaxy and expands undisturbed to larger size due to the thicker H I layer (e.g. Skillman & Bender 1995). As soon the shell starts to break out, the shallow gravitational potential well of the dwarf galaxy makes it more likely for the bubble to reach large distances from the host galaxy. The low metalicity inhibits cooling which helps maintain a high pressure in the bubble (before breakout).

The catch in this scenario is the extended dark matter halo of dwarf galaxies. If the maximum

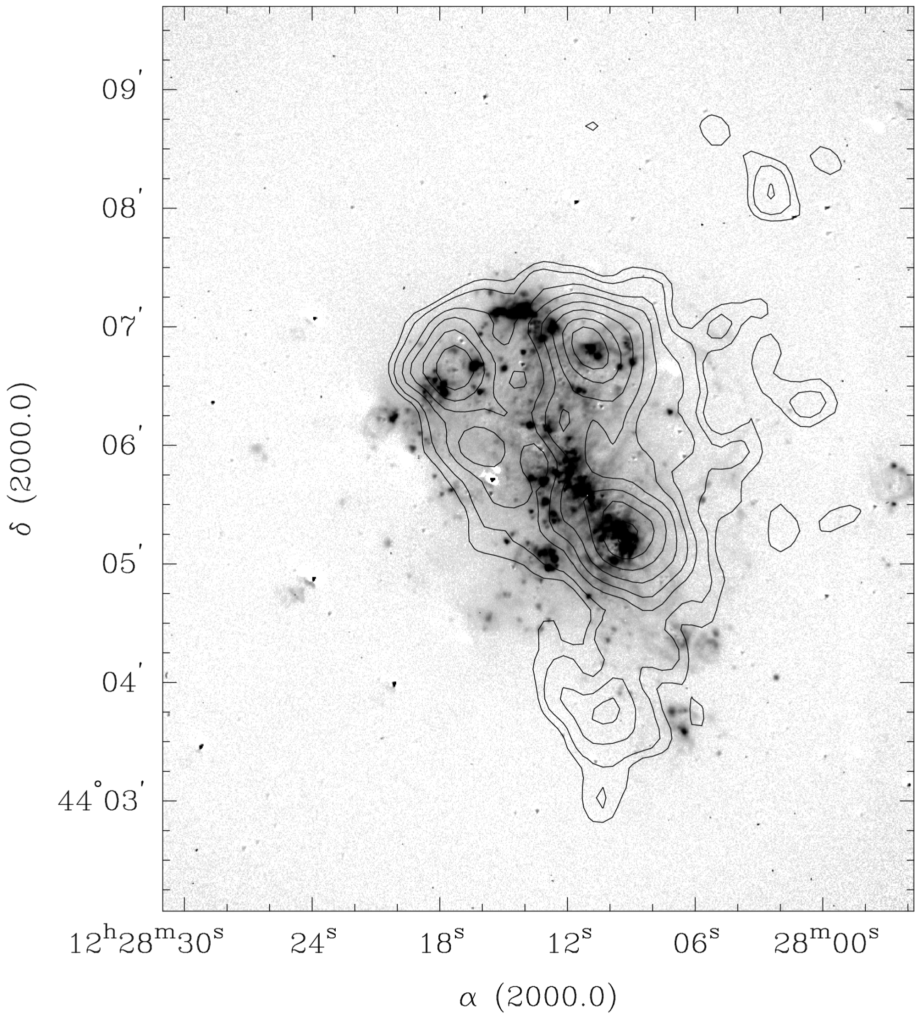

Figure 1: Continuum subtracted Hα image of the irregular galaxy NGC 4449 with contours of X-ray emission from ROSAT PSPC overplotted.

disk interpretation of rotation curves of dwarf galaxies is correct (Swaters 1999), dwarf galaxies are even more dark matter dominated than disk galaxies. This implies, that we need some assumptions on shape and total size of the dark matter halo to estimate if vented out gas will stay in the gravitational potential or will be lost into the intergalactic medium.

Even in the small current sample (see Bomans 2001) at least 6 larger and smaller dwarf galaxies show exactly what this picture implies: strong star formation and large Hα shells and filaments sticking out into the lower halo. Good examples are NGC 4449 (Bomans et al. 1997; Vogler & Pietsch 1997) (Fig. 1) and NGC 1569 (Heckman et al. 1995). Indeed, diffuse X-ray emission can be found inside some of the shells (e.g. Heckman et al. 1995, Bomans et al. 1997), but the integration times used for the PSPC observations turned out to be to small for deriving useful spectra to determine the plasma conditions and especially the metalicity of the hot gas. The most favorable object for the metalicity test is I Zw 18, the most metal poor galaxy known (e.g. Skillman & Kennicutt 1993). Because of the low metalicity of about 1/50 solar, any enrichment of the hot gas would make a big difference in the plasma emissivity. Unfortunately, the ROSAT spectrum (Martin 1996) is again not good enough to determine the metalicity of the hot gas to reasonable degree of certainty (Bomans 1999).

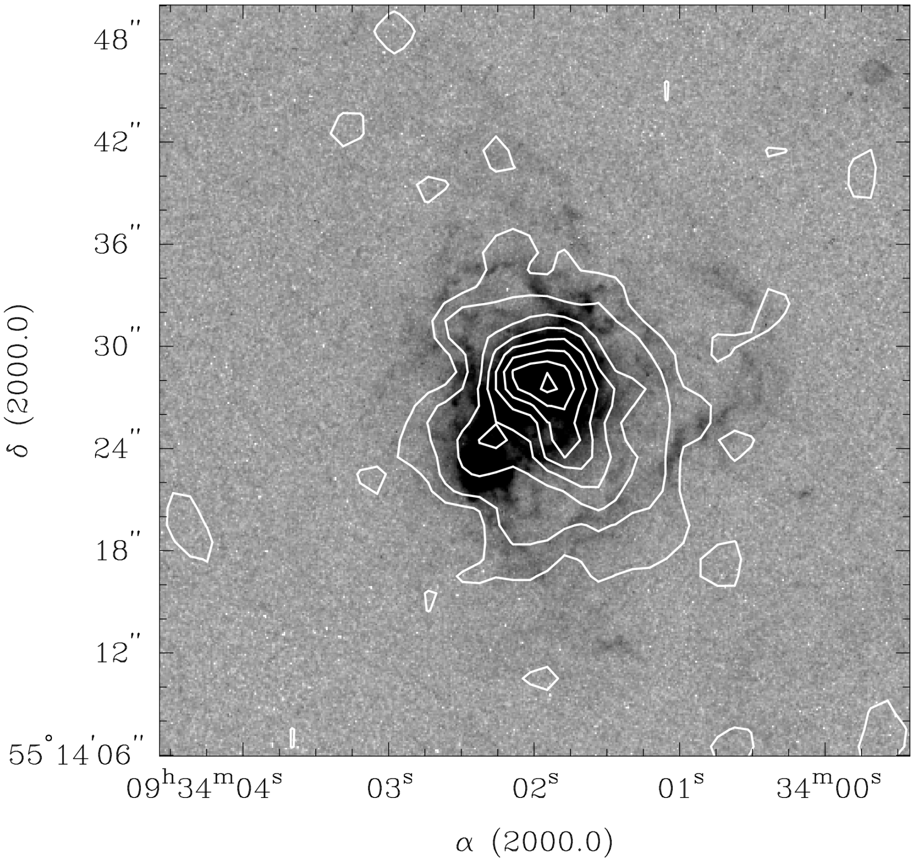

Figure 2: Continuum subtracted HST WFPC2 Hα image of the dwarf galaxy I Zw 18 with contours of X-ray emission from ROSAT HRI overplotted.

Due to their small intrinsic size, even at moderate distances the galaxies represent only a few resolution elements of the ROSAT PSPC or even worse the ASCA SIS and GIS. This makes contamination from point sources a real concern (e.g. Vogler & Pietsch 1997). The ROSAT HRI with its about 5 times better spatial resolution (but without spectral resolution) had also a much higher background, making it an inferior instrument for the detection of the low surface brightness diffuse emission. Still, with long exposures, the point source content of the PSPC images can be checked and the brighter diffuse emission be studied (Bomans 1999, Strickland & Stevens 1999). Fig. 2 shows a deep ROSAT HRI image of I Zw 18 as contours overlayed over an HST Hα image (Bomans et al. 2001a, in prep.).

Another problem is inherent to the plasma itself. If it expands rapidly into the lower density halo, the gas cools adiabatically, but roughly maintains its ionization pattern, recombination lags behind cooling (Breitschwerdt & Schmutzler 1999). Therefore the standard analysis of X-ray spectrum using the coronal equilibrium plasma codes (Raymond & Smith 1977; Mewe et al. 1995) does not necessarily determine the physical parameters correctly, even if one has a very good spectrum. Much higher spectral resolution together with good signal to noise ratio is needed in the spectra to check for the presence and size of the effect and finally account for non-equilibrium conditions in the derived plasma properties.

3 Diffuse warm gas

Structure, occurrence, and ionization of the diffuse warm gas and especially the presence of large ionized shells in dwarf galaxies were discussed in a number of recent publications (e.g. Martin 1997, 1998; Hunter & Gallagher 1997; Hunter et al. 1993).

First it is important to note here, that the warm ionized gas cannot be used for the metalicity determination of the outflows. There are signs of at least some mixing at the boundary layers between hot and cold gas and therefore a metal enrichment of warm gas (Hughes et al. 1998). This makes the observation of the optical emission lines of the shells and outflows tempting as alternative way to estimate the metal content of the outflows. Still the spectra cannot be treated with the usual methods as used for normal H II regions. Line ratios clearly indicate a complex interplay of normal stellar photoionization, photoionization by a diffuse photon field, shock ionization, photoionization by X-ray, and even turbulent mixing layers (Hunter & Gallagher 1997; Martin 1998, Tüllmann & Dettmar 2000). With insufficient information to even determine the ionization mechanism(s), a direct derivation of ionic abundances from optical emission lines for the diffuse ionized gas is out of the question (at least for now). A helpful alternative method may be the use of interstellar UV absorption lines to background quasars. Unfortunately, no usable chance alignment of a dwarf galaxy outflow with a sufficiently bright background source has been found.

When one finds a dwarf galaxy showing large Hα shells, which extend to a size larger than the stellar body of the dwarf galaxy, the first critical question is if this ionized gas is really expanding away from the dwarf galaxy. Observationally the dynamics of the ionized gas can be studied either with high-dispersion, long-slit spectroscopy, or using a Fabry-Perot interferometer.

As an example I present here an analysis of the galaxy NGC 1705. NGC 1705 contains several large Hα shells (Meurer et al. 1992), two of which show up in a deep ROSAT PSPC pointing as very soft, diffuse X-ray sources (Hensler et al. 1998). The data presented here were taken with the ESO VLT and the ESO NTT and are going to be discussed in detail in Bomans et al. (2001b, in prep.). In Fig. 3 the continuum subtracted Hα image of NGC 1705 is shown with contours of the Gunn-r continuum image overlayed. The smooth red stellar body of the galaxy is nearly filled with H II regions. Large ionized shells and filaments extend radially out to more than 2.5 kpc from the center of the dwarf galaxy. The structure appears roughly bipolar, consistent with hydrodynamic simulations, but shows a very complex substructure with interlocking and overlapping individual shells and filaments. The currently available H I synthesis map is of to low spatial resolution to study the detailed dynamic of the gas, but shows that NGC 1705 is embedded in a large H I envelope (Meurer et al. 1998).

Fig. 4 shows a long-slit spectrum taken with a position angle of 310 deg, roughly aligned to the central star cluster of NGC 1705 and the bright foreground star in the north-west. The spectrogram runs top to bottom from north-west to south-east and shows a spectral range of 60Å centered on the Hα line and the two [N II] lines. Just below the bright star the Hα line splits into two components and merges again at the beginning of the stellar body. This Doppler ellipse is the sign of an expanding bubble and coincides exactly with the bright loop in the north-west. The expansion velocity is 75 km s^{-1}. At the bottom of the spectrogram the Hα line does not show a line split, but a large velocity width. This implies strong turbulence or bulk motions with velocities just below the spectral resolution of $\sim$ 30 km s^{-1}. The slit cuts here through another large shell, which is, contrary to the shells in the north-west, not detected in the deep ROSAT image. It is tempting to make a link between the lower expansion velocity of the shell in the south-east and the missing X-ray emission. Still, neither the 75 km s^{-1} nor the 30 km s^{-1} shock speed would give rise to X-ray emission. Motion with about 200 km s^{-1} is required to get post-shock temperatures above 10^6 K (McKee 1987). Simple projection effects are not likely to make a large effect for expanding bubbles. The probable explanation comes from the inherent selection effect of using the warm

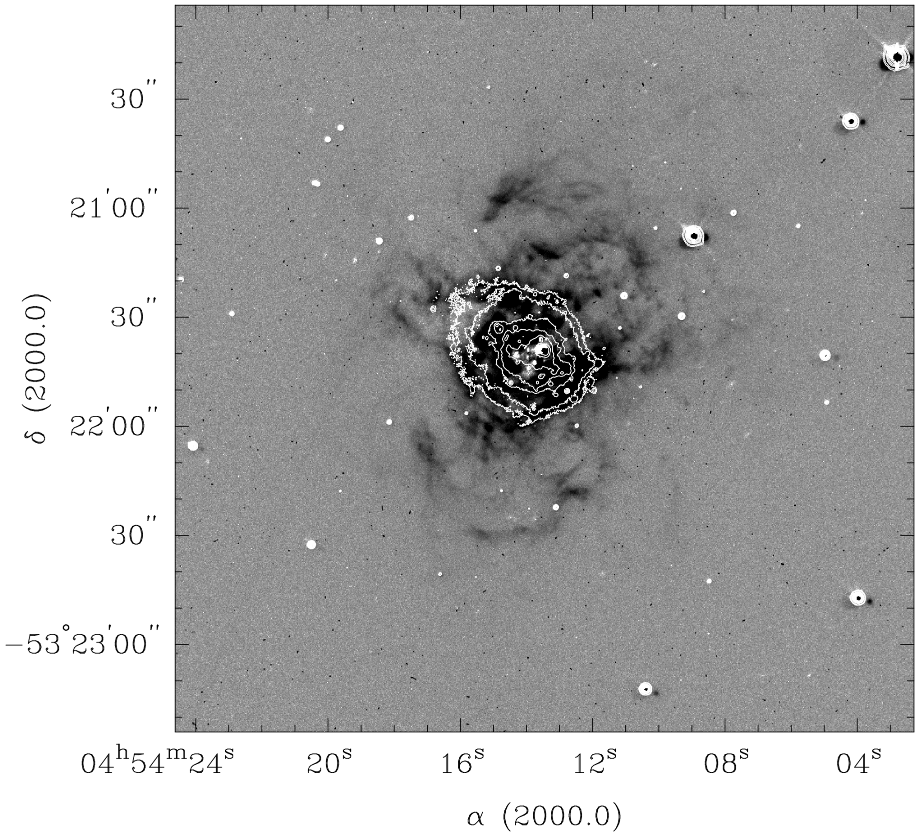

Figure 3: Continuum corrected VLT Hα image of NGC 1705 with contours of the continuum emission overplotted.

ionized gas as tracer of the flow: the gas detected with the spectrometer is the gas with highest surface brightness and therefore density, which is the least probable to show the highest velocities. We apparently measure the large scale expansion of the superbubble driven by the overpressure of the hot gas inside, which is heated by the supernovae. The temperature of the hot gas is not the simple post-shock temperature from the large-scale shock, hitting the surrounding interstellar medium, but the effect of local heating near the inner shell wall.

The shells of NGC 1705 are clearly expanding out of the galaxy and they are (at least in part) filled with hot gas. The question is now, what will be the fate of this bubbles? The faintest shells and filaments visible on our VLT Hα image reach the rim of the H I envelope of NGC 1705. If they are still expanding at this radius, they are likely going to speed up when hitting the gas density gradient. Unfortunately, the filaments are very faint and it is hard to measure their radial velocity. Even with a measured velocity, the lack of H I also means that the rotation curve and therefore the potential of the galaxy is not well constrained there. These problems are generic to the analysis method and should be kept in mind when evaluating similar analyzes of the mass loss from dwarf galaxies (e.g. Martin 1998).

Finally, ordered magnetic fields, if present, could have a large influence on the conditions of the outflows and the kinematics of the warm and hot gas. Unfortunately, the knowledge about magnetic fields in dwarf galaxies is very sparse. From theoretical considerations no large-scale ordered magnetic fields are to be expected in dwarf galaxies, but at least the LMC (Klein et al. 1993) and NGC 4449 (Chyży et al. 2000) do show such magnetic fields. Still, both galaxies are at the upper mass and luminosity boundary for dwarf galaxies and the conditions in lower mass

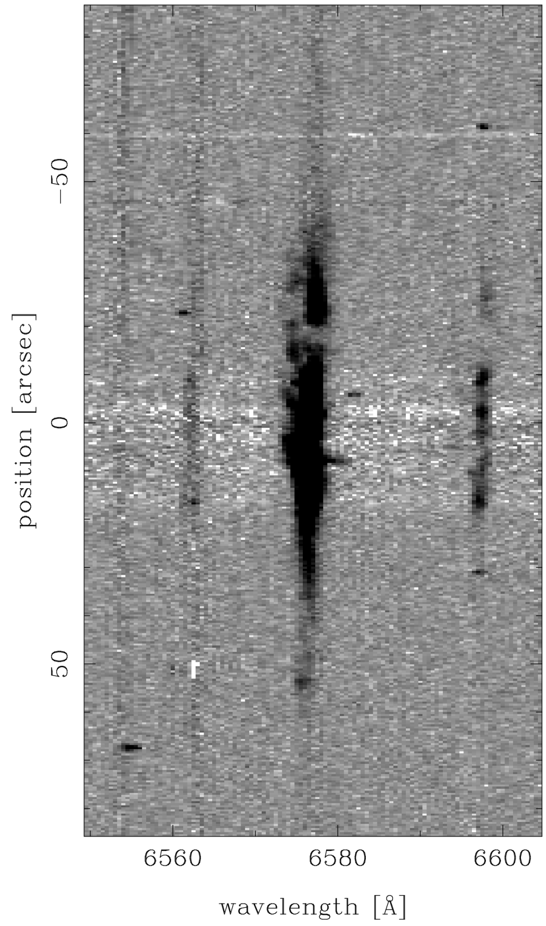

Figure 4: High-dispersion spectrogram of one slit position through NGC 1705.

dwarf galaxies are unexplored yet.

4 Conclusions and Outlook

The link between superbubbles in the interstellar medium and diffuse X-ray emission has been clearly demonstrated (e.g. Chu & Mac Low 1990) and even some larger bubbles have been shown to be filled with hot gas (e.g. Wang et al. 1991, Bomans et al. 1994). The detailed physics of such bubbles is up to now ill observed, but the future looks bright:

The determination of the physical parameters of the hot gas are hampered by the insufficient quality of the X-ray spectra and the contamination with point sources. New X-ray telescopes (XMM-NEWTON and CHANDRA) are now in orbit and are working well and will provide a big step forward in testing the current dwarf galaxy evolution scenarios.

For the diffuse warm gas, the near futures looks also promising, with several 8-10m class telescopes currently coming online. This will enable us to study the kinematics of the outflows even at low surface brightness, hunt for very high velocity gas and presumably extremely faint outer halo gas using emission lines and quasar absorption lines. These methods should also help to better determine the mass distribution and total mass of dwarf galaxies, leading to improved estimates on the escape fraction of the hot gas and therefore the metals.

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