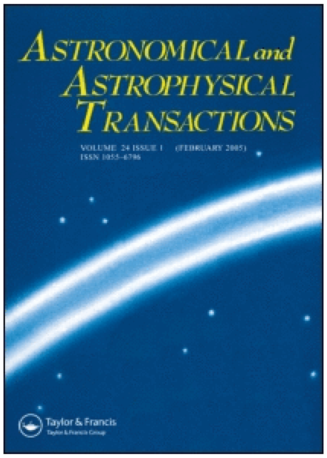

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BUBBLES IN THE GALACTIC HALOES

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We briefly discuss a possible interconnection of vertical HI structures observed in the Milky Way galaxy with large scale blowing out explosions by clustered SNe. We argue that the observed OB associations can produce only about 60 such events, or approximately one chimney per 3 kpc^2 within the solar circle. We also discuss the overall properties of HI shells in nearby face-on galaxies and the distribution of Hα and dust in edge-on galaxies. We argue that the presence of dust in galactic haloes may indicate that radiation pressure is the most probable mechanism capable of transporting dust to large heights above the galactic plane. In order to make this possible, the galactic magnetic field must have a strong vertical component. We mention that SNe explosions can initiate the Parker instability which in turn creates large scale magnetic loops with a strong vertical component. Recent observations of nearby edge-on galaxies favour this suggestion.

KEY WORDS Galaxy: halo of – Interstellar medium: clouds: general – Shock waves – Interstellar medium: dust – Hydrodynamics

1 INTRODUCTION

Bubbles and shells in the interstellar gas can be discriminated by their sizes in three classes: bubbles with a characteristic size of 10 pc, superbubbles of about 100 pc in size, and supershells which extend up to 1 kpc or more. This classification reflects the distinguishing characteristics of the dynamics of the expanding gas on scales of the local environment ($\sim$ 10 pc, corresponding to a parent cloud where a star drives a wind or explodes as a SN), on characteristic scales of cold thin interstellar discs ($\sim$ 100 pc), and on the much larger scales of gaseous haloes ($\sim$ 1 kpc). In this contribution, we will concentrate on large scale structures, which extend far from the galactic planes – the supershells. Our knowledge about these structures stems from observations of the gas distribution and its kinematics in the Milky Way and in nearby face-on and edge-on galaxies.

2 THE MILKY WAY GALAXY

In our Galaxy evidence for the existence of large scale shells extending far above the galactic plane stems from observations of neutral gas structures oriented predominantly in the vertical direction and reaching heights of 200 pc to 1 kpc, the so-called worms (Heiles 1984). The most obvious and simple interpretation of worms is to regard them as vertical walls of chimneys – large scale vertical outflows produced by clustered SNe explosions (Norman and Ikeuchi 1989). (A less obvious and completely unexplored possibility may be connected with hydrodynamical instabilities producing vortices and vertical gas outflows similar to a tornado in the atmosphere). Following numerical simulations (see Mac Low *et al.*, 1989; Silich *et al.*, 1996), one can assume, that the total energy required for an expanding supershell to reach a distance of 1–1.5 kpc above the plane is of the order of ~ 1–3×10^{53} erg. Then for a power law distribution of OB associations in the Galaxy (Kennicutt *et al.*, 1989; Heiles, 1990; Williams and McKee, 1997)

$$N_a(L) = 5.5 \left(\frac{475}{L_{49}} - 1 \right), \tag{1}$$

where $N_a(L)$ is the number of associations with an ionizing photon luminosity larger than L, $L_{49} = L/(10^{49}\ textergs^{-1})$, one obtains the total number of chimneys $N_{\rm ch} \simeq 60$, where $L_{49} = 0.2$ for an O9 star is assumed (Shchekinov, 1996). Thus for the total number of chimney walls seen in the projection we get $\simeq 120$ which is consistent with the observed number of worms $N_{\rm w} = 118$ (Koo *et al.*, 1992). Approximately half of the observed worms are associated with HII regions which very likely contain clustered SNe. In the infrared all the worms show a sufficiently large ratio $I(60\ \mu{\rm m})/I(100\ \mu{\rm m}) \simeq 0.28$ (Koo *et al.*, 1992) which may be connected with an excess of small grains (indicating probably that the material of worms has been processed by destructive shock waves). Apparently, the closest chimney has been detected in the Cas OB6 association in the Perseus arm (Normandeau *et al.*, 1996). Assuming the distance to Cas OB6 ~ 2.2 kpc, one obtains the number of chimneys in the disc $N_{\rm ch} \sim (15\ {\rm kpc}/2.2\ {\rm kpc})^2 \simeq 46$ which is consistent with the above estimates. These arguments favour the interpretation of worms as chimneys or supershells driven from the galactic plane by SNe explosions.

3 FACE-ON GALAXIES

Large scale HI shells in nearby face-on galaxies have been known for almost 20 years since the first detection in M31 (Brinks, 1981). Since then HI shells have been studied in detail in several dozen face-on galaxies – besides M31 these are: M33 (Deul and den Hartog, 1990), Holmberg II (Puche *et al.*, 1992), M101 and NGC 6496 (Kamphius 1993), SMC (Staveley-Smith *et al.*, 1997), IC 10 (Wilcots and Miller, 1998), LMC (Kim *et al.*, 1998, 1999), IC 2574 (Walter and Brinks, 1999). Typically 50 to 100 shells with sizes ranging in the interval 100 pc – 1 kpc have been observed,

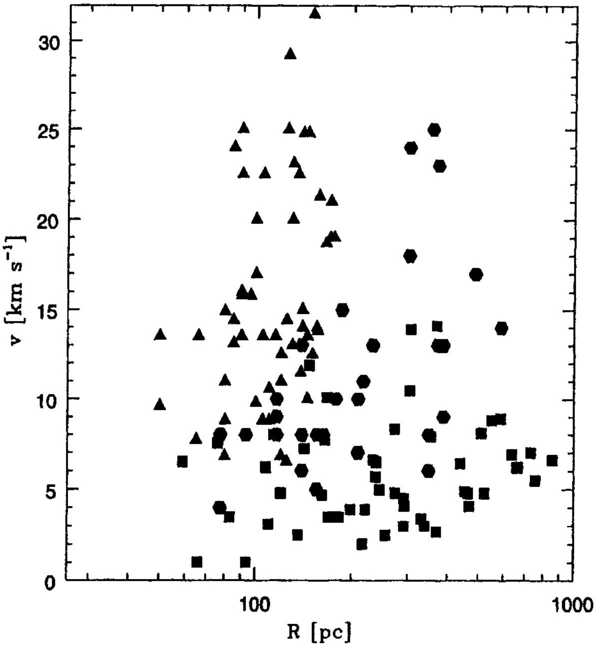

Figure 1 Expansion velocities of the HI shells versus their radius observed in three face-on galaxies: LMC (triangles), HoII (squares), IC 2574 (hexagons) from Kim *et al.* (1999), Puche *et al.* (1992), and Walter and Brinks (1999), respectively.

and this allows simple statistical conclusions. Three quantities are observed: the radius R (more precisely the angular diameter) of the shell in the galactic plane, the expansion velocity v along the line of sight, and the column density of HI $\sigma(HI)$ in the close vicinity of the shell; the volume density $n(HI)$ can then be inferred from $\sigma(HI)$ and the estimated scale height (for details see: Puche *et al.*, 1992; Walter and Brinks, 1999). When the observed points are plotted in the radius–velocity plane, no obvious correlation is seen. They are distributed randomly (Figure 1, here data for HoII, LMC and IC 2574 are plotted). However, the quantity nv^2R^3 (which is, as is readily seen, the explosion energy E calculated under the assumption that the expansion remains always adiabatic) shows a clear correlation (see Figure 2 where on the vertical axis $E^{1/3} = [nv^2R^3]^{1/3}$ is plotted). This correlation justifies the assumption that regardless of the origin of the correlation, all the shells are produced by a SN energy input. (Note, that this correlation means merely $nv^2 \simeq$ constant, which corresponds to pressure modified stages of expansion when the ram pressure is close to the external pressure. From this point of view the scatter is partially due to the fact that the expansion velocities are not exactly equal to the sound speed). However, one feature captures the attention: the velocities corresponding to the holes in HoII are mostly subsonic. It is easily seen from Figure 1 that approximately 75% of the points lie below the sound speed (which for HoII is $\simeq$ 8 km s^{-1}). Half of the subsonic shells have ages of about 100 Myr or more. Thus, three questions

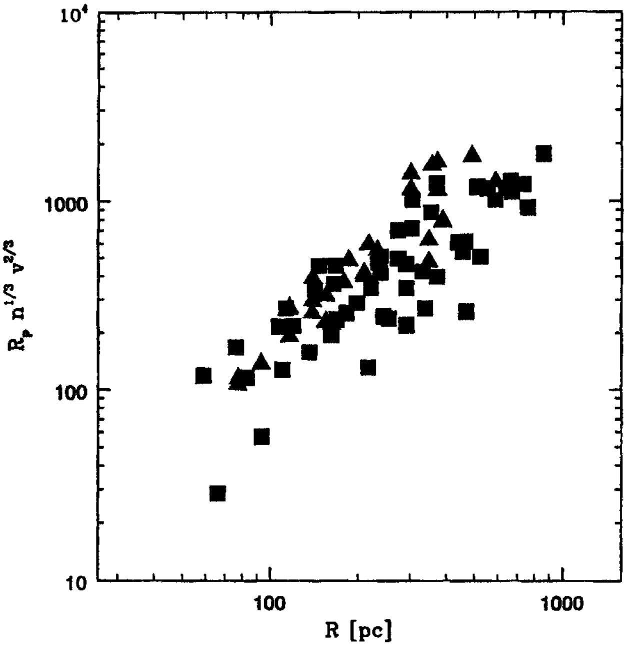

Figure 2 $E^{1/3} = Rn^{1/3}v^{2/3}$ (see text) versus radius for IC 2574 (triangles), and HoII (squares).

have to be answered: how can the subsonic shells (whose dynamics therefore is strongly modified by the external pressure) possibly follow approximately the same trend as the supersonic shells in IC 2574 do, how do they keep their integrity during such a long time and why are they not destroyed by external turbulent motions? Note that turbulence destroys subsonic shells with a characteristic time $t_{\rm d} \sim R/c_s$ which is less than the estimated age $\sim R/v$. It is worth stressing that at late stages radiation pressure acting on the expanding shells can be dynamically important. For a typical value of the interstellar radiation energy flux $\Phi \sim 10^{-2}$ erg cm^{-2} s^{-1}, the radiation force per unit volume is $f_R \sim 3 \times 10^{-34}\xi n$ cgs, where ξ is the dust-to-gas ratio normalized to its value in the local ISM and n is the mean density in the shell. At the same time, the gradient of thermal pressure in the remnant is $\nabla p \sim E/2\pi R^4 \sim 5 \times 10^{-34}$ cgs, $E = 3 \times 10^{53}$ erg is the explosion energy, $R \sim 1$ kpc, its radius (Puche *et al.*, 1992). It is seen that for $n \sim 1 - 3$ cm^{-3}, f_R is comparable to ∇p, and it can be even larger if the dust-to-gas ratio ξ is enhanced in haloes as suggested by Dettmar *et al.* (2001).

The mass and energy distribution functions of the shells are usually peaked, with a maximal number of shells at $M \sim 10^5 - 10^6\ M_\odot$, and at $E \sim 1 - 3 \times 10^{51}$ erg for different galaxies (see discussion in Walter and Brinks, 1999). The HI spatial resolution (around $\sim$ 100 pc) corresponds to considerably smaller masses of $\sim$ (3–10) $\times\ 10^3\ M_\odot$, and thus the decline in the mass (and correspondingly, in the energy) distribution at low masses cannot be attributed to the spatial resolution. Since these distributions peak at energies corresponding to a few SNe, the decline may be connected with the cutoff in the distribution of OB associations at the low luminosity end. The decline in distributions at higher energies and masses may reflect a universal power-law luminosity function of OB associations.

Walter *et al.* (1998) have detected soft X-ray emission from a region coincident with an HI supershell in IC 2574. Its spectrum agrees with a Raymond-Smith spectrum at $T = 10^{6.8}$ K indicating that combined effects of stellar wind and sequential SNe explosions are the energy source for this region (although a contribution from binaries cannot be excluded). However, the expansion velocity of the HI shell, ~ 25 km s^{-1}, suggests rather late stages of the bubble when its temperature is at least ten times smaller, ~ (3–5) × 10^5 K (see, Slavin and Cox, 1992). A possible explanation of this disagreement may be connected with a SN explosion which occurred recently ($t \ll 10$ Myr) so that the blast wave has not yet reached the expanding HI shell.

4 EDGE-ON GALAXIES

Edge-on galaxies provide us with direct information about the vertical distribution of gas, cosmic rays and magnetic fields in galactic haloes (Dettmar, 1992). Recent high-resolution observations with the unsharp-masked technique have shown the presence of highly organized dust features far from the galactic planes of edge-on galaxies. For example, Sofue *et al.* (1994) have found multiple vertical 'dust streamers' in the nearly edge-on galaxy NGC253 (the inclination 78°) extending coherently up to 1 - 2 kpc. Howk and Savage (1997, 2000) have obtained deep optical images in BVI and Hα of the edge-on galaxy NGC891. They found that dust and ionized gas extend up to distances $|z| \sim 2$ kpc from the midplane. Dust extinction and Hα emission are found to have a filamentary and clumpy structure, however without a direct physical relationship between the two components. In most cases at lower heights ($|z| \lesssim 1$ kpc) the structure seen in Hα is mostly due to absorption by dust-bearing clouds (Howk and Savage 2000). This probably suggests that dust features and Hα gas have a distinct origin. The presence of dust may indicate that commonly discussed strong blowouts from SNe cannot be considered as a dominant transport mechanism of material in the vertical direction. For a blowout to occur, the SN shock wave must always be supersonic, which means that when the shock enters the predominantly hot phase ($T \sim 10^6$ K) at $|z| \sim 0.4$–0.5 kpc, its velocity must be $v_{sh} > 100$ km s^{-1}. However, when being processed by such shocks dust grains are easily destroyed (Drain, 1995). More detailed calculations show that up to 30–50 % are destroyed by such shock waves (Dettmar *et al.*, 2001). Therefore, 'soft' transport mechanisms are needed to provide for the elevation of dust far above the galactic planes.

Among such mechanisms (see the detailed discussion in Howk and Savage, 1997), the radiation pressure of stellar light acting on dust particles is considered as effective (Barsella *et al.*, 1989; Franco *et al.*, 1991; Ferrara *et al.*, 1991; Ferrara,

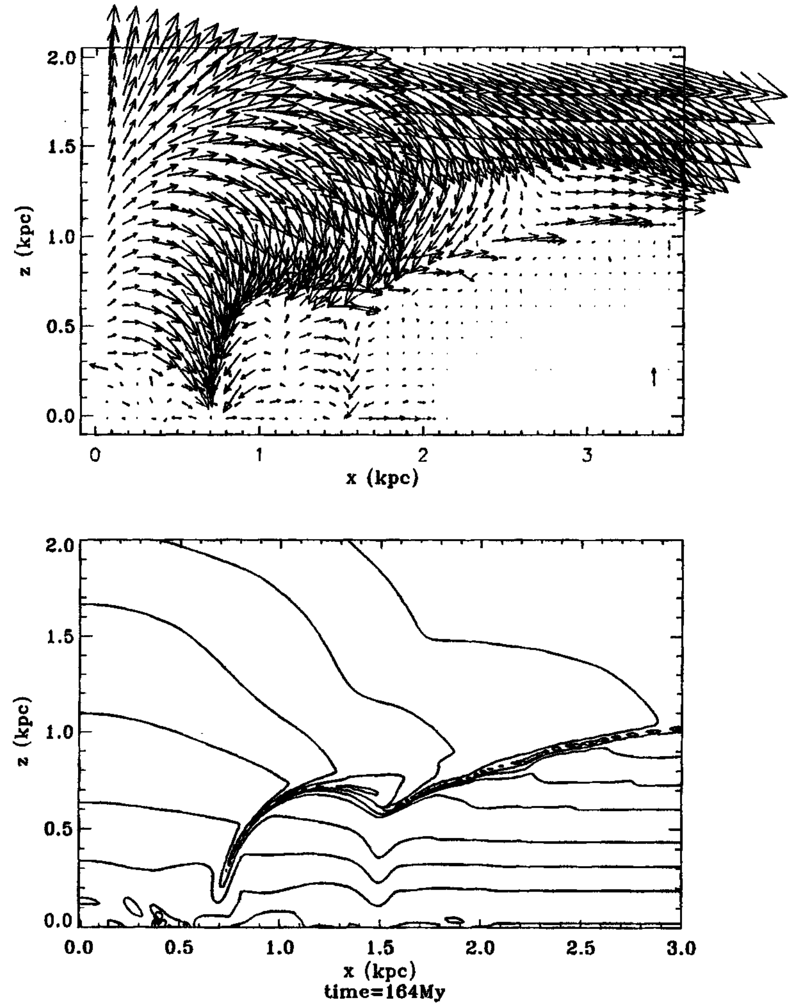

Figure 3 Magnetic loop formed by the Parker instability initiated by a SN explosion (in the origin) after 164 Myr (Steinacker and Shchekinov 2000).

1998). However, because dust particles are charged (carrying positive charge when immersed in a diffuse gas) they are strongly coupled to the magnetic field – the gyroradius is about $r_G \sim 3 \times 10^{11} v_d$ for $B \sim 3\ \mu$G, and the grain radius $a \sim 0.1\ \mu$m, v_d is the velocity of a dust particle in cgs; for subsonic particles r_G is less than 1 pc. In principle, they can intermittently spend some time in neutral states due to charge fluctuations as mentioned by Ferrara (1998), however the characteristic charging time is normally much shorter than 1 yr, and the contribution of such intermittent periods is negligibly small. Thus, in order to be efficient, this mechanism requires the presence of a locally strong vertical magnetic field component in the interstellar

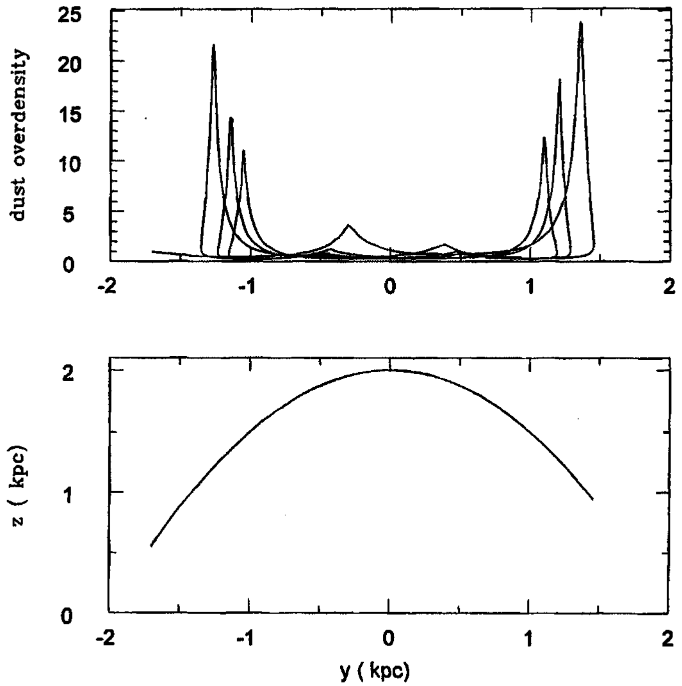

Figure 4 Dust density distribution (upper panel) formed by the radiation pressure driving the dust particles along a magnetic arc (lower panel).

medium. A possible mechanism to produce such a configuration is the Parker instability (Sokoloff and Shukurov, 1990). Recent simulations (Kamaya *et al.*, 1996; Steinacker and Shchekinov, 2001) show that the instability can be triggered by SN explosions even if their total energy release is moderate (E $\ll 10^{53}$ erg). However, Steinacker and Shchekinov have shown that the time scale on which significantly large loops are being formed, depends on the magnitude of the gravitational acceleration g. Only for $g \geq 4.5 \times 10^{-9}$ cm s^{-2}, do the loops become sufficiently prominent within a characteristic time comparable to the rotation period of the galactic disc. In these cases, the loops can extend up to 2–3 kpc into the halo (Figure 3). The production of such prominent loops can be facilitated, if the Parker instability and the SN remnant expansion can operate simultaneously and interact. In order for this interaction to take place, the energy provided by the explosion must be larger than the minimal energy required for the Parker instability to be initiated and lower than the minimal energy required for a blow-out to occur. In this case the instability evacuates gas from the expanding shell, therefore facilitating the expansion of the interior hot bubble, or the expanding bubble carries material away, allowing for the magnetic field to rise faster. Furthermore, they have shown that even one SN explosion can generate multiple loops. These secondary loops are a consequence of the fact that the perturbation induced by the explosion propagates through the disc.

As seen from the above estimates of the radiation pressure, a local increase of the radiation flux from a young OB association can also initiate the Parker instability.

Once formed, a magnetic loop can serve as a conductor for radiatively driven dust particles. At heights $z \sim 200$ pc collisional coupling between the dust and gas weakens because of the exponential decrease of the gas density, and at higher z dust moves practically friction-free so that the dust-to-gas ratio gets enhanced. At heights $z \sim 1.5$ kpc the friction between the dust and gas is so weak that dust particles oscillate along the magnetic arch, and form a horn-like density distribution as shown in Figure 4 (Dettmar *et al.*, 2001). The peak density of dust in the clumps is around 20 times the midplane value, and as dust and gas are dynamically weakly coupled at these heights, actual dust-to-gas ratios can be considerably higher.

5 SUMMARY

The total number of chimneys in the Milky Way produced by clustered SN explosions with the observed luminosity function for OB associations is in agreement with total number of worms (Koo *et al.*, 1992), and the chimneys detected in the Cas OB6 association (Normandeau *et al.*, 1996).

The presence of subsonic HI shells in HoII can be connected with the action of radiation pressure at late stages of the expanding SNR remnants.

Dust observed in haloes of the edge-on galaxies may indicate that radiation pressure plays a dominant role in vertical transport of matter. For such a transport mechanism to be possible the interstellar magnetic field must be organized by the Parker instability to have a considerable vertical component. In its turn, the Parker instability can be initiated by a relatively small energy release from SN explosions.

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