Bubbles in galactic haloes

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ABSTRACT

We briefly discuss a possible interconnection of vertical HI structures observed in the Milky Way Galaxy with large scale blow-outs caused by the explosions of multiple 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 H$\alpha$ 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.

Subject headings: 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 (\(\sim 10 \text{ pc}\), corresponding to a parent cloud where a star drives a wind or explodes as a SN), on characteristic scales of cold thin interstellar discs (\(\sim 100 \text{ pc}\)), and on the much larger scales of gaseous haloes (\(\sim 1 \text{ kpc}\)). 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 comes from observations of neutral gas structures oriented predominantly in 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 & Ikeuchi 1989). (A less obvious and completely unexplored possibility can 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 \(1 - 1.5 \text{ kpc}\) above the plane is of the order of \(\sim 1 - 3 \times 10^{53} \text{ erg}\). Then for a power law distribution of OB associations in the Galaxy (Kennicutt et al., 1989, Heiles 1990, Williams & McKee 1997)

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

where \(N_a(L)\) is the number of associations with an ionizing photon luminosity larger than \(L, L_{49} = L/(10^{49} \text{ s}^{-1})\), one obtains the total number of chimneys \(N_{ch} \simeq 60\), where \(L_{49} = 0.2\) for an O9 star is assumed (Shchekinov 1996). Thus for a total number of chimney walls seen in the projection we get \(\simeq 120\) which is consistent with the observed number of worms \(N_w = 118\) (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 \(I(60 \mu m)/I(100 \mu m) \simeq 0.28\) (Koo et al., 1992) which can 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 was detected in Cas OB6 association in the Perseus arm (Normandeau et al., 1996). Assuming the distance to Cas OB6 \(\sim 2.2 \text{ kpc}\), one obtains the number of chimneys in the disc \(N_{ch} \sim (15 \text{ kpc}/2.2 \text{ kpc})^2 \simeq 46\) 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 tens of face-on galaxies - besides M31 the most interesting of these are: M33 (Deul & den Hartog 1990), Holmberg II (Puche et al., 1992), M101 and NGC 6496 (Kamphius 1993), SMC (Staveley-Smith et al., 1997), IC 10 (Wilcots & Miller 1998), LMC (Kim et al., 1998, 1999), IC 2574 (Walter & Brinks 1999). Typically 50 to 100 shells with sizes ranging in the interval 100 pc – 1 kpc have been observed, and this allows simple statistical conclusions. Three quantities are observed: the radius $R$ (more precisely the angular diameter) of a shell in the galactic plane, the expansion velocity $v$ along the line of sight, and the column density of HI, $\sigma(HI)$, in a 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 & Brinks 1999). When the observed points are plotted in the radius–velocity plane, no obvious correlation is seen. They are distributed randomly (Fig. 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 always remains adiabatic) shows a clear correlation (see Fig. 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 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 Fig. 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 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 $t_d \sim R/c_s$ 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 $\xi$ 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 $\nabla p$, and it can be even larger if the dust-to-gas ratio $\xi$ 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 & 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 can 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 can 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 winds 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, $\sim 25$ km s$^{-1}$, suggests rather late stages of the bubble when its temperature is at least ten times smaller, $\sim 3 - 5 \times 10^5$ K (see, Slavin & Cox 1992). A possible explanation for this disagreement can be based on a SN explosion which has 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 unsharp-masked technique have shown the presence of highly organized dust features far from the galactic planes of edge-on galaxies. E.g., Sofue et al., (1994) have found multiple vertical “dust streamers” in the nearly edge-on galaxy NGC253 (inclination $78^\circ$) extending coherently up to 1 - 2 kpc. Howk & Savage (1997, 2000) have obtained deep optical images in BVI and H$\alpha$ 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| < ∼ 1 kpc) the structure seen in Hα is mostly due to absorption by dust-bearing clouds (Howk & 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 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 ∼ 10^6 K) at |z| ∼ 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 an elevation of dust far above the galactic planes.

Among such mechanisms (see detailed discussion in Howk & 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 1998). However, because dust particles are charged (carrying a positive charge when immersed in a diffuse gas) they are strongly coupled to the magnetic field – the gyro-radius is about r_G ∼ 3 \times 10^{11} v_d for B ∼ 3 \mu G, and grain radius a ∼ 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 spend intermittently 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 medium. A possible mechanism to produce such a configuration is the Parker instability (Sokoloff & Shukurov, 1990). Recent simulations (Kamaya et al., 1996, Steinacker & 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 & 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 ≥ 4.5 \times 10^{-9} \text{ 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 (Fig. 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 Fig. 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 the total number of worms (Koo et al., 1992) and the chimneys detected in 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 SN remnants.

The underlying cause for the observed presence of dust in the haloes of edge-on galaxies may be explained as a combined effect of magnetic fields and radiation pressure acting to transport matter vertically. In order for this transport mechanism to occur, the interstellar magnetic field must be reorganized by the Parker instability, hence gaining a considerable vertical component. The Parker instability, in turn, can be initiated by a relatively small amount of energy released from the SN explosions.

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REFERENCES

Barsella, B., Ferrini, F., Greenberg, J. M., & Aiello, S. 1989, A&A, 209, 349

Brinks, E. 1981, A&A, 95, L1

Dettmar, R.-J., 1992, Fundam. Cosmic Phys., 15, 143

Dettmar, R.-J., Schröer, A., Shchekinov, Yu. A. 2001, A&A, in preparation

Deul, H.-J., den Hartog, R. H. 1990, A&A, 229, 362

Draine, B. T. 1995, in Shocks in Astrophysics, ed. T. J. Miller, Ap&SS, 233, 111

Ferrara, A., 1998, in Lecture Notes in Physics, v. 506: The Local Bubble and Beyond, Lyman-Spitzer-Colloquium, eds. D. Breitschwerdt, M.J. Freyberg, J. Trümper, (Berlin: Springer-Vrlag), p. 371

Ferrara, A., Ferrini, F., Franco, J., Barsella, B., 1991, ApJ, 381, 137

Franco, J., Ferrini, F., Ferrara, A., Barsella, B., 1991, ApJ, 366, 443

Heiles, C., 1984, ApJS, 55, 585

Howk, J. C., Savage, B. D., 2000, AJ, 119, 644

Howk, J. C., Savage, B. D., 1997, AJ, 114, 2463

Kamaya, H., Mineshige, S., Shibata, K., & Matsumoto, R. 1996, ApJ, 458, L25

Kamphius, J. J. 1993, PhD Thesis, University of Groningen

Kennicutt, R. C., Edgar, B. K., Hodge, P. W. 1989, ApJ, 337, 761

Kim, S., Staveley-Smith, L., Dopita, M. A., Freeman, K. C., Sault, R. J., Kesteven, M. J., McConnel, D. 1998, ApJ, 503, 729

Kim, S., Dopita, M. A., Staveley-Smith, L., Bessel, M. S. 1999, AJ, 118, 2797

Koo, B.-C., Heiles, C., Reach, W. T., 1992, ApJ, 390, 108

Mac Low, M., McCray, R., & Norman, M. L., 1989, ApJ, 337, 141

Norman, C. A., Ikeuchi, S., 1989, ApJ, 345, 372

Normandeau, M., Taylor, A. R., & Dewdney, P. E. 1996, Nature, 380, 687
Puche, D., Westpfahl, D., Brinks, E. 1992, AJ, 103, 1841
Shchekinov, Yu. A. 1996, A&A, 314, 927
Silich, S. S., Franco, J., Palouš, J., Tenorio-Tagle, G. 1996, ApJ, 468, 722
Slavin, J. D., & Cox, D. P. 1992, ApJ, 392, 131
Sofue, Y., Wakamatsu, K.-I., Malin, D. F., 1994, AJ, 108, 2102
Sokoloff, D., & Shukurov, A. 1990, Nature, 347, 51
Steinacker, A., & Shchekinov, Yu. A. 2001, MNRAS, in press
Staveley-Smith, L., Sault, R. J., Hatzidimitrou, D., Kesteven, M. J., McConnel, D. 1997, MNRAS, 289, 225
Walter, F., Kerp, J., Duric, N., Brinks, E., Klein, U. 1998, ApJ, 502, L143
Walter, F., Brinks, E. 1999, AJ, 118, 273
Wilcots, E. M., Miller, B. W. 1998, AJ, 116, 2363
Williams, J. P., McKee, C. F. 1997, ApJ, 476, 144

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Fig. 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 & Brinks 1999, respectively.
Fig. 2.— $E^{1/3} = R n^{1/3} v^{2/3}$ (see text) versus radius for IC 2574 (triangles), and HoII (squares).
Fig. 3.— Magnetic lop formed by the Parker instability initiated by a SN explosion (in the origin) after 164 Myr (Steinacker & Shchekinov 2000).
Fig. 4.— Dust density distribution (upper panel) formed by the radiation pressure driving the dust particles along a magnetic arc (lower panel).