THE GLOBAL MASS, ENERGY AND PHOTOIONIZATION BALANCE OF THE DISK-HALO INTERACTION

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ABSTRACT. The observational evidence for chimney models of the interstellar medium is reviewed. The variation of the state of the interstellar medium of an external galaxy between the three-phase mode, the chimney mode and the two-phase mode as a function of: galaxy type, galactocentric radius within a given galaxy, and the time varying star formation rate is discussed.

In the context of the chimney models it is shown how the photoionization of the halo can be achieved by utilizing both direct ionizing rays from the central OB association and diffuse reradiation from the chimney walls that will create an extended low ionization halo around chimneys with SII/Hα $\sim$ 0.5.

A number of considerations for future studies that are a direct result of the work discussed at this conference are outlined.

1. INTRODUCTION: THE BASIC MODEL

Observational studies of the interstellar medium in nearby galaxies are now revealing a wealth of details and structures. Early work on M31 by Brinks and Bajaja (1986) indicated that large holes were present in its interstellar medium and the natural explanation is that correlated type II supernovae are the primary cause. If correlated explosions occur in gas disks with exponential scale heights, they will accelerate rapidly outwards normal to the plane and break out of the gas layer forming chimney like structures (c.f. Norman and Ikeuchi 1989). The walls of these chimneys are seen in our own Galaxy where they are identified with Heiles' supershells (c.f. Heiles 1987, 1989). Large structures consistent with the chimney morphology in HI and Hα are seen in the LMC (Meaburn *et al.* 1987, Dopita *et al.* 1985) , M31 (c.f. Brinks 1990 , Braun 1990, Walterbos 1990), M33 (Deul and den Hartog 1990), NGC 891 (Rand, Kulkarni and Hester 1990, Dettmar 1990) and M101 (Kamphuis 1990).

The chimneys models explicitly indicate that the flow of mass, energy, momentum and magnetic flux from the disk to the halo is funneled through the chimneys that have been created by $\sim 10^2$ correlated type II supernovae per superbubble.

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 337–344.

The flow back down to the disk is the result of cooling and infall and occurs over the whole disk.

When considering the multiphase structure of the interstellar medium of external galaxies a number of parameters are significant, namely, the level of star formation, the amount of clustering of the energy input from type II supernovae, the mean ambient density, the galaxy type, and the variation of the physical quantities with Hubble type.

It turns out that depending on the state of these quantities a galaxy can be in either the three-phase mode (McKee and Ostriker 1977), the chimney mode (Norman and Ikeuchi 1989) or the two-phase mode (Field, Goldsmith and Habing 1969). These states can change as a function of galactocentric distance, Hubble type and time as the level of star formation changes. In extreme cases such as starbursts huge central starburst driven winds can be blown out of galaxies with outflow rates up to $100 M_{\odot}$ yr^{-1}(Heckman 1990). More typical numbers are an energy flow into the halo of $\sim 10^{40} - 10^{41}$ erg s^{-1}, and a mass circulation rate of $\sim 1 M_{\odot}$ yr^{-1}. Detailed modelling of the observational signatures of the interstellar medium has been undertaken by Li and Ikeuchi (1990).

The ionization requirement of the extended ionized layer above the disk of our Galaxy indicates that a significant fraction of the total ionizing photons of all the OB stars in the disk (Reynolds 1990) must be utilized and therefore must be able to escape from their original location in the thin star forming part of the disk. The vertical extent of the ionized layer is $\sim$ 1500 pc and, if this warm ionized component of the interstellar medium is at a temperature $T \sim 10^4$K then the power required to ionize it is 4×10^{-5} erg s^{-1} cm^{-2}. Similar extended ionized disks have been seen in other galaxies and the effect is most apparent in NGC 891 where the layer extends to $\sim$ 4.5 kpc above the plane and has an estimated mass of $4 \times 10^8 M_{\odot}$ (Dettmar 1990, Rand, Kulkarni and Hester 1990). The radial extent of the extended warm ionized medium is apparently $\sim 30 kpc$ and there are clear indications of chimneys blown out by multiple supernovae explosions occurring in OB associations. The estimate of the superbubble formation rate necessary to power this extended ionized gas component in NGC 891 is an order of magnitude greater than that of our Galactic disk (Heiles 1987, Norman and Ikeuchi 1989, 1990, Rand et al. 1990). Correlations of OB associations with HI in the gas distribution of the Magellanic Clouds, M31, M33, IC 10 and 1C 1613 have been summarized by Brinks (1990). It is worth emphasizing that in the LMC where it is possible to study such details the observed Hα shells lie just inside the HI shells.

The general problem of the ionization of the halo has been studied by Chevalier and Fransson (1984) using background ionizing radiation from quasars and Bregman and Harrington (1986) using photons from OB stars that have leaked out into the halo. Other sources of radiation that have been suggested are planetary nebulae, white dwarfs (Panagia and Terzian 1984), and the soft x-ray background. Thuan (1975) presented indications of how OB stars with a population scale height of $\leq$ 200 pc could have burnt a hole in the HI layer and has estimated that about 20% of the ionizing photons can escape. Mathis (1986) has estimated that about 10% of the diffuse ionizing photon field associated with O stars in the disk can achieve significant distances above the galactic plane. Thus the observations of the widespread SII/Hα ratio of ~ 0.5 corresponding to diffuse ionized gas can be satisfactorily explained. Finally, Sciama (1990) has recently suggested that the decay of dark matter in the halo accompanied by UV photon emission is the natural explanation of the ionization power budget problem.

Here we shall show that OB associations embedded in chimneys can directly ionize the halo gas above the top of the chimney. The chimney walls are also ionized and the diffuse ionizing radiation re-emitted by the walls can also ionize halo gas over a much wider range of subtended angle than that available to the directly ionizing rays. Details are given in Norman and Panagia (1990). The characteristic ionization structure above a chimney is that of a directly ionized hard HII region with species such as HeI, OIII, SIII and a softer more extended halo due to the diffuse radiation from the chimney walls associated with OII, SII, NII, CIII. Using canonical chimney model parameters the filling factor of the softer spectrum is found to be of order unity. The spatial variation between hard and soft spectra associated with chimney should be readily observed in our own galaxy and external galaxies.

The most important aspect of this meeting was the large number of excellent observations that now lead to a number of very interesting studies that require immediate further study. These include the nature and significance of the hot gas component in the interstellar medium, the effect of magnetic fields, the question of realistic dynamo models in realistic interstellar media, the general ionization state of our Galaxy and external galaxies, the morphology of the cool component of the interstellar medium, the physical significance of the morphological characterization of chimneys, walls, worms etc. (i.e. are they the same or different) the general characterization of the interstellar medium with Hubble type and the propagation of cosmic rays in the various types of interstellar media.

A significant question was asked at the meeting concerning whether or not chimneys break out of the extended diffuse ionized layer. The answer is only rarely for the most powerful superbubbles even though all respectable superbubbles can break out of the thin neutral layer and undergo acceleration to form chimneys, holes etc. As I argue in section III, the answer is that the superbubbles rising up above the thin disk probably feed mass into the extended Reynold's layer and therefore sustain it.

2. IONIZATION STRUCTURE ABOVE CHIMNEYS

The concept of an OB association embedded in a superbubble or chimney that is powered by multiple supernovae has been much discussed (Norman and Ikeuchi 1989, MacLow et al. 1989). We analyze here the escape of ionizing photons into the halo in such a chimney structure. Since we wish to avoid very specific geometries we have studied three particular cases of an ionizing source where the OB association is placed at the center of a cube, a hemisphere and a cylinder. We solve the integral equation for the ionization of the walls and the subsequent re-emission of the diffuse ionizing radiation from them. The direct ionizing radiation is penetrating a density profile that is exponential given by $n_e = n_{e0}e^{-z/H}$ where $n_{e0} \sim 0.025$ cm^{-3} and H is $\sim$ 1500 pc (Reynolds 1990).

To simplify the analysis of the emission and reabsorption of ionizing photon at a chimney wall we use a plane parallel approximation at the chimney wall interface. In terms of the standard recombination formula given in, say, Osterbrock (1989) and Spitzer (1978) we define ξ as the ratio of the recombination coefficient to the ground state over the total recombination coefficient. Such recombinations to the ground state will re-emit ionizing photons at 13.6 eV $+\delta$, where δ is of order $\sim$ 1 eV, which originates from the kinetic energy of the recombining electrons. Estimates of ξ depend on temperature but are in the range of 0.4. The efficiency of conversion of directly absorbed ionizing radiation into re-radiated diffuse ionizing radiation is given by, ϵ, the ratio of outgoing to incoming ionizing flux is found to be

$$\epsilon = \frac{2}{\xi}\left((1-\frac{\xi}{2}) - (1-\xi)^{\frac{1}{2}}\right) \tag{1}$$

For numerical estimates we adopt a typical value here of 13%.

Let us describe the solution of the hemi-spherical case in spherical coordinates (R, Θ, Φ). Details are given in Norman and Panagia (1990). The equation for the intensity radiated by the walls $I_w(z)$ is

$$I_w(z) = \frac{\epsilon S_o}{2R^2(1-z)} + 2\pi\epsilon \int_{-1}^{z_0} dz \frac{I_w(z)}{(z-z')^2} \tag{2}$$

where $z = cos\Theta$, S_0 is the luminosity of the central source and R is the radius of the hemisphere. The first interaction is obtained by using the source term as the zeroth approximation for $I_w(z)$ in the integral. This gives

$$I_w(z) = \frac{\epsilon S_0}{2R^2(1-z)}\left[1 + \frac{2\pi\epsilon}{(1-z)}\left[\ln\left(\frac{2(z_0-z)}{(z_0-1)(z+1)}\right) - \frac{(1+z_0)(1-z)}{(z_0-z)(1+z)}\right]\right] \tag{3}$$

The total intensity at a point outside the hemispherical surface $I(r, \theta, \phi)$ can be well approximated for $\theta > 45^0$ by

$$I(r, \theta, \phi) = \frac{\epsilon So}{r^2}\left(\frac{\pi}{2}\right)\ln(1 + \sin 2\theta). \tag{4}$$

Similar results hold for the open cylinder where the zeroth order solution is

$$I(r, \theta, z) = \frac{\epsilon So}{r^2}\pi\left[\arctan\left(\frac{L}{R}\right) - \arctan\left(\frac{L}{R} - \frac{2z}{r}\right)\right] \tag{5}$$

The ionization sphere for the directly ionized material above the chimney is given by (Spitzer 1978 §5-1),

$$r_{s1} = \left(\frac{S_0}{\frac{4}{3}\pi n_e^2 \alpha} \right)^{\frac{1}{3}} . \tag{6}$$

For the diffuse ionizing radiation from the walls, the ionizing sphere in the non-directly (i.e. diffusely) ionized region ($\theta \geq 45^0$) has a shape given by

$$r_{s2} = \left(\frac{\epsilon S_0}{\frac{4}{3}\pi n_e^2 \alpha} \right)^{\frac{1}{3}} \left(\ln(1 + \sin 2\theta) \right)^{\frac{1}{3}} \approx \epsilon^{1/3} r_{s1}. \tag{7}$$

Results for cylinders and cubes give similar answers. For canonical halo parameters we choose (Reynolds 1990) ($\alpha \sim 2 \times 10^{-13}$ cm^3 s^{-1}, $n_e \sim 0.025$ cm^{-3} up to a scale height of 1500 pc and $S_0 \sim 10^{50} - 10^{51}$ s^{-1}) we find

$$r_{s1} = 2.4\mathrm{kpc} \left(\frac{S_0}{10^{50}\mathrm{s}^{-1}} \right)^{\frac{1}{3}} \left(\frac{0.025\mathrm{cm}^{-3}}{n_e} \right)^{\frac{2}{3}} \left(\frac{2 \times 10^{-13}\mathrm{cm}^3\mathrm{s}^{-1}}{\alpha} \right) \tag{8}$$

which shows that for canonical numbers the free electron layer directly above the chimney can be ionized readily. In fact, because the density distribution is exponential the hard ionization region above the chimney is density bounded.

The characteristic size of the ionization region created by the diffuse radiation from the walls is

$$\begin{aligned} r_{s2} &\sim \epsilon^{\frac{1}{3}} r_{s1} \\ &\sim 1.2\mathrm{kpc} \left(\frac{\epsilon}{0.16} \right)^{\frac{1}{3}} \left(\frac{So}{10^{50}\mathrm{s}^{-1}} \right)^{\frac{2}{3}} \left(\frac{0.025\mathrm{cm}^{-3}}{n_e} \right)^{2/3} \left(\frac{2 \times 10^{-13}\mathrm{cm}^3\mathrm{s}^{-1}}{\alpha} \right)^{\frac{1}{3}} . \end{aligned} \tag{9}$$

Therefore the effective cross section of the softer diffuse radiation associated with a chimney has a cylindrical radius of ~ 1.2 kpc.

The filling factor of the ionizing radiation from OB associations embedded in chimneys is calculated assuming that the diffuse radiation above a chimney is cylindrical with scale height 1.5*kpc* and radius 1.2 kpc. For N such chimneys in a galaxy the filling factor is given by

$$\begin{aligned} Q = \frac{\pi N r_{s2}^2}{\pi R_g^2} &\sim \left(\frac{N^{\frac{1}{2}} r_{s2}}{R_g} \right)^2 \\ &\approx 1 \left(\frac{N}{100} \right) \left(\frac{\epsilon}{0.16} \right)^{\frac{2}{3}} \left(\frac{So}{10^{50}\mathrm{s}^{-1}} \right)^{\frac{2}{3}} \left(\frac{0.025\mathrm{cm}^{-3}}{n_e} \right)^{\phi} \left(\frac{15\mathrm{kpc}}{R_g} \right)^2 \end{aligned} \tag{10}$$

Since the superbubble and chimney formation process is stochastic some regions will find themselves without an ionization source at any given time. The recombination time is short so that significant cooling and possibly infall may occur. (It is conceivable that this could be a self regulating process with the cooling and infall triggering a further massive burst of star formation).

For edge-on systems there should be a characteristic change from hard to soft ionization species as one scans across the top of a chimney. For face-on systems a characteristic hard core with an extended soft halo should be seen across the holes blown by the chimney.

3. FURTHER STUDIES

The most important aspect of the meeting for me was the large number of further studies that need to be undertaken as a result of the new observational studies presented at the meeting many of which are based on outstanding new observations of external galaxies. I will try to summarize some of the most important of these problems needing further and urgent study.

The hot gas component content of our Galaxy seems to have a very uncertain role at least if one believes the discussions at this meeting where its filling factor and contribution to the energy balance of the interstellar medium ranged from very important to irrelevant. Clearly ROSAT and AXAF observations of the observed holes, bubbles, worms and chimneys in both face-on and edge-on external galaxies will be crucial here in helping us understand the significance and extent of the hot gas component in the energy balance of the interstellar media of galaxies.

The effect of magnetic fields on the propagation of supernovae and superbubbles needs to be closely studied. It is still uncertain whether the effect is of minor importance or dominant. The general dynamo theory for disks with realistic interstellar media is still awaiting a full development. In simple models it is the Parker instability that allows transport of field normal to the disk, with Coriolis force twisting the flux tubes followed by reconnection and subsequent infall back to the disk thus closing the dynamo action loop. Clearly, with chimneys the flux would be forced up the chimneys and the dynamo action with the standard twisting and reconnection would be less clear. Also important here is a better understanding of the structure of magnetized clouds and the relation of the field structure to the cloud structure and cloud distribution.

Important observational studies to be performed are those that study the ionization structure of the disk and halo. It is important to pin down observationally the contribution to the ionization of the halo of the various candidates including white dwarfs, planetary nebulae, OB associations and the metagalactic radiation field. Detailed observations in HI 21 cm, SII and Hα, etc. of a large sample of nearby galaxies will eventually tell us the source of the ionization of the halo. It will be a fairly complicated data set and comparison with simplified models such as that presented here in section 2 could prove useful.

The general morphology of the components of the interstellar medium seems most intriguing. Fascinating data presented at this meeting indicated how filamentary and sheetlike was the HI component with a covering factor near unity and a filling factor that is very small. It is not yet clear whether this could naturally arise from the cooled intersecting shells of supernovae and superbubbles or whether it is necessary to invoke a general cooling process in a magnetized medium where the filaments would naturally occur along the filaments.

The many observations of holes, worms, chimneys in various wavebands their association with regions of massive star formation require some systematic classification scheme with regard to their velocity fields, morphology, general physical conditions as revealed by line ratios, radio fluxes, polarization, dust content etc. The interplay between models and observations both current and planned are potentially very fruitful here. The physical distinctions and similarities between holes, worms, and chimneys need to be clarified and given a sound physical basis.

In this context it is important to undertake large surveys of a wide range of galaxy types and relative orientations in all possible wavebands including ROSAT imaging, HST absorption line studies, 21cm line studies, radio continuum, infrared imaging, narrow band imaging in the optical and UV from the ground and in space, and molecular line studies in the millimeter and submillimeter bands. The range of galaxies should extend from large edge-on systems such as NGC891 through more face on systems such as M33 to more active galaxies and starbursts such as NGC3079 through to blue compact dwarf galaxies such as 1Zw18.

The propagation of cosmic rays in the different types of interstellar media described here will differ in a number of respects. The damping of Alfven waves in a predominantly neutral medium such as is envisaged in the two- phase and chimney models can allow relatively free streaming of cosmic rays out of the galactic plane. In contrast in the three phase models the cosmic rays remain locked to the hot fluid. The chimney models could have large scale shock acceleration in the halo due to interaction with the large scale shocks propagating above the chimneys. The electron component is still somewhat of a mystery and the source of the cosmic ray electrons and their subsequent reacceleration in both the disk and the halo needs considerable further study.

An important issue at the meeting became whether or not the superbubbles could break out of the extended ionized layer discovered by Reynolds. There is no question that superbubbles do break out of the smaller scale height neutral layer. As discussed at this meeting it is only the most rare and energetic explosions that can break out of the Reynolds layer. I see no real problem here as the natural explanation is that the superbubbles break out of the disk forming holes, worms and chimneys as they propagate upwards. Their combined action is to *produce* the Reynolds layer. This would explain why the superbubbles don't normally propagate through the layer since they *form* it and also can explain the origin of the layer itself.

A related issue concerns the source of ionization for the chimney model of the ionization of the Reynolds layer. It is obvious that the massive stars that created the chimney through which the direct and diffuse components are emanating are not the source since they would have died earlier. The source is likely to be the massive stars triggered later by the propagation of the superbubble. This mode of star formation is given considerable credence by the observations of the inner shells of $H\alpha$ lining the walls of the supershells seen in the Magellanic clouds.

It is a pleasure to thank Robert Braun, Eli Brinks, Don Cox, Laura Danly, Don Garnett, Tim Heckman, Jeff Hester, Jim Pringle, Ron Reynolds Nick Scoville and Rene Walterbos for interesting discussions and help in understanding some of these difficult problems. I especially thank both Nino Panagia who shared his wisdom on HII regions with me in our collaboration on the ionization of the halo and Satoru Ikeuchi for many profound insights on the physics of the interstellar medium. It was a pleasure to be back in Leiden where some of my thoughts on this subject were developed in the early eighties. It was also good to hear such excellent talks here from a number of those who were graduate students during that time and who are now major contributors to the field.

REFERENCES

Braun, R. (1990) *Ap. J. Suppl.* **72**, 755

Bregman, J.N., Harington, J.P. (1986) *Ap. J.* **309**, 833

Brinks, E. (1990) in *The Interstellar Medium in External Galaxies*, ed. H.A. Thronson and J. M. Shull

Brinks, E. (1990) in *The Interstellar Medium in Galaxies*, ed. H.A. Thronson and J. M. Shull, p. 39 (Kluwer)

Brinks, E. and Bajaja, E. (1986) *Astr. Astrophys.* **169**, 14

Chevalier, R.A., Fransson, C. (1984) *Ap. J. (Letters)* **275**, L71

Dettmar, R.J. (1990) *Astron. Astrophys.* **232**, L15

Deul, E.R. and den Hartog, R.H. (1990) *Astron. Astrophys.* **229**, 362

Dopita, M.A., Mathewson, D.S. and Ford, V.L. (1985) *Ap. J.* **297**, 599

Field, G.B., Goldsmith, D.W. and Habing, H.J. (1969) *Ap. J. (Letters)* **155**, L149

Heiles, C. (1990) *Ap. J.* **354**, 483

Heiles, C. (1987) *Ap. J.* **315**, 555

Kamphuis, J. (1990) poster presented at this meeting

Li, F. and Ikeuchi, S. (1990) *Ap. J. Suppl.* **73**, 401

Mathis, J.S. (1986) *Ap.J.* **301**, 423

McKee, C.F. and Ostriker, J.P. (1977) *Ap. J.* **218**, 148

Meaburn, J., Marston, A.P., McGee, R.X. and Newton, L.M. (1987) *M.N.R.A.S.* **225**, 591.

Norman, C. A. and Ikeuchi, S. (1989) *Ap. J.* **345**, 372

Norman, C.A. and Panagia, N. (1990) *Ap. J.*, in preparation

Osterbrock, D.E. (1989) *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (University Science Books)

Rand, R.J., Kulkarni, S., and Hester, J.J. (1990) *Ap. J. (Letters)* **352**, L1

Reynolds, R.J. (1990) *Ap. J.* **349**, L17

Sciama, D.M. (1990) *M.N.R.A.S.* **244**, 1p

Spitzer, L. (1978) *Physical Processes in the Interstellar Medium* (Wiley-Interscience)

Thuan, T.X. (1975) *Ap. J.* **198**, 307

Walterbos, R.A. (1990) these proceedings