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Nonthermal radiocontinuum from blow-outs and magnetic Parker loops

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Abstract. Blow-outs and inflating magnetic Parker loops initiated by SNe explosions in galactic discs are thought to be responsible for transport of gas, dust, and magnetic fields from galactic discs into halos. Dynamically, the two scenarios – blow-outs and Parker loops – differ qualitatively: the flow from a blow-out represents shocked gas restricted by two expanding discontinuities while in a magnetic Parker loop the flow is restricted from one side by the underlying hot bubble and inflating progressively outwards. The behavior of cosmic rays (in particular, the relativistic electrons) is quite different in these two cases: in blow-outs the CRs are concentrated (and likely accelerated) between the two discontinuities, while in Parker loops they expand free (and probably, only weakly trapped by secondary shocks possible in inflating Parker outflows).

We discuss these differences with particular emphasize on their observational manifestations. Within a simple prescription of the two outflows we estimate expected radio-fluxes from relativistic electrons and show that in the outflows associated with magnetic Parker loops the radiocontinuum emission shows a deficit in comparison to blow-outs. We discuss also possibilities for the observational discrimination of these scenarios.

1 Introduction

The observed presence of various components of the interstellar medium (ISM) in galactic halos is best understood as the consequence of the so-called interstellar disk-halo interaction, a scenario in which the energy input from star-formation regions by supernovae and stellar winds determines the energetics of the ISM resulting in a transport of matter from the disk into the halo by processes called galactic fountains, winds, or chimneys. For more recent reviews of this topic see, e.g., Dettmar (2000) or Dahlem (1997). From radiocontinuum observations it is obvious that also cosmic rays (CRs) participate in this transport. However, their rôle in the involved physics is still under discussion. Since Parker (1965) CRs are assumed to be connectively transported into galactic haloes. Owens & Jokipii (1977) and Lerche & Schlickeiser (1980) have considered a 1D steady-state diffusion-convection CR transport. Breitschwerdt, McKenzie & Völk (1991) have described a quasi-2D steady-state CR driven galactic wind in a diverging funnel. In this contribution we address qualitatively the question of CR electron transport and possible observational consequences on a "microscopic" level corresponding to a single non-steady-state growing Parker loop.

2 Energetics

The perturbation needed for the Parker instability to occur can be connected with the energy input provided in the midplane either by the kinetic energy released by young stars in SNe explosions and winds or by their stellar radiation field. Two large-scale fundamental dynamical processes are associated with SNe explosions: strong blow-outs and slow Parker outflows. The energy required for a blow-out to occur was recently estimated (Steinacker & Shchekinov 2001) to be

$$E^B_{min} \sim 14\rho c_s^2 H^3 \sim 6\times 10^{53}\ \mathrm{erg}\ n_{0.01} c_{100}^2 H_1^3, \qquad (1)$$

where $n_{0.01}$ is the halo midplane density in 0.01 cm^{-3}, c_{100} the sound speed in the halo in 100 km s^{-1}, and H_1 the halo scale height in 1 kpc. Numerical simulations (Mac Low *et al.,* 1989, Silich *et al.*, 1996) give for the Milky Way an estimate $E^B_{min} \sim$ 1-3$\times 10^{53}$ erg. Thus, if a power-law luminosity function for OB associations (Kennicutt *et al.*, 1989, Heiles 1990, Williams & McKee 1997)

$$N_a(L) = 5.5\left(\frac{475}{L_{49}} - 1\right), \qquad (2)$$

where $N_a(L)$ is the number of associations with ionizing photon luminosity larger than L, $L_{49} = L/(10^{49}\ \mathrm{s}^{-1})$, is

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universal, then only a small fraction (∼ 0.01) of all SNe can contribute to blow-outs. Clustered SNe explosions with a smaller total explosion energy seem to form at initial stages shells (or supershells, depending on the energy input) breaking through the thin cold disk (of thickness $\sim 100-200$ pc), and at later stages are developing as the Parker instability.

2D numerical simulations (Kamaya *et al.,* 1996, Hanasz & Lesch 2000, Steinacker & Shchekinov 2001) demonstrate that a relatively small energy input (equivalent even to a single SN) can already initiate a large scale motion associated with the Parker instability. Therefore it seems that most SNe contribute to the disk-halo connection through the "Parker motions" covering the entire range of vertical scales, from the thin disk to the extended halo. By its nature a Parker instability works to decrease the potential energy of the system, *i.e.,* to bring a "heavy" fluid (gas) downwards. At the same time it opens galactic magnetic field lines and thus provides conditions for a galactic wind to expell cosmic rays (Parker 1965).

3 Dust and radiation

Another effect provided by Parker instabilities addresses the large scale distribution of dust since the resulting magnetic field allows the interstellar radiation field to drive the charged (and therefore coupled) dust into the halos. This process thus allows for "soft" enough conditions for dust particles to survive when they are transported to large distances from the midplane. In principle, the radiation field can even initiate Parker instabilities (as was mentioned first by Ferrara 1998). Indeed, the momentum flux from the interstellar radiation field is

$$\Phi_p = \frac{\Phi_E}{c} \simeq (1.7-5)\times 10^{-13}\ \mathrm{erg\ cm^{-3}}, \tag{3}$$

where $\Phi_E = (5-15)\times 10^{-3}$ erg cm^{-2} s^{-1} is the average radiation flux. In the vicinity of OB associations Φ_E can reach $\sim 5\times 10^{-2}$ erg cm^{-2} s^{-1}, with a corresponding momentum flux $\Phi_p \sim 1.7\times 10^{-12}$ erg cm^{-3}. This value is comparable to the momentum flux from SNe explosions

$$\Phi_p^{SN} = \frac{E}{v_R A_G}\nu_{SN} \simeq 5.8\times 10^{-12}\ \mathrm{erg\ cm^{-3}}, \tag{4}$$

where $E = 10^{51}$ erg is the explosion energy, v_R is the velocity of the remnant when it turns to a radiative stage, A_G is the disk area, $\nu_{SN} \sim (30\ \mathrm{yr})^{-1}$ is the SNe rate. Thus the interstellar radiation field itself could be able to initiate Parker instabilities similar to SNe explosions. The difference though is that radiatively driven dust particles become collisionly decoupled from the gas at heights of about 200 pc from the plane and the expelled material is enriched with dust (Dettmar, Schröer & Shchekinov 2001).

4 Radiocontinuum from blow-out shells

A blowout shell is presumably produced by sequential explosions of SNe in an OB association with the total energy input of $\sim\ 10^{53}$ erg and its structure is determined by a superposition of the energy injected from different massive stars through stellar wind and SNe. At such conditions one can expect injection of nonthermal particles into the shell from winds and subsequent SNe, so that the acceleration of electrons can take place at late stages, although it can not be as efficient as in young SN remnants. One can assume that CRs store approximately a constant fraction of the total explosion energy. At pre-blow-out stages the magnetic field is confined to a relatively thin shell containing most of the swept-out gas. From flux conservation $B/\rho r =$ const (see Chevalier 1999), where ρ is the density in the shell and r its radius, it follows that the magnetic energy is also a constant fraction of the total explosion energy. With these assumptions one can use for a conservative estimate of the surface brightness of a supershell extending far into halo the $\Sigma - D$ relation for radio SNRs. This is, *e.g.,* described in Huang *et al.,* (1994) where they found a cumulative $\Sigma - D$ relation for the Galaxy, the Magellanic Clouds, and M82 which for $\nu = 8.4$ GHz writes as

$$\Sigma_{8.4} \simeq 6.6\times 10^{-16} D_{\mathrm{pc}}^{-3.6}\ \mathrm{W\ Hz^{-1}\ m^{-2}\ sr^{-1}}. \tag{5}$$

[Note, that Loops I–IV have surface brightness of factor of 30 larger than is given by (5), Berkhuijsen 1986]. If one assumes that the energy of relativistic electrons is a constant fraction of the total thermal energy of a remnant than Σ scales with the energy input as $\sim\ E^{(x+5)/4}$ and with frequency as $\sim \nu^{-(x-1)/2}$ (see Huang *et al.,* 1994), where the electrons are assumed to have an energy spectrum in the form $N(\epsilon)d\epsilon \propto \epsilon^{-x}d\epsilon$. Thus, for $x \sim 2-2.5$ and for a blowing-out explosion with $E \sim 10^{53}$ erg one can estimate the surface brightness at $\nu = 1.49$ Hz as

$$\Sigma_{1.49} \simeq (4.9-7,4)\times 10^{-12} D_{\mathrm{pc}}^{-3.6}\mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}, \tag{6}$$

which gives for $D\ =\ 3$ kpc $\Sigma_{1.49}\ \simeq\ (7.8-10)\times 10^{-23}$ comparable to a 3σ level reached in a typical radiocontinuum map such as that for NGC 891 (Dahlem, Dettmar & Hummel 1994) and therefore can be marginally detected as an increased surface brightness.

In order to estimate the total amount of such structures and a characteristic separation between them in an edge-on galaxy, let us assume that the SF rate is proportional to the total number of OB associations in the galaxy. If the observed $\simeq 120$ galactic worms (Koo *et al.,* 1992) represent chimney walls, one can expect for the Milky Way the number of blow-out explosions to be ≃60 [note, that this number is consistent with the number of blow-outs, *i.e.,* explosions with the total energy $1-3\times 10^{53}$ erg, $N_{Bo} \simeq 40-125$, which can be estimated from (2) assuming for an O9 star $L_{49} = 0.2$]. Thus, the number of blow-out supershells in an edge-on galaxy can be found as $N_{Bo} \simeq 60(SFR)_{E-o}/(SFR)_{MW}$, where $(SFR)_{E-o}$ and $(SFR)_{MW}$ are the SF rates in an edge-on galaxy and in the Milky Way, and the projected mean separation between the associated structures is $L \sim R_{E-o}/N_{Bo} \sim 0.02\ R_{E-o}(SFR)_{E-o}/(SFR)_{MW}$.

5 Radiocontinuum from Parker loops

Contrary to the previous case where magnetic field and CR electrons are confined in a relatively thin shell, in an expanding Parker loop they fill the whole volume of an inflating flow so that the corresponding energy densities decrease.

At later stages of a growing Parker instability the characteristic outflow velocity can reach in a hot halo $u \sim 100{-}150$ km s^{-1} (Steinacker & Shchekinov 2001), so the characteristic time of convective transport on scales of 1-3 kpc is 10-30 Myrs. The diffusion time on the same scales can be estimated by using the diffusion coefficient $\kappa \simeq (2-10) \times 10^{27}$ cm^2 s^{-1} given by Lerche & Schlickeiser (1980) and results in 30 Myrs to 1 Gyr. Thus one can neglect the diffusive transport in the growing loop both from the sources inside and outside the loop in comparison with convection. At these conditions the energy density of relativistic electrons varies with the scale of the loop as $\varepsilon \propto D^{-4}$, where D now describes the characteristic size of the Parker loop, and therefore the $\Sigma - D$ relation can be written as (cf. Huang *et al.*, 1994)

$$\Sigma_{8.4} \simeq 6.6 \times 10^{-16} \frac{D_P}{D} D_{\rm pc}^{-3.6} \ {\rm W\ Hz^{-1}\ m^{-2}\ sr^{-1}}, \qquad (7)$$

with D_P being the size of a remnant when the shock-driven expansion turns into the Parker instability. In 2D numerical models (Steinacker & Shchekinov 2001) D_P varies from 200 pc to 500 pc and when the Parker loop extends far into the halo ($D \sim 1-3$ kpc) its surface brightness is several to 10 times less than (5), and several orders of magnitude smaller than (6) for a blowing-out supershell.

The energy-dependent diffusion-convection transport implies a steepening of the energy distribution of electrons (Lerche & Schlickeiser 1980) from $\sim \epsilon^{-x}$ at the source by $\Delta x = (\mu + 1)/2$ where the diffusion coefficient is assumed in the form $\kappa = \kappa_0 \epsilon^\mu$. The break energy ϵ_B depends on the interrelation between the bulk (convective) velocity of CR and κ_0. In a convection-dominated transport within the Parker loop, where as we see above $D \gg D_c = \kappa(\epsilon_B)/u$, the energy distribution will shift to smaller energies as D^{-1}, leaving the shape unchanged. As a result the characteristic synchrotron frequency corresponding to the break, $\nu_c = 16\ B_{\mu{\rm G}} \epsilon^2_{\rm GeV}$ MHz will shift, so that radio-synchrotron emission at higher distances from the plane must show a break at lower frequencies. If we assume that B varies as D^{-1} (as in the 2D model of the Parker instability), we get $\nu_c \propto D^{-3}$. This variation in the break frequency is accompanied in this model with a decrease of the surface brightness as shown above. At a given frequency this results in a steepening of the radiocontinuum with height, as at higher distances the contribution comes from electrons having a steeper energy spectrum. In the Milky Way ϵ_B lies between 1 to 10 GeV, the characteristic frequency is then $\nu_c \simeq 2$ GHz (assuming specifically $\epsilon_B = 5$ GeV, $B = 6\ \mu$G). Applying this to a Parker loop with $D \sim 3$ kpc starting from $D_P = 500$ pc we arrive at $\nu_c \simeq 10$ MHz. If we assume similar conditions for an edge-on galaxy, then observations around $\nu \sim 1$ GHz $< \nu_c(z = 0)$ near the mid-plane will give the slope $(x-1)/2$ (0.75 for $x = 2.5$), while far from the plane at the same frequency which is now $> \nu_c(z = D)$ the slope will be found $(x + \mu)/2$ (> 1.25 for $x = 2.5$).

One should mention in this context a more recent paper by Case & Bhattacharaya (1998), where a much flatter $\Sigma - D$ relation for the Galaxy is found based on new kinematic distances to Galactic SNRs (corresponding to $R_\odot = 8.5$ kpc and $V_\odot = 220$ km s^{-1}) than in (6) with $\Sigma \propto D^{-2.38}$. If this relation is applied to the case of NGC 891 the expected surface brightness can reach 10^{-21} W m^{-2} Hz^{-1} s^{-1} sr^{-1} which is much brighter than the structures seen in this galaxy (Dahlem, Dettmar & Hummel 1994). However, for structures produced by the Parker loop outflow the surface brightness can be roughly estimated as (7) with the scaling factor D_P/D which reduces it to the level detected in NGC 891. Probably this uncertainty can be resolved by observations of the spectral index of the radiocontinuum emission. For blowout supershells we expect the flat spectrum (as in the shell-like SNRs of Chevalier 1999), while in the Parker outflows the spectra must be steeper if the above arguments are correct.

From this point of view it is interesting to note a possible implication with regard to the interpretation of the observed steepening of radio-continuum spectra in NGC 891 and NGC 5775 (Duric, Irwin & Bloemen 1998).

6 Summary

We expect spatial fluctuations in the radiocontinuum emission of CR electrons associated with blow-out events corresponding to the rate of energy input from very large (more than 100 SNe) explosions with characteristic projection distance between the radiocontinuum spots of

$$L \sim 0.02 R_{\rm E-o} \frac{(SFR)_{\rm E-o}}{(SFR)_{\rm MW}}. \qquad (8)$$

The observed smooth distribution in edge-ons comes likely from the Parker loops extending far into the halos, as they provide favorable conditions for the propagation of electrons. If the electrons were transported by strong blow-outs a more patchy distribution should be observed.

If this picture is correct, the spectral index at a given frequency must be increasing with distance from the plane because the characteristic frequency corresponding to a break in the energy spectrum of CR electrons decreases.

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