Time-dependent Galactic Winds Driven by Cosmic Ray Advection and Diffusion

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Abstract

Numerical solutions are discussed for a time-dependent galactic wind driven by advection and diffusion of cosmic rays. In this paper we present the time-asymptotic solutions characterized by different diffusion coefficients ($\bar{\kappa} = 10^{27} - 10^{30}\,\mathrm{cm\,s^{-1}}$) but having the same cosmic rays flux at the inner boundary.

1 Introduction:

From observational facts it is evident that cosmic rays leave our galaxy and therefore this energy flux can be used to drive an outflow if the thermal gas can couple to these streaming particles, e.g. momentum transfer provided by a resonant excitation of MHD waves. Adopting this mechanism it is possible to obtain cosmic ray driven winds (e.g. Ipavich 1975, Breitschwerdt et al. 1987, 1991, 1993) which drive large scale outflows from normal spiral galaxies without invoking a large amount of hot interstellar plasma necessary for a thermal driven wind. However, all these previous models are calculated for stationary situations without diffusion of cosmic rays. It is widely believed that the bulk of the galactic cosmic rays are accelerated in SNRs up to energies of about $10^{15}\,\mathrm{eV/nuc}$. Hence, the SN-rate as well as the location within a galaxy will influence the generation of a galactic winds emerging e.g. above a superbubble produced by an OB-association. Concerning the finite lifetime (of the order of a few $10^7\,\mathrm{years}$) of an OB-association with repeated SN-explosions a galactic wind can be a localized as well as a time-dependent phenomenon. On larger scales, i.e. the case of a star burst or the central regions of a galaxy, the time-dependence has to be taken into account since the typical flow times t_{flow} (see also Table 1) through the wind may largely exceed the time scale driving such a galactic wind. Nevertheless, for normal spiral galaxies these effects may average out over the relevant flow time so that one can discuss the mean properties of galactic winds on a stationary bases.

2 Physical model:

Since the theoretical aspects have been developed in detail by Breitschwerdt et al. (1991,1993 and further references therein) and generalized by the inclusion of a galactic rotation and the tension of a frozen-in magnetic field by Zirakashvili et al. (1996) we will give here only a brief summary of the main features of such galactic wind models. We adopt a given one-dimensional flux-tube geometry to account for the galactic disk structure. The area cross section increases with the distance from the galactic plane z according to

$$A(z) = A_0 \left[1 + \left(\frac{z}{Z_0} \right)^2 \right], \tag{1}$$

where $Z_0 = 15\,\mathrm{kpc}$ is used. The equations of mass and momentum conservation are augmented by three energy equations describing the thermal gas, the cosmic rays and the hydromagnetic wave field in the hydrodynamical limit with $\gamma_{\mathrm{g}} = 5/3$ and $\gamma_{\mathrm{c}} = 4/3$. The mean cosmic ray diffusion coefficient $\bar{\kappa}$ averaged over the particle distribution function, is taken as a free parameter. According to cosmic ray propagation models (e.g. Ginzburg & Ptuskin 1985) this diffusion coefficient is estimated to be of the order of $10^{29}\,\mathrm{cm\,s^{-1}}$. The overall magnetic field follows from flux conservation and the gravitational field is calculated from a bulge-disk mater distribution together with a spherical halo potential truncated at $100\,\mathrm{kpc}$. Radiative losses have been neglected in this study which could alter the overall flow structure (see Breitschwerdt & Schmutzler 1994).

This system of 5 coupled partial differential equations is solved by an implicit numerical method using a conservative scheme on an adaptive grid. Such a procedure allows large time steps and can also calculate the time-asymptotic solutions. Again, details of this numerical strategy are omitted here but the general properties of the method can be found in Dorfi (1998).

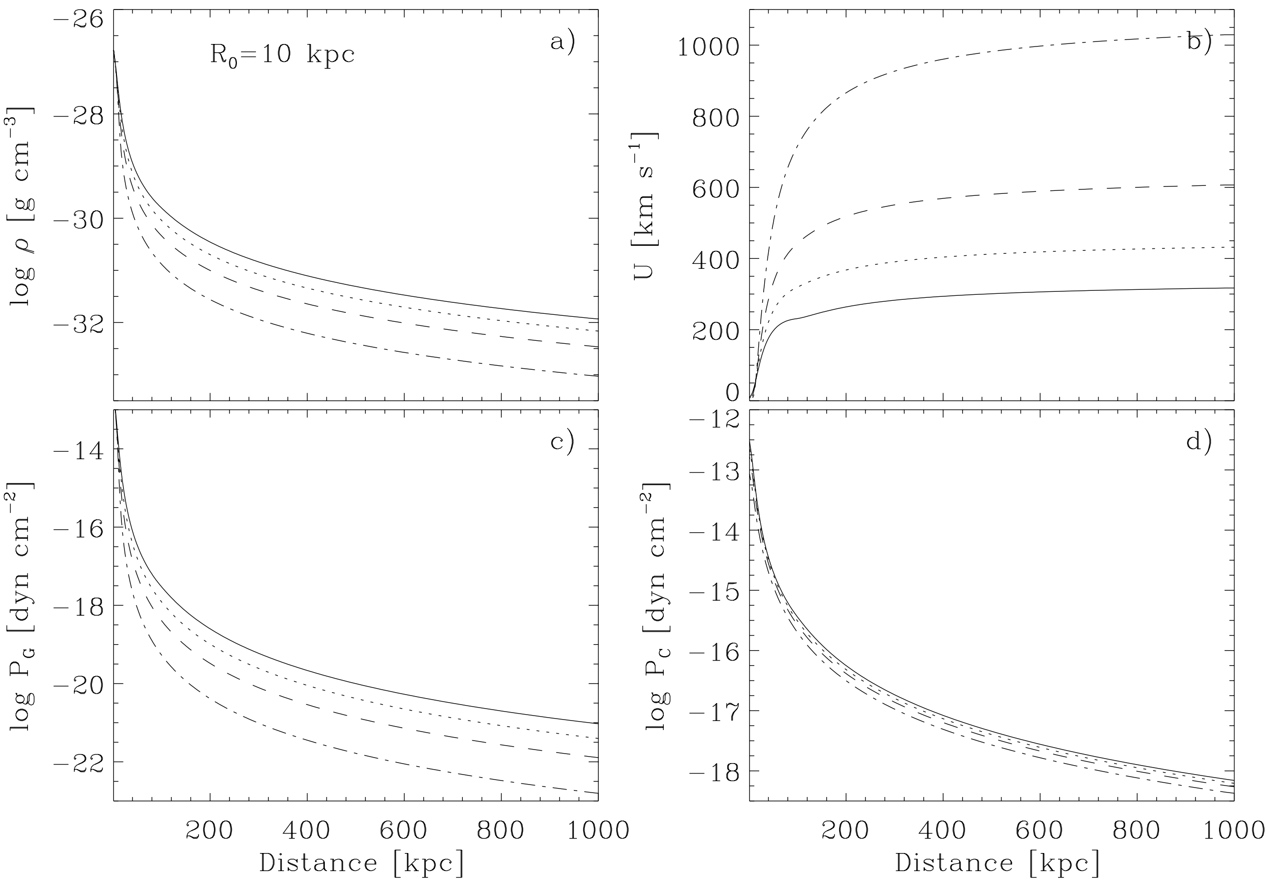

Figure 1: The time-asymptotic flow structure of a galactic wind with different cosmic ray diffusion coefficients $\bar{\kappa}$ between $1\,\mathrm{kpc}$ and $1\,\mathrm{Mpc}$. The case $\bar{\kappa} = 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ (full line) is almost identical to $\bar{\kappa} = 0$, dotted line: $\bar{\kappa} = 10^{29}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, dashed line: $\bar{\kappa} = 3\cdot 10^{29}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, dashed-dotted line: $\bar{\kappa} = 10^{30}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$. a) gas density, b) gas velocity, c) thermal gas pressure, d) cosmic ray pressure.

3 Time-asymptotic results:

3.1 Flow structure: The results plotted in Fig. 1 exhibit the changes of the overall flow structure for different cosmic ray diffusion coefficients $\bar{\kappa} = 10^{27} - 10^{30}\,\mathrm{cm\,s}^{-1}$. We start at a reference level of $1\,\mathrm{kpc}$ and follow the flow up a distance of $1000\,\mathrm{kpc}$. For these computations the numerical parameters correspond to our Galaxy and we kept fixed most quantities at the inner boundary, i.e. the gas density of $\rho_0 = 1.67{\cdot}10^{-27}\mathrm{g\,cm}^{-3}$, the thermal gas pressure $P_{\mathrm{g},0} = 2.8{\cdot}10^{-13}\mathrm{dyne\,cm}^{-2}$, the vertical magnetic field component $B_0 = 1\,\mu\mathrm{G}$ and the initial wave pressure $P_{\mathrm{w},0} = 4{\cdot}10^{-16}\mathrm{dyne\,cm}^{-2}$ which corresponds to magnetic fluctuations at a level of $0.1\,B_0$. In the case of no diffusion ($\bar{\kappa} = 0$) the velocity is determined by critical point (CP) and left as a free inflow boundary for the diffusive cases. To investigate the effect of cosmic ray diffusion we fixed the total cosmic ray flux at the inner boundary through the condition

$$f_{\mathrm{c},0} = \frac{\gamma_\mathrm{c}}{\gamma_\mathrm{c}-1}(u+v_\mathrm{A})P_\mathrm{c} - \frac{\bar{\kappa}}{\gamma_\mathrm{c}-1}\frac{\partial P_\mathrm{c}}{\partial z}, \qquad (2)$$

where u denotes the gas velocity and $v_{\rm A}$ the Alfvén speed, respectively. A value of $f_{\rm c,0} = 10^{-5}\,{\rm erg\,cm^{-2}\,s^{-1}}$ is used. The cosmic ray pressure for the case of no diffusion is given by $P_{\rm c,0} = 3\cdot 10^{-13}{\rm dyn\,cm^{-2}}$. All calculations are performed for a galactocentric distance of the flux tube of $R_0 = 10\,{\rm kpc}$. The outer boundary is stated as an outflow boundary where all gradients vanish.

The numerical solutions are obtained by increasing the value of $\bar\kappa$ starting from the solutions calculated by Breitschwerdt et al. (1991). Taking a typical length scale of $l \simeq 1\,{\rm kpc}$ together with the gas velocity $u_0 \simeq 10\,{\rm km\,s^{-1}}$ we can estimate a minimum diffusion coefficient of $\bar\kappa \simeq l\,u_0 \simeq= 3\cdot 10^{27}\,{\rm cm^2\,s^{-1}}$ which is needed to modify the cosmic ray gradients at the inner boundary (see Table 1). Therefore we can start our investigations with such values of $\bar\kappa$ and calculate a sequence of models with increasing values of $\bar\kappa$. Using the time-dependent equations (discussed in a forthcoming paper) the implicit method allows a relaxation towards a time-asymptotic solution characterized by constantly growing time steps. Technically, we define this limit when the time steps exceeds $1000\,t_{\rm flow}$. We can reach these asymptotic solutions from different starting solutions and therefore it seems plausible that these solutions are stable and (at least locally) unique. Including the second order diffusion term does not alter the overall flow pattern in the time-asymptotic limit and we expect even smoother variations within all variables since the particle pressure gradient is the dominant force driving the outflow. As inferred from Fig. 1 we see that less thermal gas is transported outwards at higher velocities since for a given cosmic ray flux $f_{\rm c,0}$ more particles can escape via diffusion if $\bar\kappa$ is increased. At the base of the flux tube Eq. (2) can only be fulfilled by lowering the gas velocity u as well as the cosmic ray pressure $P_{\rm c,0}$ and stationarity demands a certain balance between these two terms. Actual values of our computations are summarized in Table 1.

3.2 Effects of diffusion: In order to simplify the second order diffusion term Zirakashvili et al. (1996, their Eq. 44) have introduced an effective adiabatic index $g_{\rm eff}$ defined through

$$\frac{g_{\rm eff}}{g_{\rm eff}-1} = \frac{\gamma_{\rm c}}{\gamma_{\rm c}-1} - \frac{\bar\kappa}{\gamma_{\rm c}-1}\frac{\partial P_{\rm c}}{\partial z}\frac{1}{(u+v_{\rm A})P_{\rm c}}. \tag{3}$$

The variation of $g_{\rm eff}$ is depicted in units of $\gamma_{\rm c} = 4/3$ in Fig. 2 and we see that only very small variations within the innermost $20\,{\rm kpc}$ occur through the inclusion of diffusion. Hence, taking $g_{\rm eff}$ constant is a good approximation. Nevertheless, the thermal flow gets accelerated within $100\,{\rm kpc}$ at for values above $\bar\kappa \simeq 10^{28}\,{\rm cm\,s^{-1}}$ no further deceleration of the flow due to the halo potential is observed. At lower distances the flow is accelerated by the gas pressure gradient which suffers more from adiabatic losses than the cosmic rays and the hydromagnetic waves. Since the generation of hydromagnetic waves depends strongly on the cosmic ray gradient we obtain also less wave pressure for larger values of $\bar\kappa$. Since the final velocities can grow up to $1000\,{\rm km\,s^{-1}}$ the flow time up to $1\,{\rm Mpc}$ is also reduced in diffusion dominated winds but the decrease of the initial velocity can compensate this effect leading to a slightly enhanced flow time for a very large amount of diffusion $\bar\kappa \simeq 10^{30}\,{\rm cm\,s^{-1}}$ compared to e.g. $\bar\kappa \simeq 3\cdot 10^{29}\,{\rm cm\,s^{-1}}$.

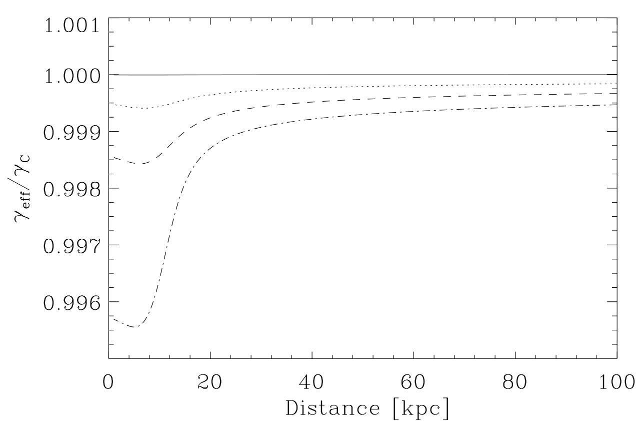

Figure 2: The variation of $g_{\rm eff}$ (see Eq. 3) in units of $\gamma_{\rm c}$ in a galactic winds within the innermost $100\,{\rm kpc}$. For larger distances an asymptotic value of $4/3$ is reached. The various linestyles are identical to those of Fig. 1.

In Table 1 the properties of the galactic wind models are summarized for a number of different diffusion coefficients. Increasing the diffusion coefficient lead to a decrease of the mass loss rate $\dot M/\dot M_0$ up to a

$\bar{\kappa}$ $[\mathrm{cm}^2/\mathrm{s}]$	$\dot{M}/\dot{M}_0$	u_0 $[\mathrm{km/s}]$	u_∞ $[\mathrm{km/s}]$	$P_\mathrm{c}/P_{\mathrm{c},0}$	CP [kpc]	t_flow [Gy]
10^{27}	1.00	9.7	320	1.00	36	2.1
10^{28}	0.98	9.6	330	0.97	35	2.0
10^{29}	0.80	7.8	430	0.78	31	1.6
$3{\cdot}10^{29}$	0.56	5.5	610	0.55	28	1.4
10^{30}	0.26	2.5	1030	0.29	27	1.5

Table 1: Properties of cosmic ray advection/diffusion driven winds.

factor of 4 compared to the case without diffusion $\dot{M}_0$ but the value of $\dot{M}_0$ depends on the value of A_0 (see Eq. (1). The total mass loss rate of a galaxy can only be calculated by computing several flux tubes at different galactocentric distances and integrating them over the entire galactic disk. Since at the inner boundary we have kept fixed the cosmic ray energy flux $f_{\mathrm{c},0}$ the gas velocity u_0 drops there to a value of $2.5\,\mathrm{km\,s^{-2}}$ but the final velocity u_∞ grows to more than $1000\,\mathrm{km\,s^{-1}}$ accompanied by a decrease of distance of the 'critical point' (CP) where the Mach number relative to the compound speed c_* of the three component system of thermal gas, cosmic rays and hydromagnetic waves (see Eq. (17) in Breitschwerdt et al. 1991) exceeds unity. The value of the cosmic ray pressure $P_{\mathrm{c},0}$ at the base of our wind models also decreases when diffusive transport of particles becomes more important. The last column gives the flow time t_flow up to $1\,\mathrm{Mpc}$ in units of Gigayears.

4 Discussion:

The inclusion of a diffusive transport of cosmic rays alters mainly the outflow velocities towards faster winds with lower mass loss rates. Although we have discussed only time-asymptotic solutions for advection/diffusion driven winds the time-dependence plays an important rôle for the overall dynamics of galactic winds. Further computations with time-dependent boundary conditions (presented in a forthcoming paper) show the propagation of shock waves into the outflowing material which are able to accelerate particles through a first order Fermi mechanism. This can lead to cosmic ray gradients directed inwards thereby changing the sign of the Alfvén velocity v_A so that the MHD waves start to travel inwards. In the case of $u < |v_\mathrm{A}|$ cosmic rays get advected back into the galaxy modifying the values at the inner boundary (reference level) located in these computations at $1\,\mathrm{kpc}$. Hence, in the case of time-dependent cosmic ray driven winds it seems necessary to include also the disk-halo interface for a proper galactic wind model.

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