Galactic magnetic fields, cosmic rays and winds

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This lecture reviews recent investigations of the dynamical effects of cosmic rays (CRs) in the interstellar medium of disk galaxies. We focus on the role of CRs for generation of galactic magnetic fields as well as galactic winds. Recent simulation models of magnetised interstellar medium, including the CR gas described by the diffusion-advection equation, indicate that cosmic rays accelerated in supernova remnants play a significant role as drivers of magnetic field amplification in galaxies. It has been demonstrated that weak dipolar magnetic fields supplied on small SN-remnant scales can be amplified exponentially, by the CR-driven dynamo, to the present equipartition values, and transformed simultaneously to large galactic-scales. The resulting magnetic field structure in an evolved galaxy appears spiral in the face-on view and reveals a so called X-shaped structure in the edge-on view. Those X-shaped structures in synchrotron radio maps result from the advection of disk magnetic fields by galactic winds. Driven by the additional pressure gradient of the CR relativistic fluid, the wind speed can exceed the escape velocity of the galaxy. The global mass loading, i.e. the ratio of the mass of gas leaving the galactic disk in the CR-driven wind to the star formation rate, becomes of order unity. These winds help in explaining the low efficiencies for the conversion of gas into stars in galaxies, as well as the early enrichment of the intergalactic medium with metals.

1 Introduction

Galactic magnetic fields observed through radio-observations in the Milky Way and in other galaxies (e.g. Vallée, 2011; Beck, 2016) are commonly interpreted as the result of the turbulent dynamo process (Parker, 1955, 1971; Ruzmaikin et al., 1988; Beck et al., 1996). (For a comprehensive review see also Widrow, 2002, and references therein).

Two types of dynamos are discussed in the general astrophysical context: (1) large-scale (mean field) dynamos, producing coherent (regular) magnetic fields on length scales much larger than the scales of the energy-carrying turbulent eddies, and (2) small-scale (fluctuation) dynamos resulting in amplification of turbulent magnetic fields on timescales of the order of the eddy turnover time and length-scales smaller than the scales of energy-carrying eddies. Galactic magnetic fields appear coherent over scales of several kpc, therefore large-scale dynamos are considered as a plausible amplification mechanism in disk galaxies.

The mean-field galactic dynamo model, referred to as the $\alpha-\omega$-dynamo, describes the amplification of the large-scale magnetic field through helical turbulence (α-effect) and differential rotation (ω-effect). The radial magnetic field component $B_{\rm r}$ is generated from the azimuthal component B_φ by helical turbulence and B_φ is generated from $B_{\rm r}$ by the shearing arising from galactic differential rotation.

Dynamos require, however, seed magnetic fields resulting from other physical processes. Various mechanisms operating prior to galaxy formation provide rather weak magnetic fields of strengths $\leq 10^{-19}$G. The Biermann battery, acting during galaxy formation, can generate magnetic fields of the order of 10^{-21}G on a scale of 10–20 kpc. On the other hand, Syrovatskii (1970); Bisnovatyi-Kogan et al. (1973); Rees (1987) proposed that the first generation of stars provide initial magnetic fields of an average strength of 10^{-9}G. Similar magnetic fields are expected from the first AGNs Rees (2006).

Models of magnetic field amplification relying on numerical simulation techniques, developed over the last decade, attempt to overcome the limitations of the mean field dynamo models. Wang & Abel Wang & Abel (2009) investigated magnetic field amplification during the gravitational collapse of a protogalactic cloud. They imposed a uniform seed field of 10^{-9}G and found growth of the field to μG level in $\sim$ 500Myr, during the disk formation phase. They found that after saturation the toroidal field in the disk dominates over the vertical component, while in the magnetised halo, the vertical component dominates over the toroidal one. Likewise, Beck et al. (2012) examined magnetic field amplification by a turbulent small-scale dynamo during the formation phase of a spherically symmetric galactic halo. They assumed a primordial seed field of 10^{-18}G and observed the agglomeration of magnetic fields together with the gas within filaments and protohaloes, where it is amplified within a couple of hundred million years up to equipartition with the turbulent energy. The turbulence is generated by the gravitational collapse and by supernova feedback. Magnetic field strengths of $\simeq 10^{-6}$G are reached in the centre of the halo and drop to $\simeq 10^{-9}$G in the intergalactic medium.

On the other hand, Kotarba et al. (2011) studied magnetic field evolution by means of SPH/N-body simulations of galaxy collisions. They took into account various physical processes such as SN feedback, radiative cooling and star formation. Their initial setup consists of two, three, and more galaxies, whose dynamical parameters are adopted to permit subsequent mergers. By assumption of initial magnetic fields in the range $10^{-9} - 10^{-6}\mu$G in the interstellar medium (ISM) and $10^{-12} - 10^{-9}\mu$G in the intergalactic medium (IGM), they find the growth of magnetic fields up to values of 1μG within the galaxies and $10^{-2}\mu$G in the IGM. They find that galactic interactions are efficient drivers of magnetic field amplification.

Mac Low & Klessen (2004) have shown that supernovae are the dominant source of turbulence energy in the ISM. This result indicates that supernova activity can be the main driver of the turbulent dynamo action in galaxies. Indeed, the results of radio-continuum observations Chyży (2008) provide evidence for a correlation between the strength of turbulent components of interstellar magnetic fields and the star formation rate (SFR). On the other hand the FIR-radio correlation for a sample of galaxies Bell (2003) clearly shows that generation processes of galactic magnetic fields are controlled by the star formation (Beck, 2012).

An example of SN-driven magnetic field amplification has been demonstrated through MHD simulation models by Gressel et al. (2008a,b, 2011). These authors take into account vertical stratification of the disk, sheared galactic rotation, effects of shock heating and cooling processes of the ISM and performed direct MHD simulations of a local 3D patch of interstellar medium. As a result they observe exponential growth of the regular magnetic field. Moreover, they show that the amplification process is consistent with the $\alpha\omega$-dynamo model.

The models of magnetic field amplification described above neglect, however, the dynamical role of cosmic rays, one of the most energetic constituents of the ISM. It is known, on the other hand, that cosmic rays significantly affect conditions for the onset of buoyancy instability and for galactic wind launching from the gravitationally stratified ISM. The aim of this lecture is to introduce the basic properties of cosmic rays in the ISM in Sect. 2 and then to discuss CR-driven galactic magnetic field amplification in Sect. 3 and finally to describe the CR-driven galactic winds in Sect. 4.

2 Cosmic rays in the ISM

The cosmic ray (CR) gas consists of relativistic high-energy protons, electrons and heavier atomic nuclei. CR spectra have been measured over many decades of energy from $E_{CR} \sim 10^{7}$eV up to energies of $E_{CR} \sim 10^{20}$eV. As the galactic CR energy spectrum is rather steep with $P \propto E^{-2.7}$, the majority of the energy is deposited at lower energies with a peak at around 1 GeV, which is the expected range of significant dynamical impact of CRs on the ISM in galaxies. The main acceleration mechanism for galactic CRs, in particular those below the 'knee' in the CR spectrum is considered to be diffusive shock acceleration (DSA, see e.g. Blandford & Ostriker, 1978) and non-linear DSA (Malkov & Drury, 2001) in shocks of supernova remnants (SNR) (see Hillas, 2005; Ackermann et al., 2013, for a review and recent observations). Measurements from instrumented balloons and satellites have shown that CRs comprise relativistic particles: protons, $\approx 10\%$ helium nuclei, $\approx 1\%$ heavier nuclei, $\approx 2\%$ electrons, and smaller amounts of positrons and antiprotons ((Blandford & Eichler, 1987; Bloemen, 1987). The abundances of CR nucleons are similar to the abundances in the solar system, which means that CRs are accelerated in stellar environments.

On macroscopic scales CRs can be described as a hot, relativistic gas which exerts pressure on the ISM, while its mass density is practically negligible. Theories of diffusive shock acceleration predict that about 10% of the SN II explosion energy is converted to CR energy. The dynamical role of CRs was recognised by Parker (1966), who noticed that vertically stratified ISM which consists of thermal gas, magnetic fields and CRs is dynamically unstable due to buoyancy of magnetic fields and CRs. If a significant fraction of energy provided by supernova explosions is 'stored' in cosmic rays it can be carried over large distances and significantly impact the ISM, provided the coupling between CRs and the thermal gas is strong enough (e.g. Breitschwerdt et al., 1991; Ptuskin et al., 1997). Dorfi & Breitschwerdt (2012) as well as other authors argue that CRs will always take part in the acceleration of outflows from galactic disks.

Observational data indicate that gas, magnetic fields and CRs appear in approximate energetic equipartition (Zweibel & Heiles, 1997). The fact that CRs escape from the Galaxy after a few tens of million years on average, setting up a pressure gradient pointing away from the disk, gives rise to the resonant excitation of MHD waves via the so-called CR streaming instability (e.g. Kulsrud & Pearce, 1969). Thus CRs are coupled to the thermal plasma by scattering off the frozen-in waves, thereby helping to push the plasma against the gravitational pull.

CR transport in the Galaxy at energies below approximately 10^{17} eV can be described by the diffusion-advection model based on the Focker-Planck equation (see the reviews by Blandford & Eichler, 1987; Strong et al., 2007). On the microscopic level, the diffusion of CRs results from particle scattering on random MHD waves and discontinuities. The resulting spatial diffusion is strongly anisotropic and is aligned with the direction of the magnetic field (see e.g. Jokipii, 1999).

Integration of CR kinetic energies over the whole range of particle momenta leads to the following macroscopic transport equation (Schlickeiser & Lerche, 1985)

$$\frac{\partial e_{\rm cr}}{\partial t} + \boldsymbol{\nabla}(e_{\rm cr}\boldsymbol{v}) = -p_{\rm cr}\boldsymbol{\nabla}\boldsymbol{v} + \boldsymbol{\nabla}(\hat{K}\boldsymbol{\nabla}e_{\rm cr}) + S_{\rm cr}, \tag{1}$$

where $e_{\rm cr}$ and $p_{\rm cr}$ are respectively the CR energy density and pressure, $\boldsymbol{v}$ is the gas velocity, $\hat{K}$ is the CR diffusion tensor and $S_{\rm cr}$ represents CR sources, such as supernova remnants. The cosmic ray pressure $p_{\rm cr}$ is given as

$$p_{\rm cr} = (\gamma_{\rm cr} - 1)e_{\rm cr}, \tag{2}$$

where $e_{\rm cr}$ is the cosmic ray energy density. The adiabatic index of CR relativistic gas is $\gamma_{\rm cr} = 4/3$, although $\gamma_{\rm cr} = 14/9$ is sometimes adopted for the GeV energy range (e.g. Ryu et al., 2003; Hanasz et al., 2009a). The convenient form of the diffusion tensor, providing anisotropic diffusion of CRs along magnetic field-lines, is

$$K_{ij} = K_{\perp}\delta_{ij} + (K_{\parallel} - K_{\perp})n_i n_j, \quad n_i = B_i/B. \tag{3}$$

The value of the parallel (field aligned) cosmic ray diffusion coefficient, fitted to observational data, is $K_{\parallel} \simeq (3 \div 5) \cdot 10^{28}\,{\rm cm}^2{\rm s}^{-1}$ (Strong et al., 2007) and the expected perpendicular component is a few percent of the parallel one (e.g. Jokipii, 1999).

The full set of equations describing cosmic rays coupled to the magnetised fluid contains the set of MHD equations and the CR transport equation. Elementary derivations and basic physical properties of MHD equations can be found in popular textbooks of classical electrodynamics (e.g. Jackson, 1999) and in introductory courses of plasma astrophysics (e.g. Choudhuri, 1998). The presence of a separate population of relativistic charged particles coupled to the classical magneto-fluid implies that the gradient of CR pressure should be included in the gas equation of motion (see e.g. Berezinskii et al., 1990).

The set of magnetohydrodynamic (MHD) equations supplementing the CR transport equation can be written in the following form

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v} = -\frac{1}{\rho}\boldsymbol{\nabla}(p_{\rm g}{+}p_{\rm cr}) \;+ \frac{1}{\rho}\nabla\left(\frac{B^2}{8\pi}\right) + \frac{\boldsymbol{B}\cdot\boldsymbol{\nabla}\boldsymbol{B}}{4\pi\rho} - \boldsymbol{\nabla}\Phi, \tag{4}$$

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) = 0, \tag{5}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B}){+}\eta\nabla^2 B, \tag{6}$$

where ρ, $\boldsymbol{v}$, $p_{\rm g}$ denote respectively the density, velocity and pressure of the thermal gas, $p_{\rm cr}$ is the cosmic ray pressure, Φ is the gravitational potential, $\boldsymbol{B}$ magnetic induction and η represents the magnetic diffusivity. It is natural to assume the magnetic diffusivity in the induction equation (6) is of the same order as the turbulent diffusivity $\eta_{turb} \sim 3 \cdot 10^{25}\,{\rm cm}^2{\rm s}^{-1}$ of the ISM (see e.g. Hanasz et al., 2009a).

In the following considerations we neglect the thermal effects of SN explosions and adopt the isothermal equation of state

$$p_{\rm g} = c_s^2\rho, \tag{7}$$

with typical sound speeds c_s of the order of $10\,{\rm km\ s}^{-1}$. An appropriate energy equation incorporating cooling and heating processes (see Girichidis et al., 2016) can be used to extend the model with thermal effects of SN shocks. To model dynamical effects of CRs in evolving galactic magnetic fields a new algorithm, incorporating anisotropic diffusion of CRs, has been implemented into ZEUS MHD code (Hanasz & Lesch, 2003) and subsequently developed in the grid MHD code PIERNIK (Hanasz et al., 2010a,b, 2012a,b).

3 Cosmic-Ray-driven dynamo

3.1 Model assumptions

The idea of CR-driven dynamo was originally raised by Parker (1992), who postulated that buoyancy of CRs together with Coriolis-force, galactic differential rotation and magnetic reconnection lead to efficient amplification of galactic magnetic fields.

First MHD numerical simulation models (Hanasz et al., 2004, 2006, 2009a) of CR-driven dynamo were realised in a local, rectangular patch of galactic disk with shearing boundary conditions and rotational pseudo-forces (tidal and Coriolis forces) incorporated to study magnetic field evolution in a rotating galactic disk. Subsequent development of numerical algorithms and increasing availability of high performance computing resources made it possible to perform numerical simulations of the CR-driven dynamo on global galactic scales.

The first global CR-driven dynamo model presented by Hanasz et al. (2009b) assumes that: (1) CRs are supplied in SN remnants. The CR input of individual SNe is assumed to be 10% of the typical SN kinetic energy output ($= 10^{51}$erg), while the thermal energy output from SNe is neglected. (2) The magnetic field is absent or negligible at the beginning of galactic evolution, and weak ($10^{-4}\mu$G), small scale ($r \sim 50$pc), randomly oriented magnetic dipoles are supplied in 10% of remnants that represent plerionic type (such as Crab nebula) SN remnants. (3) The initial gas distribution follows the global Milky Way model by Ferrière (1998). (4) Differential rotation of the interstellar gas results from an assumed analytical model of an axisymmetric galactic gravitational potential (e.g. Allen & Santillan, 1991) or from a live N-body galactic disk, bulge and dark matter halo system (Wółtański, 2015; Wółtański et al., 2017).

3.2 CR-driven dynamo simulations

Magnetic field amplification originating from the small-scale, randomly oriented dipolar magnetic fields is apparent through the exponential growth by several orders of magnitude of both the magnetic flux and the magnetic energy (for details see Hanasz et al., 2009b). The growth of magnetic field saturates at about $t = 4$Gyr, reaching values of $3 - 5\mu$G in the disk. During the amplification phase, magnetic flux and total magnetic energy grow by about 6 and 10 orders of magnitude, respectively. The average e-folding time of magnetic flux amplification is approximately equal to 270Myr, corresponding to the rotation at the galactocentric radius (≈ 10kpc). The magnetic field is initially chaotic, as shown in Fig. 1, since it originates from randomly oriented magnetic dipoles. Later on, the toroidal magnetic field component forms a spiral structure revealing reversals in the plane of the disk. Magnetic field structure evolves gradually by increasing its correlation scale. The toroidal magnetic field component becomes almost uniform inside the disk around $t = 2.5$Gyr. The volume occupied by the well-ordered magnetic field expands continuously until the end of the simulation.

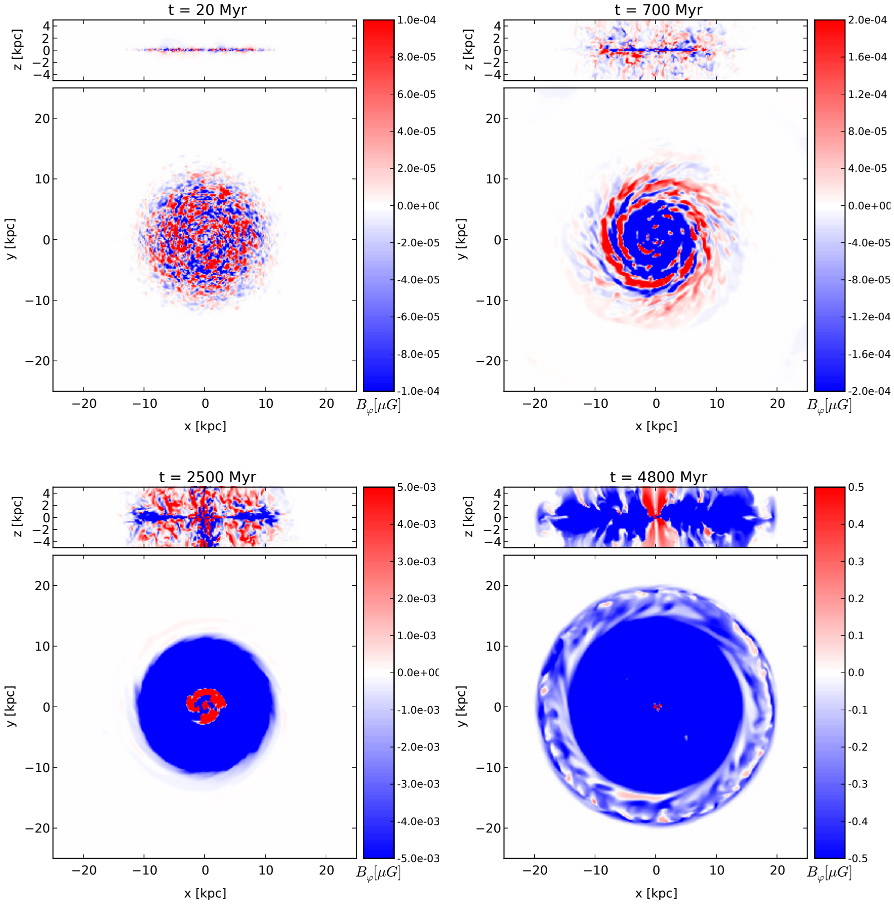

Fig. 1: Distribution of toroidal magnetic field at t = 20Myr (top-left), t = 700Myr (top-right), t = 2.5Gyr (bottom-left), and t = 4.8Gyr (bottom-right). Unmagnetised regions of the volume are white, while positive and negative toroidal magnetic fields are marked with red and blue respectively. Note that the colour scale in magnetic field maps is saturated to enhance weaker magnetic field structures in disk peripheries. The maximum magnetic field strength are $5.9 \cdot 10^{-4}$, $4.4 \cdot 10^{-3}$, 1.5 and 29 μG at $t = 0.02$, 0.7, 2.5 and 4.8Gyr respectively.

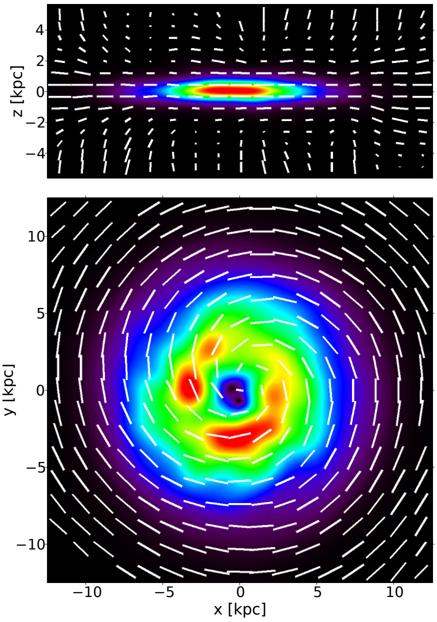

Fig. 2: Synthetic radio maps of polarised intensity (PI) of synchrotron emission, together with polarisation vectors are shown for the edge-on and face-on views of the galaxy at $t = 4.8$Myr. The vectors' directions resemble electric vectors rotated by 90°, and their lengths are proportional to the degree of polarisation.

In order to visualise the magnetic field structure in a manner resembling radio observations of external galaxies, synthetic radio maps of the synchrotron radio-emission are constructed. It is assumed that energy density of CR electrons equals 1% energy density of CR nucleons. The polarised intensity of synchrotron emission is shown in Fig. 1 together with polarisation vectors. Electric vectors, computed on the basis of integrated Stokes parameters, are rotated by 90° to reproduce the magnetic field direction projected onto the plane of sky. Faraday rotation effects are neglected. Polarisation vectors, indicating the mean magnetic field direction, reveal a regular spiral structure in the face-on view, and the so-called *X-shaped structure* is present in the edge-on view. A particular similarity can be noticed between the edge-on synthetic radio map and the radio maps of observed edge-on galaxies such as NGC 891 (Krause, 2009). In the present global model, the X-shaped configuration is an intrinsic property of the magnetic field structure, since it corresponds closely to the flaring radial distribution of magnetic field in the disk and its neighbourhood, as shown in Figure 1.

Face-on synchrotron radio maps reveal a spiral structure of the magnetic field, however, due to the assumed axisymmetric gravitational potential no features resembling spiral magnetic arms are present. To make the model more realistic, a non-axisymmetric component of the gravitational potential has been introduced by using two different approaches. The first one relies on the addition of an analytical elliptical perturbation to the axisymmetric gravitational potential (Kulpa-Dybeł et al., 2011). In presence of the bar perturbation the CR-driven dynamo reveals new properties, such as the presence of a ring-like structure as well as a shift of the magnetic arms with respect to the crests of spiral density waves.

As a further step towards more realistic galactic magnetic field models (Wółtański, 2015) performed N-body simulations of a disk-bulge-halo system with the VINE code (Wetzstein et al., 2009), and the corresponding CR and MHD simulations with the PIERNIK code. Spiral density waves are excited in the disk by the addition of a small satellite galaxy. Similarly to the former case of a galaxy rotating in the axisymmetric gravitational potential, amplification of magnetic flux by the CR-driven dynamo leads to saturation of the large-scale magnetic field component around 10μG with local maxima in the range of $20 - 30\mu$G, located near the spiral crests of gas density. The magnetic field vectors become parallel to the gaseous spiral arms as is observed in real galaxies (Fletcher et al., 2011).

Wółtański (2015) and Wółtański et al. (2017) find, in accordance with the previously studied cases of barred galaxies (Kulpa-Dybeł et al., 2011, 2015), that the strongest magnetic fields tend to reside in between gaseous spiral arms. These features resemble magnetic arms observed in NGC 6946 (Beck, 2007) and IC 343 (Beck, 2015).

The edge-on synchrotron radio maps of the galaxy exhibit polarised synchrotron emission, extending several kiloparsecs above and below the disk plane, which indicates intense magnetic field transport out of the disk by the global CR-driven galactic wind. Similar structures are common in radio-images of edge on galaxies (see e.g Krause, 2009; Soida et al., 2011; Mora & Krause, 2013). It turns out that the X-type structures are present in all global models of CR-driven galactic dynamo (Hanasz et al., 2009b; Kulpa-Dybeł et al., 2011, 2015).

4 Cosmic-ray driven galactic winds

Star-forming galaxies drive powerful galactic winds which can transport a significant fraction of the gas away from the central galaxy making it temporarily unavailable for star formation. Spatially resolved high-redshift observations indicate that these winds are launched directly from the sites of typically strongly-clustered star formation (Genzel et al., 2011; Newman et al., 2012a,b). The estimated outflow rates $\dot{M}_{\rm out}$ can be several times higher than the star formation rates (SFRs). The resulting high mass loading $\eta = \dot{M}_{\rm out}/{\rm SFR}$ indicates that, even at the peak epoch of cosmic star formation, the amount of gas expelled from the galaxies is comparable to the amount of gas converted into stars inside the galaxies.

A number of physical processes are, in principle, energetic enough to expel gas from star-forming galactic disks. Besides active galactic nuclei for high mass galaxies (Croton et al., 2006), type II supernovae have long been considered the most promising candidates, in particular for lower mass galaxies (Larson, 1974; Dekel & Silk, 1986). Although the amount of energy per event is significant, the thermal energy is mainly deposited at the sites of star formation, i.e. dense molecular clouds. Here the cooling times are very short and the energy can be efficiently radiated away, making it difficult, but not impossible, to drive large scale galactic winds (for recent discussions, see, e.g., Brook et al., 2011; Dalla Vecchia & Schaye, 2012). However, even before the supernova explosions, the momentum and energy input from massive stars in the form of stellar winds and stellar luminosity is significant and might support the driving of the wind (Murray et al., 2005; Hopkins et al., 2012; Agertz et al., 2013).

As supernovae drive strong shocks into the interstellar medium (ISM), some fraction of the explosion energy is consumed to accelerate ionised particles to relativistic energies, which are then injected into the ISM as CRs (Krymskii, 1977; Bell, 1978;

Blandford & Ostriker, 1978). This relativistic fluid is coupled to the galactic magnetic field and, in particular the hadronic component, is less prone to energy losses than the gaseous component of the ISM.

The concept of CR wind driving has been put forward by Ipavich (1975) and developed by numerous authors including Breitschwerdt et al. (1991, 1993, 2002); Uhlig et al. (2012); Dorfi & Breitschwerdt (2012), who find that CRs together with magnetic fields and thermal pressure can contribute to the galactic winds phenomenon. Everett et al. (2008) apply a wind model, driven by combined cosmic-ray and thermal-gas pressure, to the Milky Way, and show that the observed Galactic diffuse soft X-ray emission can be better explained by a wind than by previous static gas models. They find that cosmic-ray pressure is essential to driving the observed wind.

CRs are strongly coupled to magnetic fields and their mutual interaction should be followed in a self-consistent way. Hanasz et al. (2004, 2009b), Siejkowski et al. (2010), and Kulpa-Dybeł et al. (2011) have shown that CRs promote buoyancy effects in the ISM, leading to the break-out of magnetic fields from galactic disks (Parker, 1992) and, at the same time, to magnetic field amplification by the buoyancy driven dynamo action. Plausibly, such processes are also relevant for star-forming galaxies at high redshift which are observed to have significant magnetic fields at the level of tens of μG (Bernet et al., 2008). Recent observations even demonstrate the existence of large magnetic fields up 50 kpc away from the galaxy, indicating strong large-scale magnetised winds (Bernet et al., 2013).

An example of CR-driven wind model in a massive, young, gas reach galaxy similar to the Milky Way at $z = 2$, was described by Hanasz et al. (2013). To recognise the pure action of CRs the gaseous disk was assumed to consist of (1) isothermal gas, with fresh gas supplied to the disk at a fixed rate $\dot{M}_{in} = 100\,\mathrm{M}_{\odot}\mathrm{yr}^{-1}$, and (2) a toroidal magnetic field $B_0 = 3\mu$G present in the initial state.

Self-gravity of the gaseous disk is taken into account and the star formation rate is assumed to fulfil the standard formula (see e.g. Mac Low & Klessen, 2004)

$$\dot{\rho}_{\mathrm{sfr}} \simeq \epsilon_{\mathrm{sf}} \frac{\rho}{\tau_{\mathrm{ff}}} \simeq \epsilon_{\mathrm{ff}} \sqrt{\frac{G\rho^3}{32\pi}} \propto \rho^{3/2} \quad \text{if} \quad \rho > \rho_{\mathrm{crit}}, \tag{8}$$

where $\tau_{\mathrm{ff}} = \sqrt{\frac{32\pi}{G\rho}}$ is the free-fall time and $\rho_{\mathrm{crit}} = 600\mathrm{cm}^{-3}$ is the threshold density above which star formation activates. The free parameter $\epsilon_{\mathrm{sf}} = 0.1$ is the star formation efficiency.

It is assumed, moreover, that massive stars explode as supernovae at the rate of 1 SN per $100\,\mathrm{M}_{\odot}$ of the gas mass converted to stars and that 10% of SN energy ($E_{SN} \simeq 10^{51}$erg) is converted into CRs. The local increment of CR energy due to current SN activity

$$\Delta e_{\mathrm{CR}} = 0.1 E_{\mathrm{SN}}\, \dot{\rho}_{\mathrm{SFR}}\, \Delta t \tag{9}$$

is added to a grid cell if $\rho > \rho_{\mathrm{crit}}$. Simulations of galactic wind driving by CRs produced in SN remnants were performed with the aid of the PIERNIK code (see Hanasz et al., 2010a,b, 2012a,b) in a computational box of $(100\mathrm{kpc})^3$ divided into 512^3 grid cells.

The galactic disk collected gas at the presumed global infall rate $\dot{M}_{\mathrm{in}}$ until it became locally gravitationally unstable. Supernovae started to explode and accelerate CRs in the ISM. After about $t \simeq 300$Myr the disk reached an equilibrium state with a SFR at a level of $\simeq 40 M_{\odot}\mathrm{Myr}^{-1}$. A typical snapshot of the system after 600Myr of evolution is shown in Figure 3. Most of the supernovae activity is confined to isolated

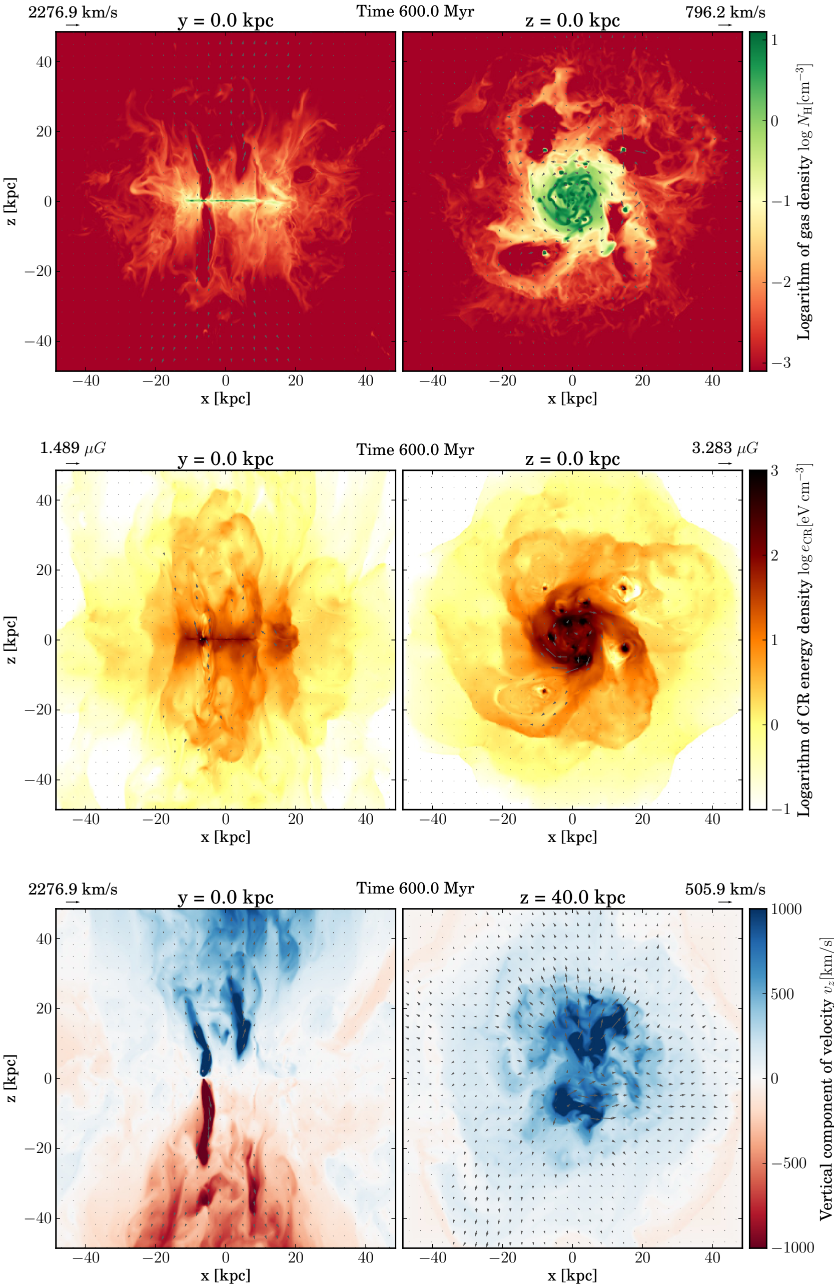

Fig. 3: Vertical (left column) and horizontal slices (right column) through the disk volume. Upper row panels: logarithm of gas density and velocity vectors at t = 600Myr. Dense gas blobs hosting star formation regions are apparent at the horizontal slice through the disk. Mid row panels: logarithm of CR energy density. The high concentration of CRs in the horizontal plane coincides with the star-forming clouds. Lower row panels: vertical component of the velocity. Narrow streams of high-velocity rarefied gas extend several 10 kpc above and below the disk. The relation of high velocity streams to the underlying star formation regions is apparent.

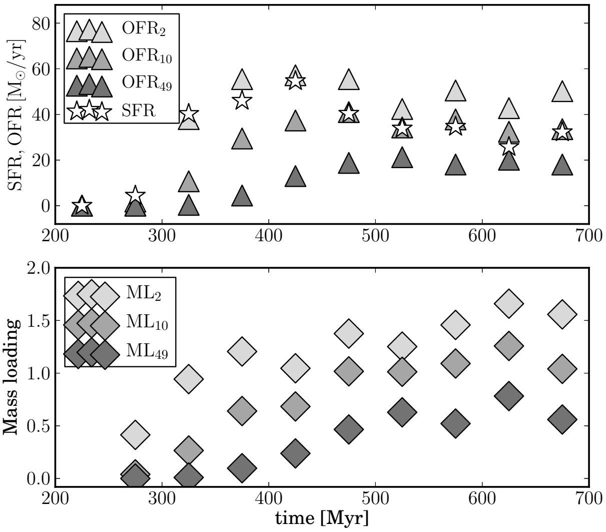

Fig. 4: Upper panel: SFR and mass outflow rate (above and below the disk) at three different altitudes of $z = \pm 2$kpc, ± 10kpc, and $z = \pm 49$kpc and binned in time intervals of 50Myr. Lower panel: the corresponding mass loading factors of order unity indicate significant outflow from the disk into the galactic halo.

regions in kpc-sized dense gas clouds (upper right panel). These regions coincide with spots of high CR energy density apparent as dark brown and black patches in the face-on map (lower right panel of Figure 3).

The vertical streams of rarefied gas visible in gas density distribution (upper–left panel) and in vertical velocity (lower–left panel of Figure 3) are accelerated, by CRs, to high velocities exceeding $10^3\,\mathrm{km\,s^{-1}}$. The streams extend to several tens of kpc above and below the disk plane and a significant fraction of the outflowing gas exceed the escape velocity.

In Figure 4 the evolution of the SFR and the integrated outflow rates are shown at different altitudes at $z = 2$kpc, 10kpc, and 49kpc above the disk plane. After about 400 Myr the SFR settles to a value of $\dot{M}_{\mathrm{SFR}} \sim 40 M_\odot \mathrm{yr}^{-1}$. The mean surface density of disk gas within the radius 10 kpc reaches an equilibrium value of $\sim 100 M_\odot \mathrm{pc}^{-2}$ and the SFR surface density is $\sim 10^{-1} M_\odot \mathrm{yr}^{-1}\mathrm{kpc}^{-2}$. These values are in good agreement with nearby highly star forming galaxies and typical massive high-redshift disks (Kennicutt, 1998; Tacconi et al., 2013). At about 10kpc away from the disk plane the mass outflow rate matches the SFR and the galaxy average mass-loading $\eta = \dot{M}_{\mathrm{out}}/\mathrm{SFR}$ becomes of order unity. Closer to the disk plane the mass-loading is higher $\eta \sim 1.5$ and further away from the disk plane it is still significant. It only decreases to values of $\eta \sim 0.5$.

It has been demonstrated as a proof of principle that the injection of only 10% of supernova energy in the form of CRs and neglecting the thermal and kinetic energy input is sufficient to drive a large-scale galactic wind in a gas-rich and highly star-forming disk with properties similar to typical star-forming high-redshift galaxies. The additional pressure gradient of the relativistic fluid, which in contrast to heated dense gas cannot easily dissipate its energy away, drives the formation of a strong bi-polar galactic wind with velocities exceeding $10^3\,\mathrm{km\,s^{-1}}$. CRs can easily escape far from dense regions with almost negligible energy losses and deposit their energy and momentum in rarefied medium. This process is supported by the CR driven break-out of field lines whose vertically open structure is maintained by the wind. CRs can rapidly diffuse along these field lines far into the galactic halo.

The interpretation of the CR wind driving mechanism can be attributed to the additional pressure gradient due to cosmic rays (Booth et al., 2013; Hanasz et al., 2013; Salem & Bryan, 2014; Simpson et al., 2016). The diffusive nature of CRs implies that the strongest vertical acceleration of gas can take place in low gas density regions above and below the dense star forming clouds.

The CR driving is so significant that the mass outflow rate can become of the same order as the SFR in the galactic disk, even in our simplified setup where thermal as well as kinetic feedback from stellar evolution and supernovae have been neglected entirely. Based on our simulations we can conclude that relativistic particles accelerated in supernova remnants in combination with strong magnetic fields (typical for high-redshift galaxies; Bernet et al., 2008) provide a natural and efficient mechanism to help explain the ubiquitously observed mass-loaded galactic winds in high-redshift galaxies (e.g., Shapley et al., 2003; Newman et al., 2012a) as well as the highly magnetised medium surrounding these galaxies (Bernet et al., 2013).

5 Summary

In this lecture we reviewed some of the recent developments in modelling of dynamical effects of CRs onto ISM of disk galaxies. We focussed in particular on the CR-driven dynamo model that is capable of amplifying the regular galactic magnetic fields on the timescale of galactic rotation. Consistently with the radio observations, the CR-driven dynamo model predicts arms of stronger regular magnetic fields in between the gaseous spiral arms. Moreover, CRs are powerful enough to drive galactic winds that can exceed the escape velocity from the galaxy. The X-shaped structures observed in synchrotron radio maps of edge-on galaxies can be explained within the CR-driven dynamo model as the result of magnetic field advection by the galactic winds. The mass loss rates of CR-driven winds are comparable to star formation rate. These winds help in explaining the low efficiencies for the conversion of gas into stars in galaxies, as well as the early enrichment of the intergalactic medium with metals. This mechanism may be at least of similar importance to the traditionally considered momentum feedback from massive stars and thermal and kinetic feedback from supernova explosions. This implies that CRs may play a significant role in galaxy evolution.

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