Cosmic-ray driven winds from high-redshift disk galaxies

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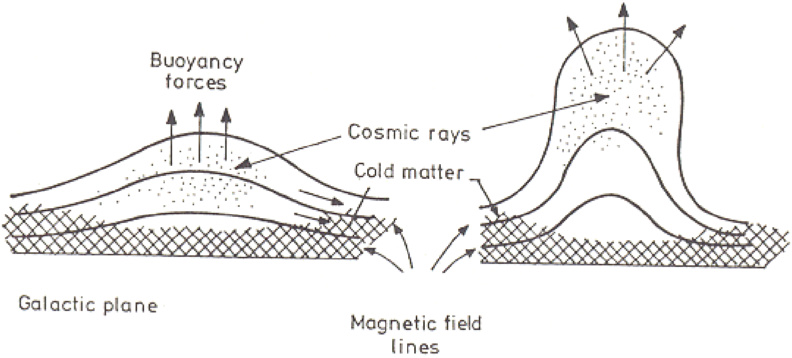
COSMIC RAY GAS

CHARGED PARTICLES : PROTONS, ELECTRONS, ATOMIC NUCLEI ACCELERATED TO RELATIVISTIC ENERGIES.

Evidence for:

- power-law ($E^{-2.7}$) spectrum from $\sim 10^9$eV to $\sim 10^{20}$eV
- CR acceleration in SN shocks
- average equipartition with turbulent and magnetic energy dens.
- 10 % of $E_{\rm SN}$ $\rightarrow$ acceleration of cosmic rays
- diffusive propagation of CRs in the ISM due to scattering of CR particles on magnetic field irregularities
- diffusion coeffcents $K \sim 10^{28} - 10^{29}{\rm cm}^2{\rm s}^{-1}$
- energy losses in ISM – mainly due to *pp* collisions
  – negligible to first approximation

Parker instability in the ISM (Parker 1966, 1967)



(picture from *High Energy Astrophysics, M. Longair)*

CR-DRIVEN WINDS

- Breitschwerdt, McKenzie & Voelk (1991), Zirakashwilli et al (1996), Ptuskin et al 1997, Dorfi & Breitschwerdt (2012), Heesen et al (2009), Everett et al (2008)
- **3D time-dependent CR-driven wind models:**
  Uhlig et al 2012, MNRAS, 423, 2374
  Booth, et al 2013, ApJ 777, L16
  Hanasz et al. 2013 , ApJ 777, L38
  Salem & Bryan 2013, MNRAS, 437, 3312

MHD SYSTEM OF EQUATIONS$^{(*)}$ + CR TRANSPORT EQUATION

Diffusion–advection equation

(eg. Schlickeiser & Lerche 1985, Berezinskii et al, 1990)

$$\partial_t e_{\rm cr} + \nabla(e_{\rm cr}\boldsymbol{v}) = -p_{\rm cr}\nabla\cdot\boldsymbol{v} + \nabla(\hat{K}\nabla e_{\rm cr}) + Q_{\rm cr},$$

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

Anisotropic diffusion of CRs

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

$$K_\parallel = 3\cdot10^{28}\mathrm{cm}^2\mathrm{s}^{-1}, \qquad K_\perp = (1-10)\%\,(K_\parallel)$$

$e_{\rm cr}$ – CR energy density, $\boldsymbol{v}$ – gas velocity,
$\hat{K}$ – the CR diffusion tensor, and $Q_{\rm cr}$ – the CR source term.

$^{(*)}$ including $\nabla p_{\rm cr}$ term coupling CR gas to thermal gas.

Numerical algorithm originally implemented in Zeus-3D:
Hanasz & Lesch (A&A 412, 331, 2003)

and in PIERNIK MHD code http://piernik.astri.umk.pl

CR diffusion–advection equation in the conservative form:

$$\partial_t e_{\rm cr} + \nabla \cdot \boldsymbol{F}_{\rm cr,adv} + \nabla \cdot \boldsymbol{F}_{\rm cr,diff} = -p_{\rm cr} \nabla \cdot \boldsymbol{v} + Q_{\rm cr}, \qquad (1)$$

CR transport:

- advection: $\boldsymbol{F}_{\rm cr,adv} = e_{\rm cr} \boldsymbol{v}$
- diffusion: $\boldsymbol{F}_{\rm cr,diff} = -\hat{K} \nabla e_{\rm cr}$

CR source terms:

- adiabatic heating/cooling: $-p_{\rm cr} \nabla \cdot \boldsymbol{v}$
- CR sources (SNR): $Q_{\rm cr}$

Consider the diffusive part of the diffusion–advection equation

$$\partial_t e_{\rm cr} + \nabla \cdot \boldsymbol{F}_{\rm cr} = 0, \qquad \boldsymbol{F}_{\rm cr} = -\hat{K}\nabla e_{\rm cr}. \tag{2}$$

In the discrete representation, the 3-D conservation law:

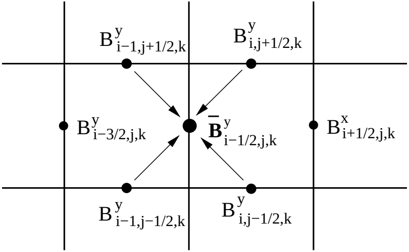
$$\begin{aligned} e^{n+1}_{{\rm cr},i,j,k} = e^{n}_{{\rm cr},i,j,k} \quad & -\frac{\Delta t}{\Delta x}\left(F_{{\rm cr},i+\frac{1}{2},j,k} - F_{{\rm cr},i-\frac{1}{2},j,k}\right) \\ & -\frac{\Delta t}{\Delta y}\left(F_{{\rm cr},i,j+\frac{1}{2},k} - F_{{\rm cr},i,j-\frac{1}{2},k}\right) \\ & -\frac{\Delta t}{\Delta z}\left(F_{{\rm cr},i,j,k+\frac{1}{2}} - F_{{\rm cr},i,j,k-\frac{1}{2}}\right) \end{aligned} \tag{3}$$

$e^{n}_{{\rm cr},i,j,k}$, $e^{n+1}_{{\rm cr},i,j,k}$ – volume averaged CR energy densities at $t = t^n, t^{n+1}$
$F_{{\rm cr},i-\frac{1}{2},j,k}$, $F_{{\rm cr},i+\frac{1}{2},j,k}$ – CR fluxes through the left and right cell bnd.

To compute components of $\hat{K}$ we need magnetic field aligned unit vectors at cell–faces:

$$\boldsymbol{n}_{i-\frac{1}{2},j,k} = \frac{\bar{\boldsymbol{B}}_{i-\frac{1}{2},j,k}}{\left|\bar{\boldsymbol{B}}_{i-\frac{1}{2},j,k}\right|}, \ldots$$

If $\boldsymbol{B}$-components are located at cell faces:

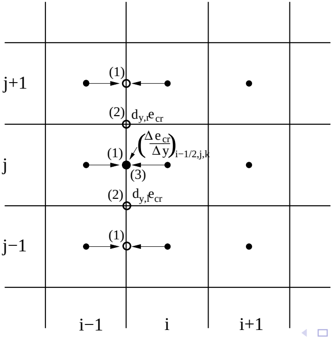


Interpolation of magnetic–field components to cell-faces – 2D projection onto xy–plane.

To compute CR diffusive fluxes we need components of $\nabla e_{\rm cr}$ at cell-faces.

1. interpolation of $e_{\rm cr}$ to face-centers (1)
2. computation of left and right finite differences of $e_{\rm cr}$, with respect to coordinates parallel to cell faces, at positions (2)
3. computation of face–centered, monotonized slopes at positions (3):

$$(\partial_y e_{\rm cr})_{(i-\frac{1}{2},j,k)} \simeq \frac{1}{4}\,(\partial_{y,l} e_{\rm cr} + \partial_{y,r} e_{\rm cr})(1 + \mathrm{sign}(1, \partial_{y,l} e_{\rm cr}\; \partial_{y,r} e_{\rm cr}))\,.$$

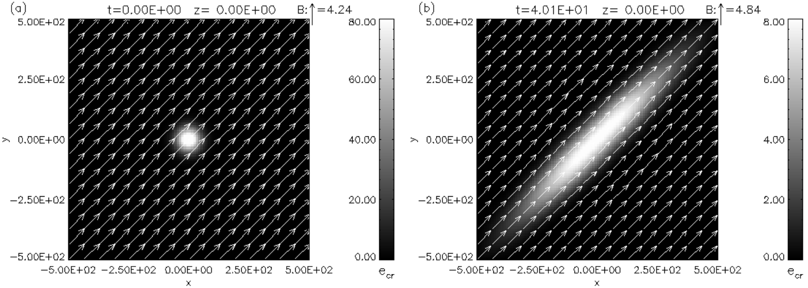


The timestep limitation for the diffusive part of the CR diffusion–advection equation imposed in the code is

$$\Delta t = 0.5\ C_{\rm cr}\ \frac{\min(\Delta x^2, \Delta y^2, \Delta z^2)}{K_\parallel + K_\perp}, \qquad (4)$$

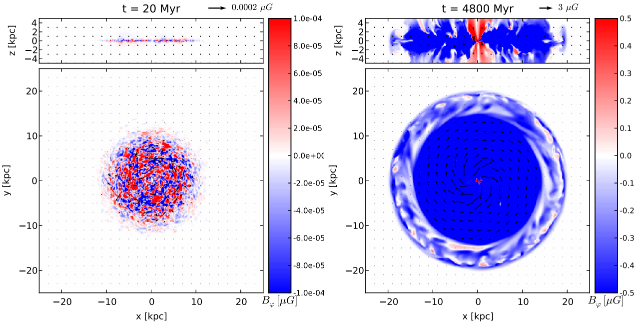
CFL stability condition: $C_{\rm cr} < 1$, for the explicit diffusion scheeme.

Test problem: anisotropic CR diffusion of cosmic rays



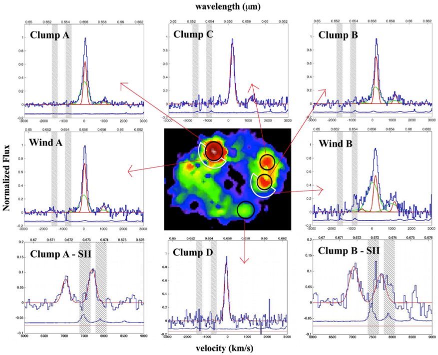
Cosmic Ray driven dynamo in disk galaxies

Hanasz, Woltański, Kowalik 2009, ApJ 706L, 155



Azimuthal magnetic field blue: $B_\varphi < 0$, red: $B_\varphi > 0$

Winds are essential for amplification and ordering of large-scale galactic magnetic fields.



- Galaxies at redshift $z \sim 1.5 - 3$ (ZC406690, $z \simeq 2$) show powerful galactic winds $v_z \geq 1000\text{km s}^{-1}$ which transport gas away from the galaxy, (eg. Genzel et al 2011, Newman et al, ApJ 752, 111, 2012)
- Winds are launched directly from the sites of strongly clustered star formation.

Cosmic rays can drive strong outflows from gas-rich high-redshift disk galaxies.

Hanasz, Lesch, Naab, Gawryszczak, Kowalik, Wółtański, ApJL, 777, L38 2013

- A galaxy similar to Milky Way (same masses of galactic halo, and stellar disk), but $\sim 10\times$ higher gas contents ($z = 2$).
- **Isothermal gas, no momentum feadback.**
- Fresh gas supplied at the fixed rate $\dot{M}_{in} = 100\,\mathrm{M}_{\odot}/\mathrm{yr}$.
- Toroidal magnetic field, $B_0 = 3\mu$G already present in the disk.
- Selfgravity forms dens gas blobs as soon as gaseous disk becomes gravitationally unstable.

- Star formation rate

$$\dot{\rho}_{\rm SFR} \simeq \epsilon_{ff} \frac{\rho}{\tau_{ff}} \simeq \epsilon_{ff} \sqrt{\frac{G\rho^3}{32\pi}} \propto \rho^{3/2} \quad \text{if} \quad \rho > \rho_{\rm crit}$$

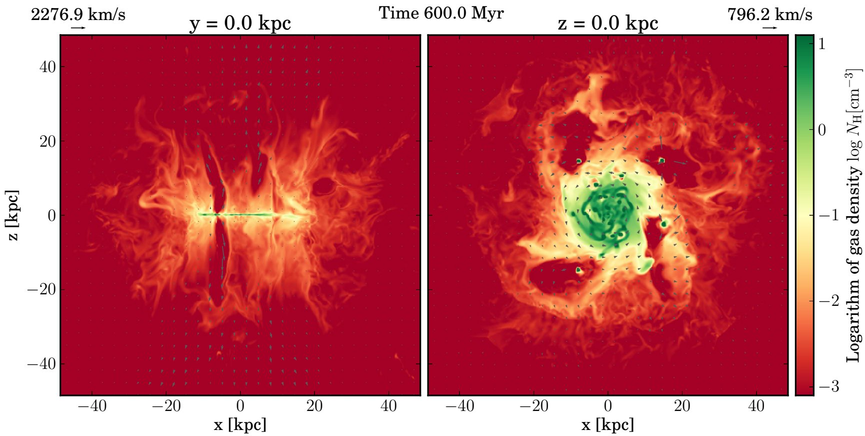
$\tau_{ff} = \sqrt{\frac{32\pi}{G\rho}}$, $\rho_{crit} = 600 \text{cm}^{-3}$, $\epsilon_{ff} = 0.1$ — star formation efficiency,

- Massive stars explode as Supernovae, 1SN appears for 100 $\mathrm{M}_\odot$ of gas converted to stars.
- Cosmic ray energy density input – 10% of E_{SN}, $E_{SN} \simeq 10^{51}$erg:

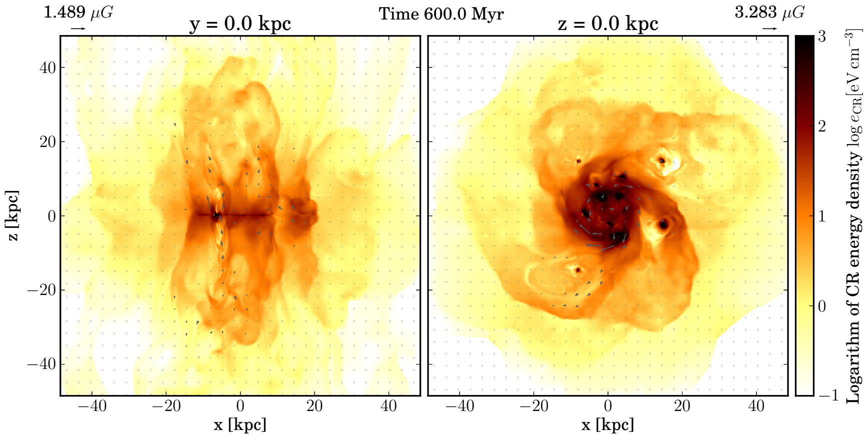
$$\Delta e_{CR} = 0.1 E_{SN}\, \dot{\rho}_{\rm SFR}\, \Delta t$$

added to a cell if $\rho > \rho_{\rm crit}$.

- Simulation box (100kpc $)^3$, fixed grid 512^3.

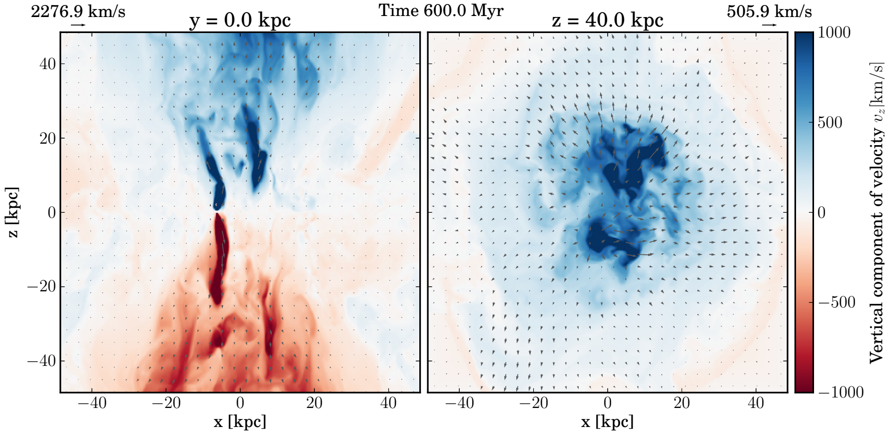


Logarithm of gas density and velocity vectors. Dense gas blobs hosting star formation regions are apparent at the horizontal slice.
Vertical streams of high velocity rarefied gas extend from star forming regions to $z = \pm 20 - 30$kpc

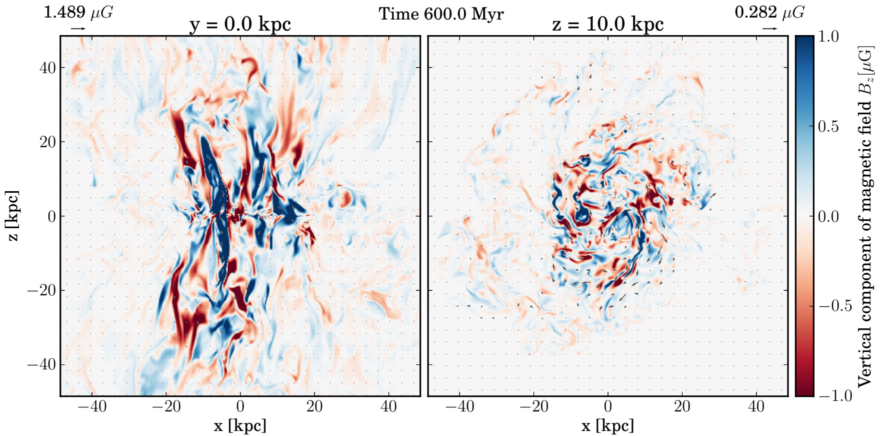


Logarithm of CR energy density and magnetic vectors. The high concentration of CRs at the horizontal plane coincides with the star forming clouds.

VERTICAL VELOCITY

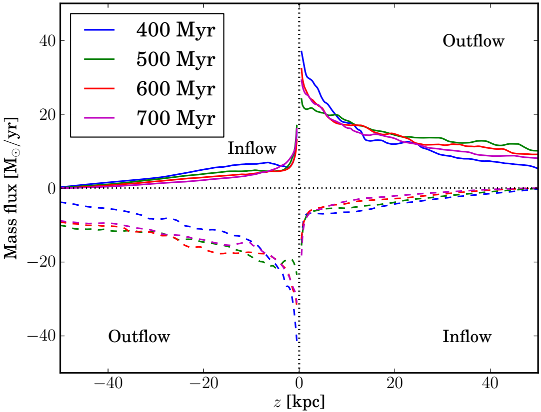


Vertical component of velocity. Collimated streams of high velocity gas extend several 10 kpc above and below the disk.

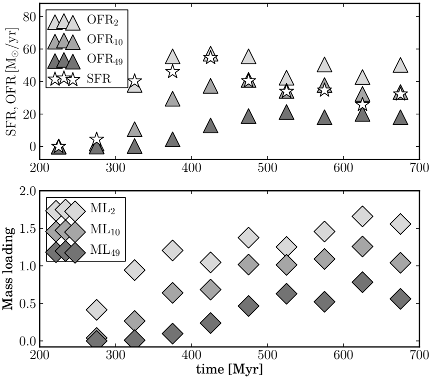


Magnitude of magnetic field **B**. Vertical filaments of $\sim 1\mu$G magnetic field extend to vertical distances of several tens of kpc from the galactic plane.

HORIZONTALLY INTEGRATED MASS FLUX



Horizontally integrated mass flux vs. vertical coordinate z. Solid lines denote gas moving in positive z-direction, dashed lines – gas moving in negative z-direction.



Top: Star formation rate and total mass outflow rate at three different levels $z = \pm 2$kpc , ± 10kpc , and $z = \pm 49$kpc .
Bottom: Mass loading factors ~ 1.

Summary

- **The CR pressure gradient drives strong bi-polar galactic wind with velocities exceeding 10^3km s^{-1} with mass loading ~ 1.**
- **Efficient wind acceleration because CR pressure gradient acts on diluted medium far away from dense gas clouds.**
- **Results consistent with Booth, et al 2013 and Salem & Bryan 2013.**