Modeling the magnetized interstellar medium in Star Forming Galaxies

Dieter Breitschwerdt

Zentrum für Astronomie und Astrophysik
Technische Universität Berlin

Wednesday, June 9, 2010
Collaborators

* Miguel de Avillez (Evora, Portugal)
* Ernst Dorfi (Vienna, Austria)
* Ingo Philipp (Vienna, Austria)
* Michael Schulreich (Berlin, Germany)
* Georg Zwettler (Vienna, Austria)
Overview

* Introduction
* Halo Dynamics
* Plasma Models of Galactic Halos
* Galactic Wind Theory & Models
* Self-consistent modeling of galactic outflows & ionization structure
* Electron transport in NGC 891 and NGC 253
* Diffuse radial $\gamma$-ray gradient in the Milky Way
* Cosmic Ray Acceleration Beyond the “Knee”
* Summary
Galaxies are essential building blocks of the Universe
they presumably form by hierarchical merging events
feedback processes in the disk and halo become ever more important for
their appearance and evolution \(\rightarrow\) Galactic Cosmic Matter Cycle
star formation generates hot plasma, “metals”, CRs, B-fields in disk & halo
no hydrostatic halo \(\rightarrow\) superbubbles, outflows (fountain & winds)
**ISM in Galaxies**

- Morphology of Galaxies: **Bulge, Disk, Halo**
- Active star formation in disk galaxies → gas and dust
- Important components to consider: **Magnetic fields, cosmic rays**

---

**Gas Phase**

<table>
<thead>
<tr>
<th>Gas Phase</th>
<th>T [K]</th>
<th>n[cm(^{-3})]</th>
<th>(f_V)</th>
<th>(f_M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  MM(^1) = Molecular Medium (H(_2))</td>
<td>(\sim 20)</td>
<td>(\sim 10^3)</td>
<td>0.01</td>
<td>0.3-0.6</td>
</tr>
<tr>
<td>II CNM = cold neutral medium</td>
<td>(\sim 100)</td>
<td>20 – 60</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>III WNM = warm neutral medium</td>
<td>(\sim 6000)</td>
<td>(\sim 0.05 – 0.3)</td>
<td>0.3 – 0.4</td>
<td></td>
</tr>
<tr>
<td>IV WIM = warm ionized medium</td>
<td>(\sim 8000)</td>
<td>(\sim 0.1 – 0.5)</td>
<td>0.1 – 0.2</td>
<td></td>
</tr>
<tr>
<td>V HIM(^2) = hot ionized medium</td>
<td>(\sim 10^6)</td>
<td>(\sim 10^{-3})</td>
<td>0.5</td>
<td>(\sim 0.01)</td>
</tr>
</tbody>
</table>

1) not in pressure equilibrium (gravitationally bound)
2) no phase transition, heated by SNRs and superbubbles

- According to classical theory gas exists in various stable phases in the p-V-diagramm
- Transitions possible by **heating** and **cooling**
- **star formation** drives matter cycle
  → **how does the interstellar gas evolve?**
Solve full **HD/MHD equations** on a large grid: 1 kpc $\times$ 1 kpc $\times$ ± 10 kpc ($\Delta x=0.625$ pc or less)

- Type Ia,b,c/II SNe random + clustered in disk
- background heating due to diffuse UV photon field
- gravitational field by stars + self-gravity
- SFR $\propto$ local density/temp.: $n > 10$ cm$^{-3}/T<100$ K
- formation and motion of OB associations (random velocity of stars)
- Evolution of computational volume for $\tau \sim 400$ My
- sufficiently long to erase memory of initial conditions!
- 3D calculations on parallel processors with adaptive mesh refinement (AMR)
High Resolution ISM Simulations

- Numerical solution of HD/MHD-Eqs.
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{u} = q
  \]
  \[
  \frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot \vec{T} = \rho \vec{f} + \vec{m}
  \]
  \[
  \frac{\partial W}{\partial t} + \nabla \cdot \vec{S} = \rho \vec{u}(\vec{f} + \vec{m}) + W_0
  \]
  \[
  \vec{E} = -\frac{1}{c} \left[ \vec{u} \times \vec{B} \right]
  \]
  \[
  \frac{\partial \vec{B}}{\partial t} = -c \left[ \nabla \times \vec{E} \right]
  \]
  \[
  \nabla \cdot \vec{B} = 0 \text{ (as initial condition)}
  \]

- ideal MHD ($\sigma \rightarrow 0$)

- with
  \[
  \vec{T} = \rho \vec{u} \otimes \vec{u} + \left[ P + \frac{B^2}{8\pi} \right] \cdot \mathbf{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi}
  \]
  \[
  W = \frac{1}{2} \rho u^2 + \frac{P}{\gamma - 1} + \frac{B^2}{8\pi}
  \]
  \[
  \vec{S} = \left( \frac{1}{2} u^2 + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} \right) \rho \vec{u} + \frac{\vec{E} \times \vec{B}}{4\pi}
  \]

- Realistic **boundary conditions**: mass, momentum, energy input by SNe and stellar winds
- **source terms**: $q=M_{ej}/(V_{ej} t_0)$, $m=q V_{ej}$,
  $\frac{dW_0}{dt}=(W_{k0}+W_{th})/t_0$
- external body force: gravitational field
- background heating, interstellar cooling
SNR/SB Driven Outflows

SNR/SB Driven Outflows

HD-Evolution of ISM II

Results

- Collective effect of SNe induces break-out of ISM disk gas → "galactic fountain" (cf. intermediate velocity clouds) → reduce disk pressure
- Density and temperature distribution shows structures on all scales (cf. observation of filaments)
- Shear flow due to expanding SNRs generate high level of turbulence → coupling of scales
- Cloud formation by shock compressed layers → clouds are transient features → generation of new stars
- Large amount of gas in thermally unstable phases
- Volume filling factor of HIM ~ 20%
- No pressure equilibrium!

Avillez & Breitschwerdt, 2010
**HD-Evolution of ISM II**

**Results**

- Collective effect of SNe induces break-out of ISM disk gas → “galactic fountain” (cf. intermediate velocity clouds) → reduce disk pressure
- Density and temperature distribution shows structures on all scales (cf. observation of filaments)
- Shear flow due to expanding SNRs generate high level of turbulence → coupling of scales
- Cloud formation by shock compressed layers → clouds are transient features → generation of new stars
- Large amount of gas in thermally unstable phases
- Volume filling factor of HIM ~ 20%
- No pressure equilibrium!

_Avillez & Breitschwerdt, 2010_
Turbulence I

- ISM is highly **compressible** and **turbulent** medium (C.F. v. Weizsäcker 1951)
- Reynolds number $Re = u L / \nu \sim 10^6 - 10^7$ high
- Term $(u \nabla) u$ is **non-linearity in Navier-Stokes (NS) equations**

\[
\nabla \left( \frac{u^2}{2} \right) = (u \nabla) \bar{u} + \bar{u} \times \bar{\omega}, \quad \bar{\omega} = \nabla \times \bar{u}
\]

write NS eqs. as function of **vorticity** $\omega$:

\[
\frac{\partial \bar{\omega}}{\partial t} = \nabla \times [\bar{u} \times \bar{\omega}] + \nu \Delta \bar{\omega}
\]

and since

\[
\nabla \times [\bar{u} \times \bar{\omega}] = (\bar{\omega} \cdot \nabla) \bar{u} - (\bar{u} \cdot \nabla) \bar{\omega}
\]

we get:

\[
\frac{D \bar{\omega}}{D t} \equiv \frac{\partial \bar{\omega}}{\partial t} + (\bar{u} \cdot \nabla) \bar{u} = (\bar{\omega} \cdot \nabla) \bar{u} + \nu \Delta \bar{\omega}
\]

Change of vorticity due to:

- Change of moment of inertia by stretching of fluid element (b))
- Viscous torques spin up or slow down fluid element (a) and change vorticity

Navier-Stokes Eq. for Newtonian fluids
Turbulence II

- **Turbulence**: 3D chaotic solution of Navier-Stokes eq.
- Stretching of fluid elements leads to increase of vorticity → “vortex tubes”

Large Eddy Simulation of isotropic turbulence in a periodic box; shown are contours of vorticity

Direct Numerical Simulation of isotropic turbulence (s.a.); Re ~1200 (Credit: Davidson)

3D-Simulation of a laboratory jet in a non-reactive gas, Re ~21000; 2D-Projektion; Credit: D. Glaze (Purdue University); velocity field is marked by arrows

*Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010*


**Turbulence II**

- **Turbulence**: 3D chaotic solution of Navier-Stokes eq.
- Stretching of fluid elements leads to increase of vorticity → “vortex tubes”

**Large Eddy Simulation** of isotropic turbulence in a periodic box; shown are contours of vorticity

**Direct Numerical Simulation** of isotropic turbulence (s.a.); Re ~1200

3D-Simulation of a laboratory jet in a non-reactive gas, Re ~21000; 2D-Projektion; Credit: D. Glaze (Purdue University); velocity field is marked by arrows

*Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km“ - Cracow, 18.5.2010*
MHD-Evolution of ISM (I)

Avillez & Breitschwerdt, 2005a

AMR $\Delta x=1.25 \text{ pc}$, $\sigma/\sigma_{\text{Del}}=1$, $B_{u,0}=3 \text{ } \mu \text{G}$

MHD-Evolution of ISM (I)

Avillez & Breitschwerdt, 2005a
MHD-Evolution of ISM (I)

Avillez & Breitschwerdt, 2005a
MHD-Evolution of ISM (I)

Avillez & Breitschwerdt, 2005a
MHD-Evolution of ISM (II)

Avillez & Breitschwerdt, 2005

B-field // to disk cannot prevent outflow into halo; Halo density is inhomogeneous (Fountain)

Which pressure determines ISM dynamics?
- For $T < 200$ K: magnetic pressure dominates,
- for $200$ K < $T < 10^6$ K ram pressure dominates,
- for $T > 10^6$ K thermal pressure dominates
Plasma Models: CIE vs. NEI

- **optically thin hot plasmas**: continuum + line spectrum
- **collisional ionization equilibrium (CIE)**: ionization by collisions (3-body process) is balanced by radiative recombination $\rightarrow$ no detailed balancing, because atomic time scales are different
- plasma is driven out of CIE $\rightarrow$ **non-equilibrium ionization (NEI)** structure
- particularly striking effect: **fast adiabatic cooling** like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)

---

**CIE**

- ionization equilibrium $\rightarrow n\left(\text{A}^{n+}\right)$
- radiative emission
  - lines
  - bremsstrahlung recombination radiation
  - 2-photon emission

**NEI**

- ionization evolution $\rightarrow \bar{n}\left(\text{A}^{n+}\right)$
- evolution of the astrophys. model

---

Top: **CIE vs. NEI plasma emission codes**; in **CIE**, plasma emission can be calculated (in coronal approx., i.e. $n_e < 10^4$ cm$^{-3}$) once and for all if $n_e$, $T_e$ and $Z$ are given; in **NEI** $Z$ + astrophysical model for dynamical evolution is required!

Left: Animation of collisional ionization by electrons

Böhringer 1998

---

Radiative recombination

Collisional ionization

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
Plasma Models: CIE vs. NEI

- **optically thin hot plasmas**: continuum + line spectrum
- **collisional ionization equilibrium (CIE)**: ionization by collisions (3-body process) is balanced by **radiative recombination** $\rightarrow$ no detailed balancing, because atomic time scales are different
- **plasma is driven out of CIE** $\rightarrow$ **non-equilibrium ionization (NEI)** structure
- **particularly striking effect**: **fast adiabatic cooling** like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)

Top: CIE vs. NEI plasma emission codes; in CIE, plasma emission can be calculated (in coronal approx., i.e. $n_e < 10^4 \text{ cm}^{-3}$) once and for all if $n_e, T_e$ and $Z$ are given; in NEI $Z +$ astrophysical model for dynamical evolution is required!

Left: Animation of collisional ionization by electrons
Plasma Models: CIE vs. NEI

- **optically thin hot plasmas**: continuum + line spectrum
- **collisional ionization equilibrium (CIE)**: ionization by collisions (3-body process) is balanced by **radiative recombination** → no detailed balancing, because atomic time scales are different
- Plasma is driven out of CIE → **non-equilibrium ionization (NEI)** structure
- Particularly striking effect: **fast adiabatic cooling** like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)

---

**CIE**

- $n_e, T_e$
- Abundances
- Ionization equilibrium $\rightarrow n (A^{n+})$
- Radiative emission
- Lines

**NEI**

- Evolution of the astrophys. model
- Ionization evolution $\rightarrow \bar{n} (A^{n+})$
- Bremsstrahlung recombination rad.
- 2-photon emission
- Spectrum
- Cooling rate

---

Top: CIE vs. NEI plasma emission codes; in CIE, plasma emission can be calculated (in coronal approx., i.e. $n_e < 10^4$ cm$^{-3}$) once and for all if $n_e$, $T_e$ and $Z$ are given; in NEI $Z +$ astrophysical model for dynamical evolution is required!

Left: Animation of collisional ionization by electrons

---

Wednesday, June 9, 2010
Plasma Models: CIE vs. NEI

- optically thin hot plasmas: continuum + line spectrum
- collisional ionization equilibrium (CIE): ionization by collisions (3-body process) is balanced by radiative recombination \( \rightarrow \) no detailed balancing, because atomic time scales are different
- plasma is driven out of CIE \( \rightarrow \) non-equilibrium ionization (NEI) structure
- particularly striking effect: fast adiabatic cooling like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)

Top: CIE vs. NEI plasma emission codes; in CIE, plasma emission can be calculated (in coronal approx., i.e. \( n_e < 10^4 \) cm\(^{-3}\)) once and for all if \( n_e, T_e \) and Z are given; in NEI Z + astrophysical model for dynamical evolution is required!

Left: Animation of collisional ionization by electrons
Plasma Models: CIE vs. NEI

- **optically thin hot plasmas:** continuum + line spectrum
- **collisional ionization equilibrium (CIE):** ionization by collisions (3-body process) is balanced by **radiative recombination** → no detailed balancing, because atomic time scales are different
- **plasma is driven out of CIE** → **non-equilibrium ionization (NEI)** structure
- **particularly striking effect:** **fast adiabatic cooling** like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)

---

**CIE**

- $n_e, T_e$
- abundances
- ionization equilibrium $\rightarrow n (A^{n+})$
- radiative emission
  - lines
  - bremsstrahlung recombination rad. 2-photon emission

**NEI**

- ionization evolution $\rightarrow \bar{n} (A^{n+})$
- evolution of the astrophys. model
- spectrum
- cooling rate

_Böhringer 1998_

---

*Top:* CIE vs. NEI plasma emission codes; in CIE, plasma emission can be calculated (in coronal approx., i.e. $n_e < 10^4$ cm$^{-3}$) once and for all if $n_e$, $T_e$ and $Z$ are given; in NEI Z + astrophysical model for dynamical evolution is required!

*Left:* Animation of collisional ionization by electrons
Example: ionization structure of oxygen in CIE and NEI

- **CIE:** ionization fraction $x$ of O depend only on temperature $T$ (for given $Z$) ➔ sharply peaked ➔ convenient diagnostic tool for determining $T$

- **NEI:** $x$ depends on dynamical and thermal history of plasma ➔ more difficult to fit spectrum, but: **evolution of plasma can be inferred!**

*Böhringer 1998*

*Breitschwerdt & Schmutzler 1999*
Modeling galactic halos with outflow (I)

- model edge-on (starburst) galaxies: e.g. NGC 253, NGC 3079
- underlying galactic wind model: steady-state outflow driven by thermal gas, CR and wave pressures (cf. Breitschwerdt et al. 1991)
- dynamically and thermally self-consistent modelling:
  - Outflow changes $\rho$ and $T$
  - this modifies ionization structure
  - which in turn modifies cooling function $\Lambda(\rho, T)$
  - which changes outflow
  - flow is described in a flux tube given by:

\[
A(z) = A_0 \left[ 1 + \left( \frac{z}{H} \right)^2 \right]
\]

Mass-loaded wind flow!!!

Top: steady-state galactic wind model, in which gas, CRs and waves drive an outflow with a smooth subsonic-supersonic transition
Modeling galactic halos with outflow (I)

- model edge-on (starburst) galaxies: e.g. NGC 253, NGC 3079
- underlying galactic wind model: steady-state outflow driven by thermal gas, CR and wave pressures (cf. Breitschwerdt et al. 1991)
- dynamically and thermally self-consistent modelling:
  - Outflow changes ρ and T
  - this modifies ionization structure
  - which in turn modifies cooling function Λ(ρ,T)
  - which changes outflow
  - flow is described in a flux tube given by:

\[ A(z) = A_0 \left[ 1 + \left( \frac{z}{H} \right)^2 \right] \]

Mass-loaded wind flow!!!

Top: steady-state galactic wind model, in which gas, CRs and waves drive an outflow with a smooth subsonic-supersonic transition

Breitschwerdt et al. 1991

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
Modeling galactic halos with outflow (II)

Procedure:

- **Generating** an outflow model and follow time-dependent evolution of ions (NEI)
- **Binning** of high-resolution unabsorbed synthetic (model) spectrum into e.g. EPIC pn channels (for XMM-Newton)
- **Folding** spectrum through detector response matrix

→ Treating observed and synthetic spectrum equally!

- **Fitting** synthetic spectrum in XSPEC (X-ray spectral fitting routine) to observational data
- **Comparing** with observed spectrum and iterate outflow model if necessary until convergence
Modeling galactic halos with outflow (III): NCG 253
Modeling galactic halos with outflow (III): NCG 253
Modeling galactic halos with outflow (III): NCG 253

The barred spiral starburst galaxy NGC 253

Bauer et al. 2008
Modeling galactic halos with outflow (III): NCG 253

- The barred spiral starburst galaxy NGC 253
- 2MASS mosaic of NGC253
- Shows also extranuclear SB

Bauer et al. 2008
Modeling galactic halos with outflow (III): NCG 253

- 2MASS mosaic of NGC253
- Shows also extranuclear SB
- XMM EPIC pn: Soft X-ray halo of NGC253 (0.2 – 0.5 keV)

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
Modeling galactic halos with outflow (IV): NCG 253

- NEI spectrum mimics a “multitemperature” halo by its characteristic lines, but is physically radically different from it
- **Reason:** Sum of CIE spectra cannot represent the specific *thermodynamic* path of a true NEI spectrum

---

**NEI Model** (Breitschwerdt & Freyberg 2003)

Top: Integrated spectrum of a dynamically and thermally self-consistent NEI simulation; the spectrum is a composite of continuum and lines, which are characteristic for the plasma history ➔ spectrum will be folded through detector response

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
Modeling galactic halos with outflow (V): NCG 3079

- **NGC 3079**: starburst LINER SBc galaxy
- Distance ~ 17 Mpc, Inclination ~ 85°
- **Low foreground absorption** $\log(N(H))=19.9$ → important for recording soft X-ray photons since photoelectric absorption $\sim E^{-3}$

*Top: NGC 3079, XMM-Newton image (EPIC pn camera); the optical disk is indicated by the $D_{25}$ ellipse; the exposure was 25 ksec.*
Modeling galactic halos with outflow (VI): NCG 3079

- large extended soft halo emission
- $0.2 \leq E \leq 1.0$ keV

- morphology: soft X-ray spurs
- hard emission largely confined to disk

Credit to A. Vogler
Modeling galactic halos with outflow (VII): NCG 3079

<table>
<thead>
<tr>
<th>Model</th>
<th>n₀ [cm⁻³]</th>
<th>T₀ [10⁶ K]</th>
<th>B₀ [µG]</th>
<th>u₀ [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>3 10⁻³</td>
<td>3.0</td>
<td>2.0</td>
<td>200.3</td>
</tr>
<tr>
<td>M2</td>
<td>3 10⁻³</td>
<td>5.0</td>
<td>5.0</td>
<td>312.9</td>
</tr>
<tr>
<td>M3</td>
<td>3 10⁻³</td>
<td>4.0</td>
<td>5.0</td>
<td>260.4</td>
</tr>
<tr>
<td>M4</td>
<td>4.2 10⁻³</td>
<td>3.7</td>
<td>5.0</td>
<td>234.1</td>
</tr>
<tr>
<td>M5</td>
<td>5 10⁻³</td>
<td>3.6</td>
<td>5.0</td>
<td>220.0</td>
</tr>
</tbody>
</table>

- changing inner boundary conditions, where wind is emanating
Modeling galactic halos with outflow (VII): NCG 3079

- bad fit in the 0.5 - 0.8 keV region
- too much emission in the 0.8 - 1 keV region \( \Rightarrow \) T too high

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
Modeling galactic halos with outflow (VII): NCG 3079

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
better fit: T still slightly too high
Modeling galactic halos with outflow (VII): NCG 3079

Top: Comparison between data and dynamically and thermally self-consistent galactic wind model → 5 iterations were necessary to achieve an acceptable fit

- best fit model: galactic wind with gravitational potential (including dark matter halo)
- $n_0 = 5 \times 10^{-3} \text{ cm}^{-3}$, $T_0 = 3.6 \times 10^6 \text{ K}$, $B_0 = 5 \mu \text{G}$, $u_0 = 220 \text{ km/s}$
- foreground absorption: $N(H) = 3.9 \times 10^{20} \text{ cm}^{-2}$
- goodness of fit: $X^2_{\text{red}} = 1.2$
- derived mass loss rate:
  - $\frac{\text{d}m}{\text{d}t} = \rho_0 u_0 = 0.055 \text{ M}_{\odot}/\text{yr}/\text{kpc}^2$
- mass loss rate in “spur” region ($R = 8\text{kpc}$): $\frac{\text{d}M}{\text{d}t} = \frac{\pi}{2} R^2 \rho_0 u_0 = 3.5 \text{ M}_{\odot}/\text{yr}$
Modeling galactic halos with outflow (V): NCG 3079

- **NGC 3079:** smooth subsonic-supersonic transition → critical point (M=1) in the flow at \( z \sim 5 \) kpc from the disk
- superbubble gas injected at the inner boundary \( (z_0 = 1 \) kpc) with initial velocity \( u_0 = 220 \) km/s (subsonic, but super-alfvenic)
- terminal velocity \( \sim 450 \) km/s

**Top:** Derived outflow characteristics for the best fit model

Breitschwerdt et al. 2003
Modeling galactic halos with outflow (V): NCG 3079

- **Cooling Function**: Cooling curve depends on the ionization state of the plasma.
- In case of a fast adiabatically expanding flow, the difference between CIE and NEI cooling curves is striking.
- Whereas the CIE cooling curve peaks at ~ $10^5$ K, the NEI curve in this particular model has a maximum ~ $10^6$ K, where OVII, OVIII lines are abundant due to delayed recombination.

*Top*: Comparison between cooling curve for CIE and for a dynamical NEI model for the starburst galaxy NGC 3079.

Breitschwerdt et al. 2003
To fit ROSAT PSPC data in a given region of the MW sky, Everett et al. (2008) show that a **CR driven wind** gives a statistically much better fit than a hydrostatic halo (especially for ROSAT R5 band)

- for lower halo here CIE is a good approximation, since deviation from NEI still small
- fiducial wind model for Milky Way: $n_0 = 6.9 \times 10^{-3} \text{ cm}^{-3}$, $T_0 = 2.9 \times 10^6 \text{ K}$, $u_0 = 173 \text{ km/s}$
CR electron transport in galactic halos (I): NCG 4631

- Non-thermal radio emission of NGC 4631: significant linear polarization for \( z \leq 5 \) kpc
- Noticeable B-field component perpendicular to galactic disk
- Modelling: solve diffusion-advection transport equation for electrons incl. synchrotron and inverse Compton losses
- Radio spectral index variation is a measure of dominant transport process: flat curve is indicative of accelerating advection flow, compensating for increasing losses with time \( \rightarrow \) galactic wind

Top: radio map superimposed with polarization vectors on optical image
Right: self-consistent spectral index variation in galactic wind model

\( \text{Breitschwerdt, 1997} \)

\( \text{Golla & Hummel 1994} \)
CR electron transport in galactic halos (II): NCG 253

Non-thermal radio emission of NGC 253:

CR electron transport equation

\[
\begin{align*}
- \frac{\partial}{\partial z} \left( D(E,z) \frac{\partial N(E,z)}{\partial z} - u(z) N(E,z) \right) \\
- \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} EN(E,z) - \frac{dE}{dt} N(E,z) \right) = Q(E,z)
\end{align*}
\]

\[Q(E,z) = K_0 E^{-\gamma_0} h_\delta(z)\]

- spectral index close to sources up to vertical distances from disk of \(z \sim 1-2\) kpc dominated by diffusion
- for \(z \geq 1-2\) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

NGC 253

Heesen et al. (2007)

\(\alpha(4.80,0.33)\)

minor axis offset [kpc]

Advection Diffusion Diffusion-Advection

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Wednesday, June 9, 2010
CR electron transport in galactic halos (II): NCG 253

* Non-thermal radio emission of NGC 253:
* CR electron transport equation

\[
\begin{align*}
\frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} \right) &\quad - \quad u(z) N(E, z) \quad - \quad \\
\frac{\partial}{\partial E} \left( \frac{1}{3} \frac{d u}{d z} E N(E, z) \right) &\quad - \quad \frac{d E}{d t} N(E, z) \quad = \quad Q(E, z) \\
Q(E, z) &= K_0 E^{-\gamma_0} h_g \delta(z)
\end{align*}
\]

* spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by **diffusion**
* for \( z \geq 1-2 \) kpc transport dominated by **advection**
* transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Wednesday, June 9, 2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[-\frac{\partial}{\partial z} \left( D(E,z) \frac{\partial N(E,z)}{\partial z} \right) - u(z) N(E,z) \]
\[-\frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} EN(E,z) - \frac{dE}{dt} N(E,z) \right) = Q(E,z) \]

\[Q(E,z) = K_0 E^{-\gamma_0} h_0 \delta(z)\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

\[\text{Diffusion} \quad \text{Diffusion-Advection}\]

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Wednesday, June 9, 2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
-Q(E,z) = K_0 E^{-\gamma_0} h_g \delta(z)
\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

Heesen et al. (2007)

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
- \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} - u(z) N(E, z) \right) - \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} E N(E, z) - \frac{dE}{dt} N(E, z) \right) = Q(E, z)
\]

\[
Q(E, z) = K_0 E^{-\gamma_0} h_g \delta(z)
\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

*In collaboration with:*
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

\( \text{Advection} \quad \text{Diffusion} \quad \text{Diffusion-Advection} \)

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

Dieser Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010
CR electron transport in galactic halos (II): NCG 253

* Non-thermal radio emission of NGC 253:
* CR electron transport equation

\[
\begin{align*}
- \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} - u(z) N(E, z) \right) & \\
- \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} E N(E, z) - \frac{dE}{dt} N(E, z) \right) & = Q(E, z)
\end{align*}
\]

\[Q(E, z) = K_0 E^{-\gamma_0} h_g \delta(z)\]

* spectral index close to sources up to vertical distances from disk of \(z \sim 1\text{-}2\) kpc dominated by diffusion
* for \(z \geq 1\text{-}2\) kpc transport dominated by advection
* transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Wednesday, June 9, 2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[ -\frac{\partial}{\partial z} \left( D(E,z) \frac{\partial N(E,z)}{\partial z} - u(z) N(E,z) \right) \]
\[ -\frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} E N(E,z) - \frac{dE}{dt} N(E,z) \right) = Q(E,z) \]
\[ Q(E,z) = K_0 E^{-\gamma_0} h_g \delta(z) \]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Wednesday, June 9, 2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
\begin{align*}
- \frac{\partial}{\partial z} \left[ D(E, z) \frac{\partial N(E, z)}{\partial z} \right] - u(z) N(E, z) &= \frac{\partial}{\partial E} \left[ \frac{1}{3} \frac{du}{dz} E N(E, z) - \frac{dE}{dt} N(E, z) \right] = Q(E, z) \\
Q(E, z) &= K_0 E^{-\gamma_0} h g \delta(z)
\end{align*}
\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \text{ kpc} \) dominated by diffusion
- for \( z \geq 1-2 \text{ kpc} \) transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar, M. Krause, V. Heesen

\[\alpha(4.80, 0.33)\]

---

*Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010*
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
\begin{align*}
- & \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} \right) - u(z) N(E, z) \\
- & \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} EN(E, z) - \frac{dE}{dt} N(E, z) \right) = Q(E, z) \\
Q(E, z) &= K_0 E^{-\gamma_0} h_0 \delta(z)
\end{align*}
\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

\textbf{Top:} Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with: R. Beck, R.-J. Dettmar, M. Krause, V. Heesen

\( \alpha = 1.4898 \)
CR electron transport in galactic halos (II): NCG 253

* Non-thermal radio emission of NGC 253:
* CR electron transport equation

\[ - \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} - u(z) N(E, z) \right) \]
\[ - \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{dE}{dz} \frac{E}{N(E, z)} - \frac{dE}{dt} N(E, z) \right) = Q(E, z) \]

\[ Q(E, z) = K_0 E^{-\gamma_0} h_g \delta(z) \]

* spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
* for \( z \geq 1-2 \) kpc transport dominated by advection
* transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

Heesen et al. (2007)

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

Dieter Breitschwerdt - Workshop on "Magnetic Fields on scales from kpc to km" - Cracow, 18.5.2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
\begin{align*}
- \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} - u(z) N(E, z) \right) \\
- \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} E N(E, z) - \frac{dE}{dt} N(E, z) \right) = Q(E, z)
\end{align*}
\]

\[Q(E, z) = K_0 E^{-\gamma_0} h_g \delta(z)\]

- spectral index close to sources up to vertical distances from disk of \(z \sim 1-2\) kpc dominated by diffusion
- for \(z \geq 1-2\) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

\[\text{Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.}\]

\[D\]ieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010

\[\text{In collaboration with:}\]
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
\begin{align*}
&\frac{\partial}{\partial z} \left( D(E,z) \frac{\partial N(E,z)}{\partial z} - u(z) N(E,z) \right) \\
&- \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} E N(E,z) - \frac{dE}{dt} N(E,z) \right) = Q(E,z) \\
Q(E,z) &= K_0 E^{-\gamma_0} h_g \delta(z)
\end{align*}
\]

- spectral index close to sources up to vertical distances from disk of \( z \sim 1-2 \) kpc dominated by diffusion
- for \( z \geq 1-2 \) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble break-out from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al. 

In collaboration with: R. Beck, R.-J. Dettmar, M. Krause, V. Heesen

Dieter Breitschwerdt - Workshop on "Magnetic Fields on scales from kpc to km" - Cracow, 18.5.2010
CR electron transport in galactic halos (II): NCG 253

- Non-thermal radio emission of NGC 253:
- CR electron transport equation

\[
- \frac{\partial}{\partial z} \left( D(E, z) \frac{\partial N(E, z)}{\partial z} \right) - u(z) N(E, z)
- \frac{\partial}{\partial E} \left( \frac{1}{3} \frac{du}{dz} EN(E, z) - \frac{dE}{dt} N(E, z) \right) = Q(E, z)
\]

\[Q(E, z) = K_0 E^{-\gamma_0} h_g \delta(z)\]

- spectral index close to sources up to vertical distances from disk of \(z \sim 1-2\) kpc dominated by diffusion
- for \(z \geq 1-2\) kpc transport dominated by advection
- transport mechanism varies locally in agreement with local superbubble breakout from galactic disk

Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

In collaboration with:
R. Beck, R.-J. Dettmar,
M. Krause, V. Heesen

"Magnetic Fields on scales from kpc to km" - Cracow, 18.5.2010
Radial Diffuse $\gamma$-ray Gradient in the Galaxy

- **Diffuse $\gamma$-ray gradient in the Milky Way**: Cos-B, EGRET measured **shallow** gradient of diffuse $\gamma$-emission
- for $E > 100$ MeV $\gamma$-rays are mainly due to $\pi^0$-decay, which are due to interaction between CR protons and HI atoms $\Rightarrow$ $\gamma$-emission should follow **CR source distribution** (SNRs and pulsars), which peaks at $R \sim 4$ kpc
- diffusion model can only marginally reproduce $\gamma$-ray gradient for huge CR halo
- **simple model**: radially dependent **diffusion-advection** boundary due to local radial variations in **star formation**

*Top*: Fermi $\gamma$-ray all-sky survey  
*Middle*: diffuse $\gamma$-ray gradient according to COS-B and EGRET observations  
*Bottom*: model (galactic wind) of diffuse $\gamma$-ray emission

\[ Q(R) \sim I_\gamma \]
CR acceleration beyond the “Knee” (I)

- Time-dependent galactic wind calculations (Dorfi & Breitschwerdt 2010) confirm stationary wind solutions as time-asymptotic flow
- for starburst galaxies we use time-dependent boundary conditions, reflecting the duration of a starburst → increase of CR & gas pressures by a factor of 10 at z=z_0
- double shock structure in the galactic wind region → post-acceleration of galactic CRs (1st order Fermi)
- particles are convected downstream of forward shock, i.e. towards the galactic disk
- particle acceleration modifies shock → sub-shock → shock strengthens as propagating down a density gradient
- within a few 10^6 - 10^7 yr, particles can reach energies up to 10^{17} - 10^{18} eV

Dorfi & Breitschwerdt (2010)

\[ \frac{dp_{\text{max}}}{dt} = \frac{A}{t^2}, \]
\[ A = \frac{3 \pi B_0 z_0^2}{4mc^3} \]

Top: density (a), velocity (b), gas (c), CR and wave pressures (d) for shocks in a galactic wind of the Milky Way for 3 \times 10^7 \leq t \leq 10^9 yr
Bottom: maximum momentum of particles post-accelerated in galactic wind for forward (filled squares) and forward + reverse shock (diamonds)
CR acceleration beyond the “Knee” (II)

- galactic wind post-acceleration of CRs in the halo, i.e. Halo CRs (HCRs) guarantee a smooth transition to the spectrum of Galactic Cosmic Rays (GCRs)
- How do we get spectral hardening at the knee? For energy-dependent CR diffusion $\sim E^{-0.6}$, we need a spectral index for CR momentum of $2 (3.1-0.6) = 5$
- Solve Fokker-Planck Equation in Flux Tube coordinates:

$$
\frac{\partial f}{\partial t} + u(z) \frac{\partial f}{\partial z} = \frac{\partial}{\partial z} \left( \kappa \frac{\partial f}{\partial z} \right) + \frac{2z}{H^2 + z^2} \kappa \frac{\partial f}{\partial z} + \frac{1}{3p} \frac{\partial}{\partial p} \left( \frac{\partial u(z)}{\partial z} + \frac{2z}{H^2 + z^2} u(z) \right)
$$

- assume self-similar velocity field:
- $u(z)=V(\xi) \xi \, dR/dt, \, \xi=z/R(t)$

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

**Metric Tensor**

$$r = r_0 \sqrt{1 + \frac{z^2}{H^2}} \Rightarrow g_{ij} = \begin{pmatrix}
1 & 0 & \frac{sr_0^2}{rH^2} \\
0 & r^2 & 0 \\
\frac{sr_0^2}{rH^2} & 0 & 1 + \frac{z^2r_0^4}{r^2H^4}
\end{pmatrix}$$

**Top:** Flux tube geometry for a galactic wind perpendicular to the disk; shown is the area cross section; $H$ is the opening distance of the flux tube from the disk

**Bottom:** observed CR differential energy spectrum

---

*Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010*
CR acceleration beyond the “Knee” (III)

- **singular perturbation analysis:**
- use a power law ansatz: \( f \sim p^{-a} R(t)^b \)
- use \( \varepsilon = \kappa / (R \, dR/dt) \) as perturbation parameter
- match “inner” to “outer” solution, e.g. expand
  \[
  f(\xi) = \sum_i f_i(\xi) \varepsilon^i
  \]
- we obtain a correction term to the CR power law index \( a \) *(for \( R \to 0 \) pert. theory breaks down)*
- \( a \) tends rapidly to \( a=5 \) for increasing \( R \) (or \( z \)) as required
- **Conclusion:** increased star formation in the disk can cause shock waves to propagate into the halo and **post-accelerate** GCRs
- HCRs can explain observed energies **and** the steepening of the spectrum

**Top:** Power law index of CR particle momentum spectrum in a galactic wind outflow (in flux tube coordinates) modified by increasing star formation

**Bottom:** same, but for Milky Way parameters
Summary & Conclusions

- ISM is a highly **turbulent** compressible medium → **nonlinear** dynamics
- **High resolution** (parallel computers, AMR) simulations necessary
- **Requirements**: (i) box sufficiently **large** not to be dominated by boundary conditions, (ii) time evolution **long** enough to wipe out memory of initial conditions, (iii) ensure that results are **resolution independent**
- SN dominated ISM shows structures on **all** scales (**turbulent coupling**)
- **Turbulence** fed by **on-going star formation**
- **Galactic fountain** acts as pressure release valve, reducing pressure in the disk → volume filling factor of hot gas is reduced
- ISM is not in pressure equilibrium, flow is **ram pressure** dominated
- interstellar clouds are **shock compressed** (transient) layers
- substantial amount of ISM in **thermally unstable** temp. range (e.g. 50% of HI mass)
- enhanced star formation and **superbubbles** drive **galactic winds**
- winds can explain **X-ray** and **radio halos** → thermally & dynamically self-consistent models → flattening of **radio spectral index** due to **advection flow**
- **CR acceleration** beyond the “**knee**” → wind shocks can explain energies & spectrum!
Thank you for your attention!

“The only part of the Universe which isn’t expanding is the budget for this place.”

Dieter Breitschwerdt - Workshop on “Magnetic Fields on scales from kpc to km” - Cracow, 18.5.2010