Interstellar plasma and magnetic fields

Katia FERRIÈRE

Institut de Recherche en Astrophysique et Planétologie,
Observatoire Midi-Pyrénées, Toulouse, France

ÉCOLE DE PHYSIQUE
des HOUCHES

The future of plasma astrophysics
Combining experiments, observations, simulations and theory
Les Houches – February 25 - March 8, 2013

Outline

1. General context
2. Interstellar gas
   - Observational status
   - Ionized component
3. Interstellar magnetic fields
   - Observational status
   - Galactic dynamo
   - Impact on the ISM

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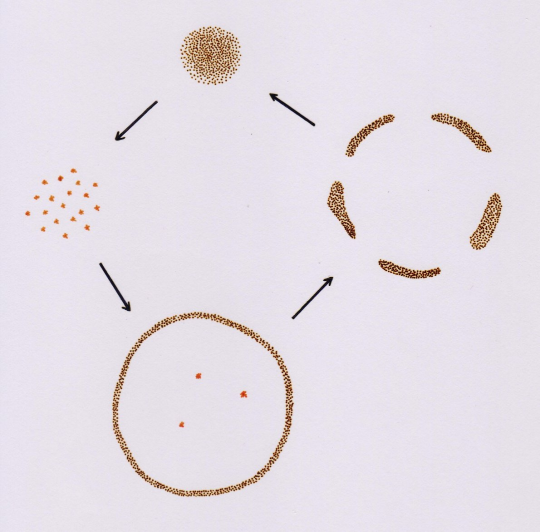
General cycle ISM $\rightleftharpoons$ Stars



The 3 basic constituents of the ISM

- Ordinary matter (gas & dust)

$$\begin{array}{lllll} n & \simeq & < 0.01 & \rightarrow & > 100 \quad \mathrm{cm}^{-3} \\ T & \simeq & 10^6 & \rightarrow & 10 - 20 \quad \mathrm{K} \end{array} \qquad (\langle n \rangle_\odot \sim 1 \ \mathrm{cm}^{-3})$$

- Cosmic rays

$$P_{\mathrm{CR}} \sim P_{\mathrm{g}}$$

- Magnetic fields

$$B \sim 5 \ \mu\mathrm{G} \quad \Rightarrow \quad P_{\mathrm{M}} \sim P_{\mathrm{g}}$$

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Main properties

- Mass
  $\sim 10 - 15\ \%$ of the total mass of the Galactic disk

- Composition

Element	Fraction by number	Fraction by mass
Hydrogen	91 %	70.6 %
Helium	9 %	27.5 %
"Metals"	0.14 %	1.9 %

☞

Gas	99 %
Dust	1 %

- Gas components

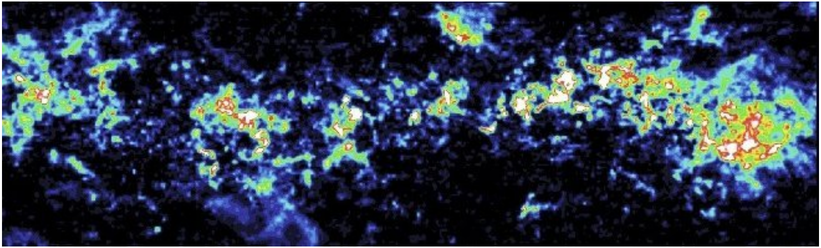
Component	T [K]	n_H [cm^{-3}]
Molecular	$10 - 20$	$10^2 - 10^6$
Cold atomic	$20 - 100$	$20 - 100$
Warm atomic	$10^3 - 10^4$	$0.2 - 2$
Warm ionized	$\sim 10^4$	$0.1 - 0.3$
Hot ionized	$\sim 10^6$	$0.003 - 0.01$

Molecular gas

Observational tools

- *Optical* & *UV* absorption lines
- *Radio* emission lines (CO $J = 1 \rightarrow 0$ line @ 2.6 mm)

^{12}CO integrated intensity map ($[280°, 300°] \times [-4°, 2°]$)



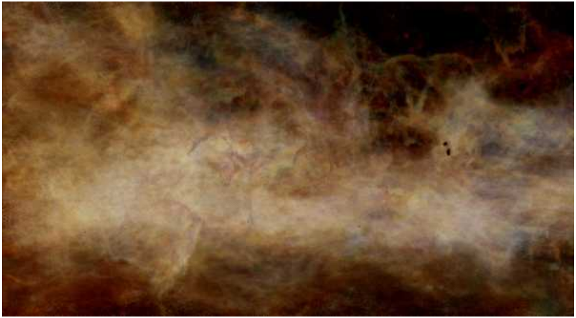
Nanten radio telescope, Nagoya University

Atomic gas

Observational tools

- *UV* absorption lines (H I Lyα line @ 1216 Å)
- *Radio* H I 21 cm line (emission & absorption)

H I 21 cm integrated intensity map ($16^\circ \times 9^\circ$ toward Perseus Arm)



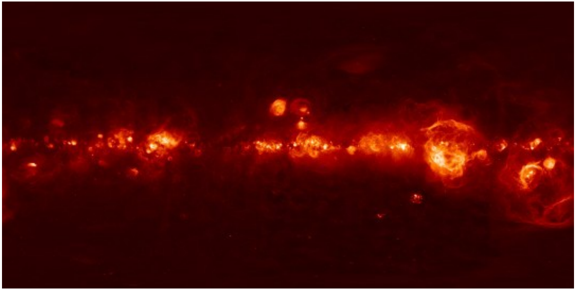
Canadian Galactic Plane Survey. Credit: Jayanne English (U. Manitoba) & Russ Taylor (U. Calgary).

Warm ionized gas

Observational tools

- *Radio* continuum (free-free) emission
- *Optical*, *IR* & *radio* emission lines (Hα recombination line @ 6563 Å)
- Pulsar dispersion measures

All-sky Hα total intensity map



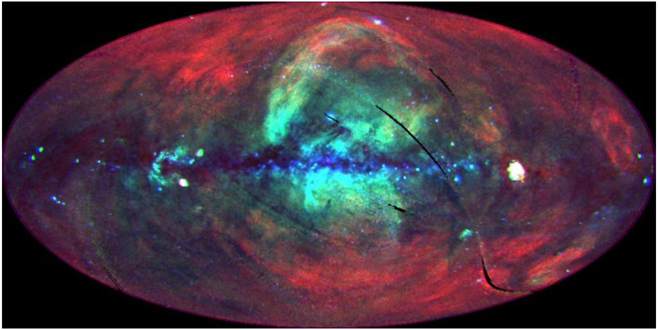
Composite of WHAM, VTSS & SHASSA. Credit: Douglas Finkbeiner.

Hot ionized gas

Observational tools

- *UV* absorption lines of high-stage ions (OVI, NV)
- *Soft X-ray* thermal emission

All-sky map of soft X-ray diffuse background

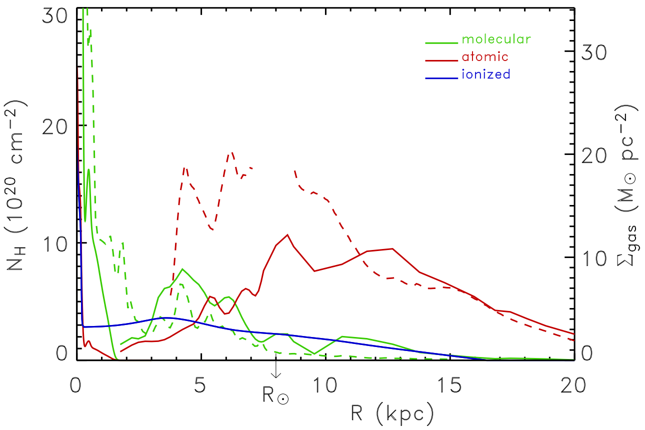


Composite from ROSAT all-sky survey (red=0.25 keV; green=0.75 keV; blue=1.5 keV). Credit: Steve Snowden.

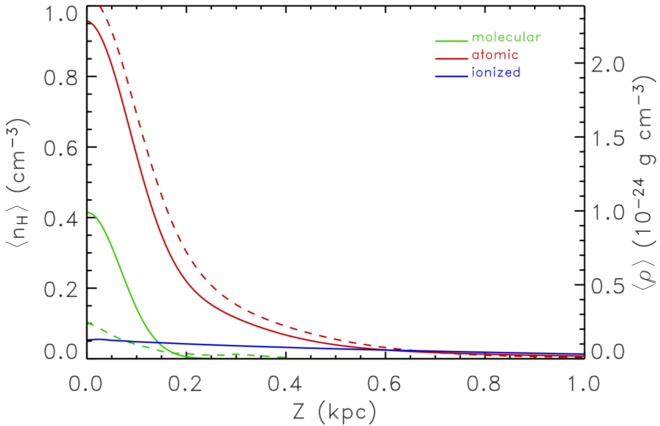
Spatial distribution at small scales

- Molecular gas
  Confined to massive, dense and cold clouds
  → Molecular clouds
- Cold atomic gas
  Confined to generally less imposing clouds
  → Diffuse clouds
- Warm & hot gas components
  Widespread distribution
  → Intercloud medium

Large-scale radial distribution



Large-scale vertical distribution



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Sources of ionization

- Neutral media (MM, CNM, WNM)

  - Low-energy cosmic rays
  - Soft X-rays
  - Starlight photons with $E < 13.6$ eV (ionization of C...)

  ☞ $x \gtrsim (10^{-8} - 10^{-6})$ in MM
  $x \sim (0.0004 - 0.001)$ in CNM
  $x \sim (0.007 - 0.05)$ in WNM

- Warm ionized medium (WIM)

  - Stellar UV photons with $E > 13.6$ eV (mainly OB stars)

  ☞ $x_{\rm H} \gtrsim 0.9$ & $x_{\rm He} \lesssim 0.3$

- Hot ionized medium (HIM)

  - High temperatures ($T \sim 10^6$ K)

  ☞ $x \simeq 1$

A few characteristic figures

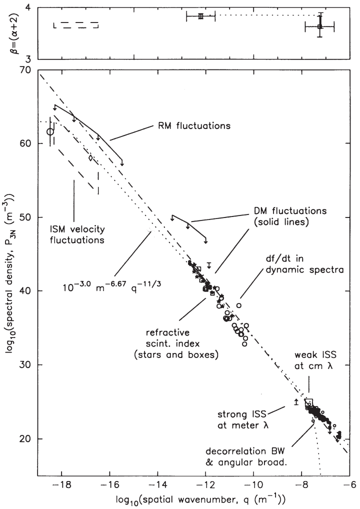
Collisional parameters

	CNM	WNM	WIM	HIM
τ_e	10 min	1 month	10 hr	20 yr
τ_p	10 hr	5 yr	20 days	10^3 yr
λ_p	$10^{4.5}$ km	10 AU	0.2 AU	0.2 pc
Pm	10^4	$10^{12.5}$	10^{11}	10^{20}
Re			10^7	10^3
Rm			10^{18}	10^{23}
τ_{in}	$(0.2 - 1)$ yr	$(10 - 100)$ yr		
τ_{ni}	$(10^2 - 10^3)$ yr	$(10^2 - 10^4)$ yr		

Gyration parameters

	For $B = 5\ \mu$G
ω_e^{-1}	0.01 sec
ω_p^{-1}	20 sec
ρ_e	(60 m) $\sqrt{T_e}$
ρ_p	(3 km) $\sqrt{T_p}$

Turbulence



Radio wave propagation measurements

- angular broadening
- interstellar scintillation (ISS)
- temporal broadening of pulsar pulses
- pulsar DM fluctuations
- RM fluctuations

☞ Spatial power spectrum of δn_e

Single power law

with $\beta \simeq \frac{11}{3}$ (Kolmogorov)

over $\ell \approx 1\,000$ km – 100 AU [a few pc]

☞ *Big power law in the sky*

(Armstrong, Rickett, & Spangler 1995)

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Observational methods

- Linear polarization of starlight & dust emission
  ☞ General orientation of $\vec{B}_\perp$
- Zeeman splitting
  ☞ $B_\parallel$ in neutral regions (molecular & atomic clouds)
- Faraday rotation
  ☞ $B_\parallel$ in ionized regions
- Synchrotron emission
  ☞ $B_\perp$ & $(\vec{B}_{\rm ord})_\perp$ in general ISM

Results on the magnetic field strength

- In neutral regions
  - In atomic clouds : $B \sim$ a few μG
  - In molecular clouds : $B \sim (10 - 3000)\ \mu$G
- In ionized regions
  - Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm turb} \sim 5\ \mu$G
- In general ISM
  - Near the Sun : $B_{\rm ord} \sim 3\ \mu$G & $B_{\rm tot} \sim 5\ \mu$G
  - Global spatial distribution : $L_{\rm B} \sim 12$ kpc & $H_{\rm B} \sim 4.5$ kpc

Results on the magnetic field direction

- Near the Sun
  - $\vec{B}_{\rm reg}$ is horizontal & nearly azimuthal $(p \simeq -7°, -8°)$
- In the Galactic Disk
  - $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal
  - $\vec{B}_{\rm reg}$ reverses direction with decreasing radius
  - $\vec{B}_{\rm reg}$ is symmetric in z
  - $\vec{B}_{\rm reg}$ is neither pure ASS nor pure BSS
- In the Galactic Halo
  - $\vec{B}_{\rm reg}$ has horizontal & vertical components
  - $\vec{B}_{\rm reg}$ is anti-symmetric in z

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Very first cosmic magnetic fields

- Universe born with a magnetic field
  ☞ $B_0 \lesssim (10^{-9} - 10^{-8})$ G

- Exotic processes during phase transition in early Universe
  ☞ $B_0 \lll$

- Battery effect

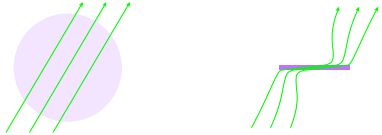
  - Biermann battery at oblique shocks (formation of protogalaxies ...) or ionization fronts (epoch of re-ionization)
    ☞ $B_0 \sim (10^{-20} - 10^{-18})$ G

  - Harrison-Rees battery in collapsing protogalaxies
    ☞ $B_0 \sim 10^{-20}$ G

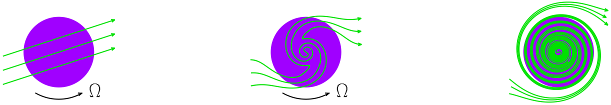
  - Battery effect in the first stars or in AGNs

Primordial galactic magnetic fields

- Compression of field lines *upon protogalaxy collapse*



- Stretching of field lines *by galactic differential rotation*



Alpha effect

Magnetic field generation in the direction $\perp \vec{B}_0$
due to small-scale cyclonic turbulence

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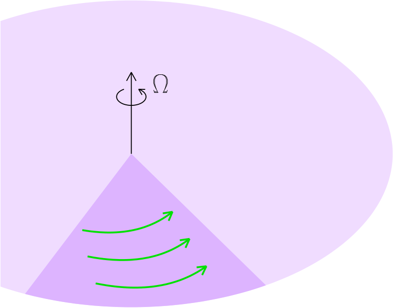

Alpha effect

Magnetic field generation in the direction $\perp \vec{B}_0$
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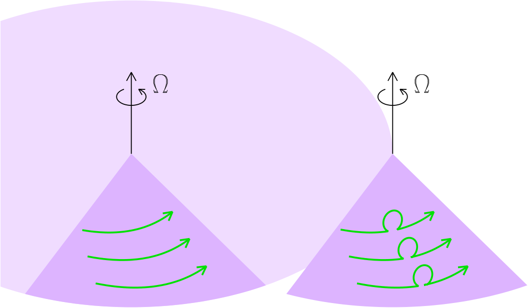

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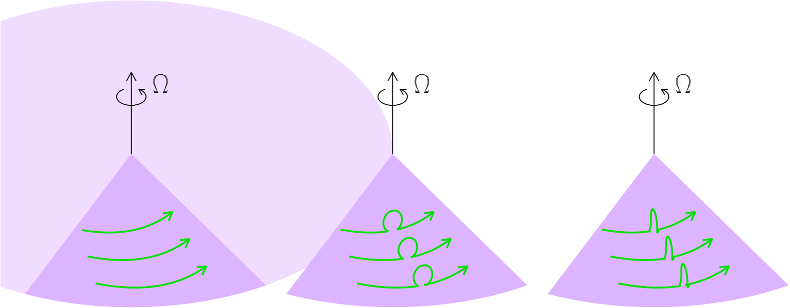

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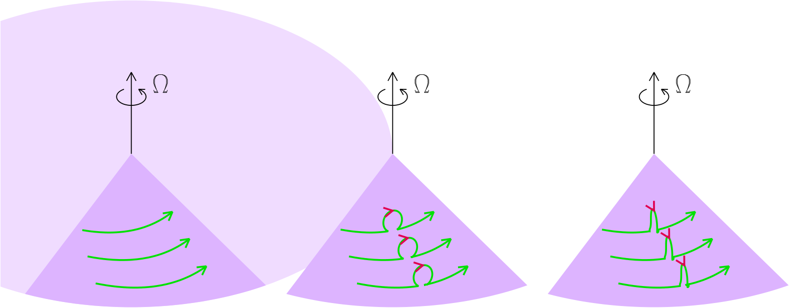

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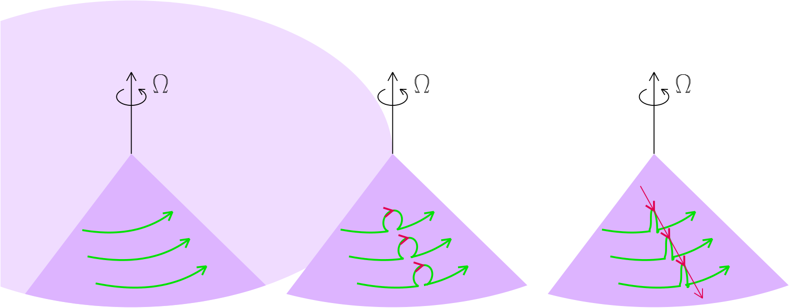


Galactic dynamo

- Azimuthal stretching of field lines *by large-scale differential rotation*

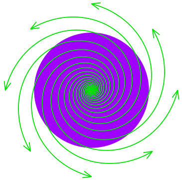
- Alpha effect *due to small-scale cyclonic turbulence*

Predictions from dynamo theory: Overall geometry

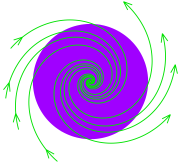
- In the disk
  - B_Φ dominant — strong differential rotation
  - $B_R \sim 0.1\ B_\Phi$ — weaker alpha effect
  - $B_Z \ll B_R$ — disk geometry $\Rightarrow\ \partial_R, \partial_\Phi \ll \partial_Z$
    $\Rightarrow$ weaker alpha effect on B_Z
- In the halo
  - $B_Z \sim B_R$ — spherical geometry
  - B_Φ large — *if* strong differential rotation
  - B_R, B_Z large — *if* Galactic wind

Azimuthal structure

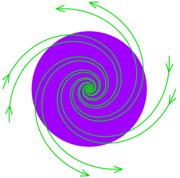
- If underlying galaxy is axisymmetric
  $\Rightarrow$ - ASS $(m = 0)$ is always easiest to amplify
  - Higher-order modes generally decay in time



- If external disturbance
  $\Rightarrow$ Possible to excite BSS $(m = 1)$

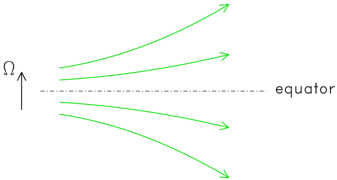


- If underlying spiral or bar
  $\Rightarrow$ Possible to excite QSS $(m = 2)$

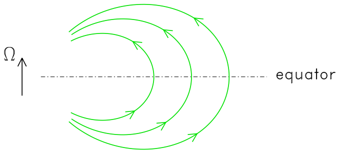


Vertical symmetry (for ASS)

- Under typical galactic conditions
  $\Rightarrow$ Both S0 & A0 are amplified



- If the disk dominates
  $\Rightarrow$ S0 grows faster



- If the halo dominates
  $\Rightarrow$ A0 grows faster

- Possibly mixed S0-A0 configuration
  with S0 dominant in the disk
  A0 dominant in the halo

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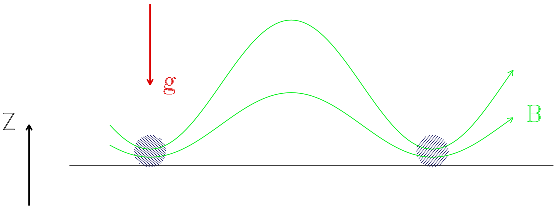
Dynamic effects

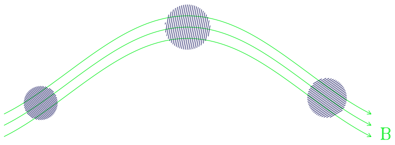
- In general
  - *Couple* the cosmic rays to the gas
  - *Stiffen* the ISM
- At large scales
  - Partake in the hydrostatic balance
    - *Support* the gas against gravity
    - *Confine* cosmic rays to the Galactic disk
  - Give rise to the *Parker instability*
- At small scales
  - *Oppose* the expansion of SNRs and SBs
  - *Constrain* the random motions of IS clouds
  - *Brake* the rotation of molecular clouds
  - *Support* molecular clouds against self-gravity
  - *Control* star formation

Parker instability

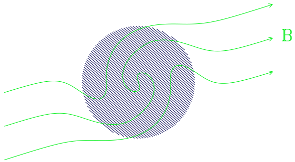


Effects of magnetic fields on cloud motions

- Translational motions



- Rotational motions



Energetic effects

- In general
  - *Suppress* thermal conduction & other diffusion processes
  - *Heat up* the gas through magnetic reconnection
  - *Accelerate* cosmic rays