The Interstellar Medium

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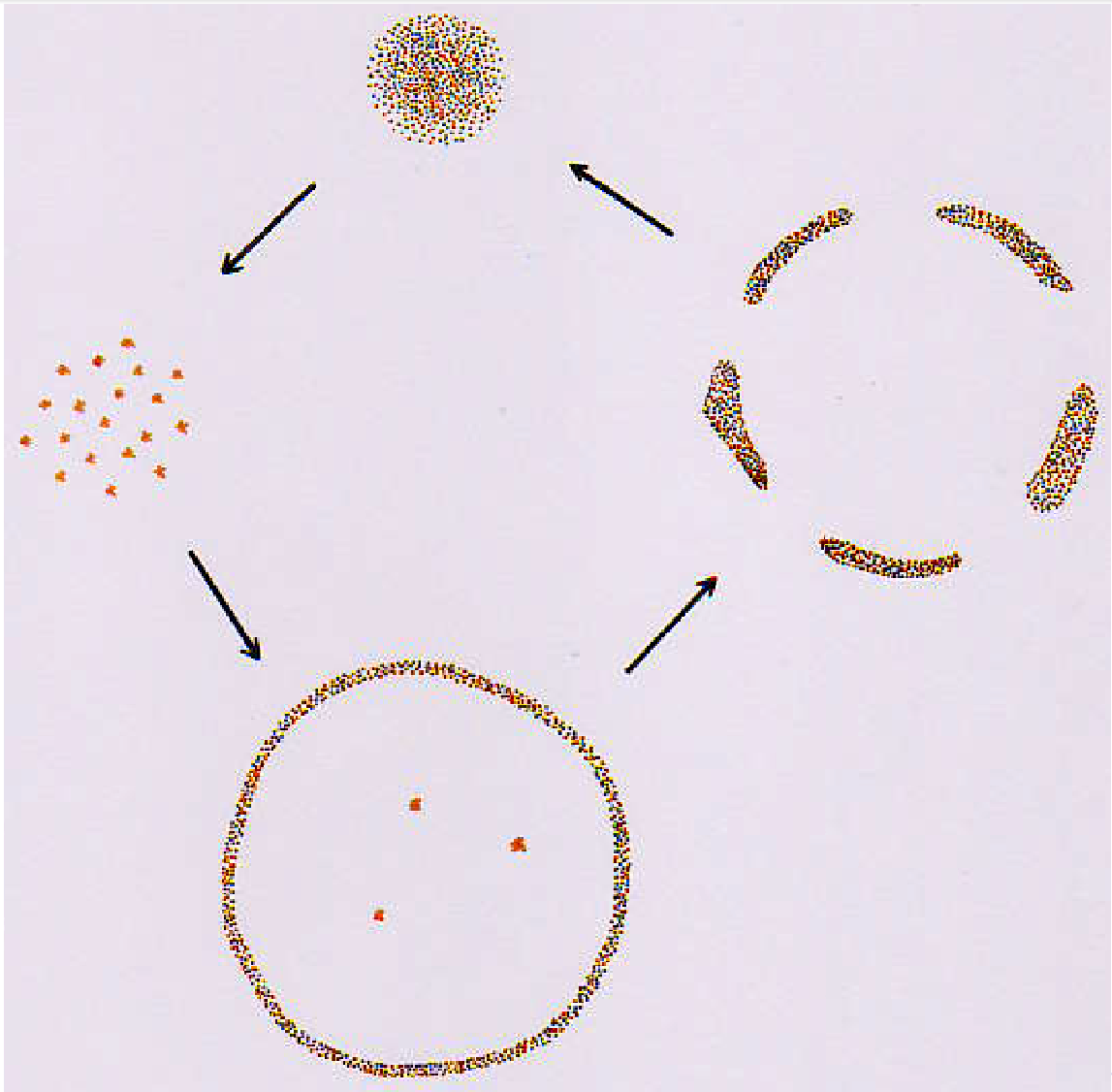
Outline

1. The 3 basic constituents of the ISM
   - Ordinary matter
   - Cosmic rays
   - Magnetic fields
2. Interactions between the 3 constituents
   - Role played by magnetic fields
   - Role played by cosmic rays
   - Role played by the gas
3. Interactions with stars
   - Role played by stars
   - Supernovae and superbubbles
4. ISM science with the SKA

General cycle ISM ⇌ Stars



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The 3 basic constituents of the ISM

- Ordinary matter (gas & dust)

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

- Cosmic rays

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

- Magnetic fields

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

Ordinary matter

- 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 %

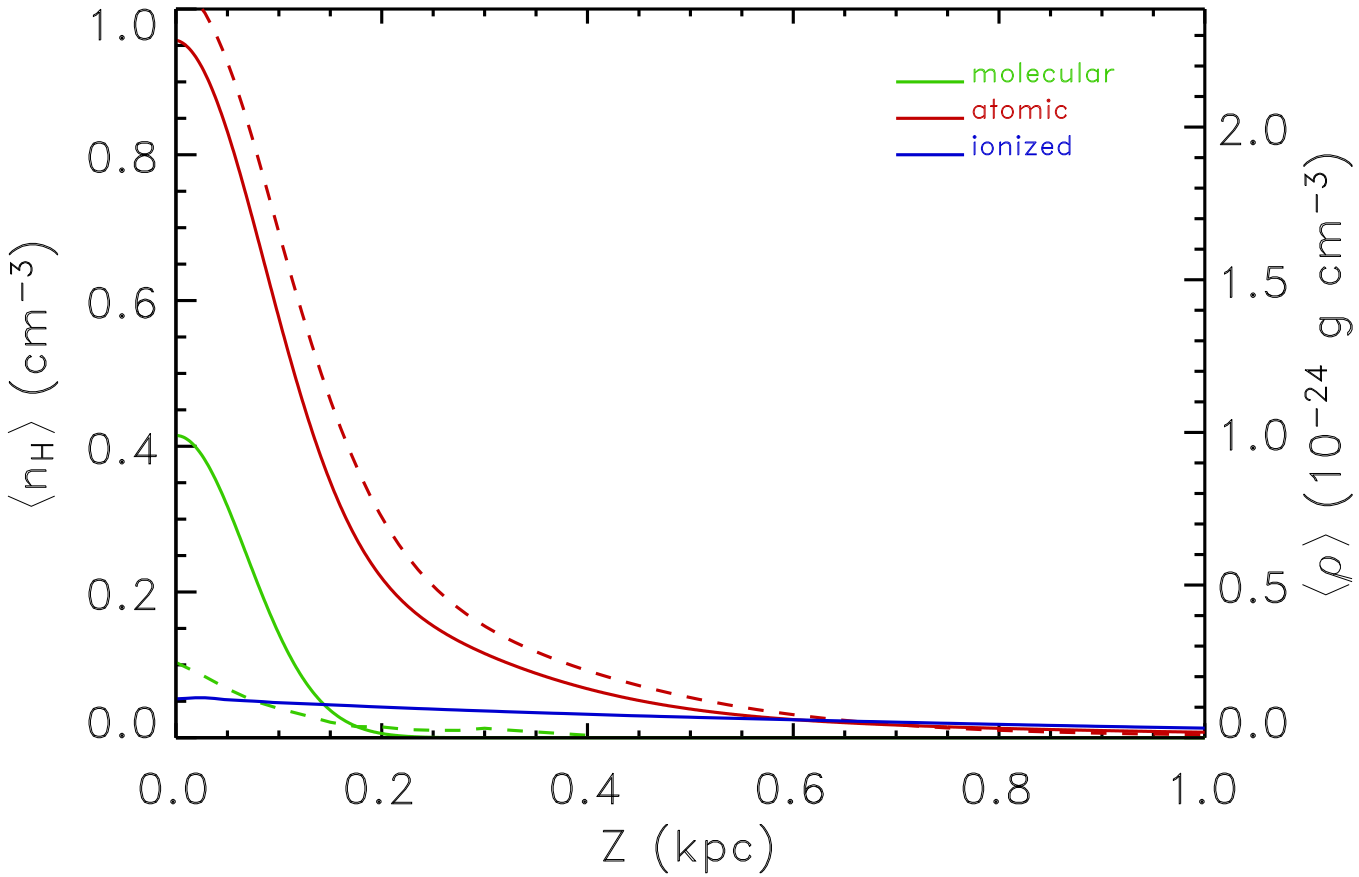
- Gas components

Component	T (K)	$n_{\rm H}$ (cm^{-3})
Molecular	$10 - 20$	$10^2 - 10^6$
Cold atomic	$20 - 100$	$20 - 100$
Warm atomic	$1\,000 - 10\,000$	$0.2 - 2.0$
Warm ionized	$\sim 8\,000$	$0.1 - 0.3$
Hot ionized	$\sim 10^6$	$0.003 - 0.01$

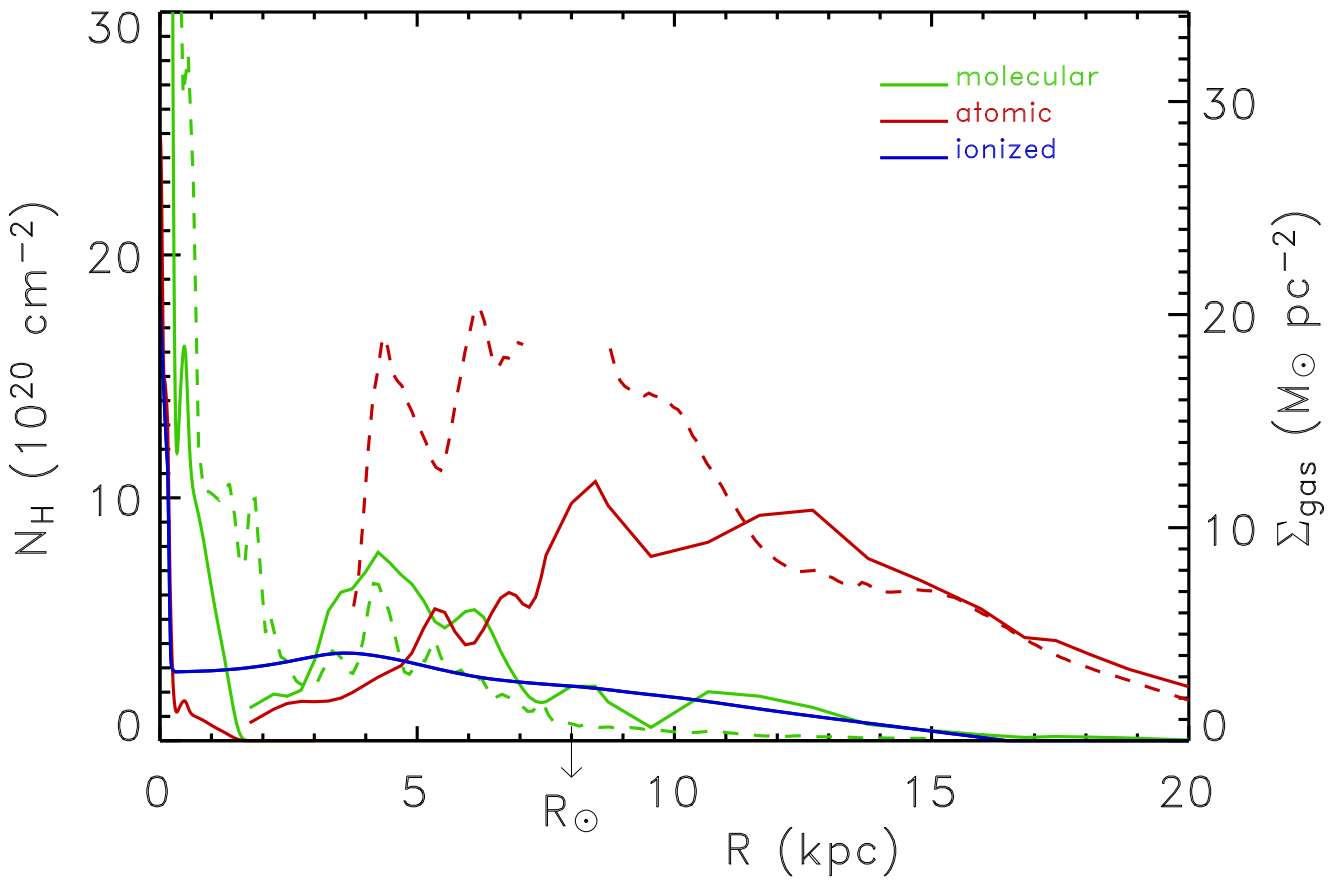
Detection methods

- Molecular gas
  - *Optical* & *UV* absorption lines
  - *Radio* emission lines (CO $J = 1 \rightarrow 0$ line @ 2.6 mm)
- Atomic gas
  - *UV* absorption lines (HI Lyα line @ 1216 Å)
  - *Radio* HI 21 cm line (emission & absorption)
- Warm ionized gas
  - *Radio* continuum emission
  - *Optical*, *IR* & *radio* emission lines (Hα recombination line @ 6563 Å)
  - Pulsar dispersion measures
- Hot ionized gas
  - *UV* absorption lines of high-stage ions (OVI, NV)
  - *Soft X-ray* thermal emission

Space-averaged density near the Sun



Surface density



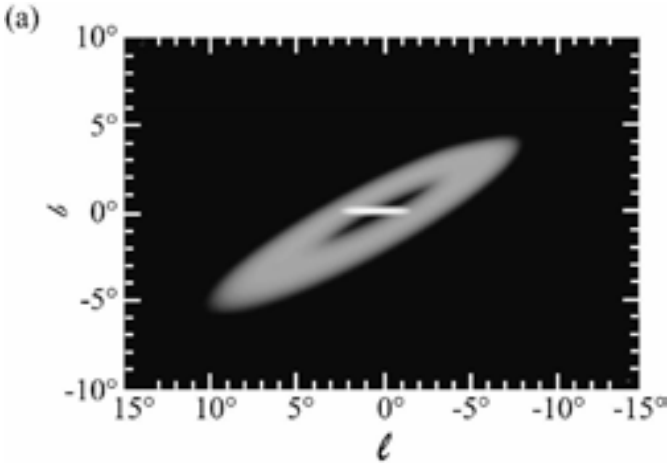
In the Galactic Bulge

- Neutral gas (~ 91% molecular & ~ 9% atomic)
  - *Central molecular zone (CMZ)*
    - Thin sheet of gas – ~ parallel to GP – displaced from GC
    - Projected radius ~ 200 pc
    - Thickness ~ 30 pc (molecular) & ~ 90 pc (atomic)
  - *Galactic Bulge (GB) disk*
    - Thicker layer of gas – tilted to GP & inclined to l.o.s.
    - Projected radius ~ 1.3 kpc
    - Thickness ~ 70 pc (molecular) & ~ 200 pc (atomic)
    - Hole around CMZ

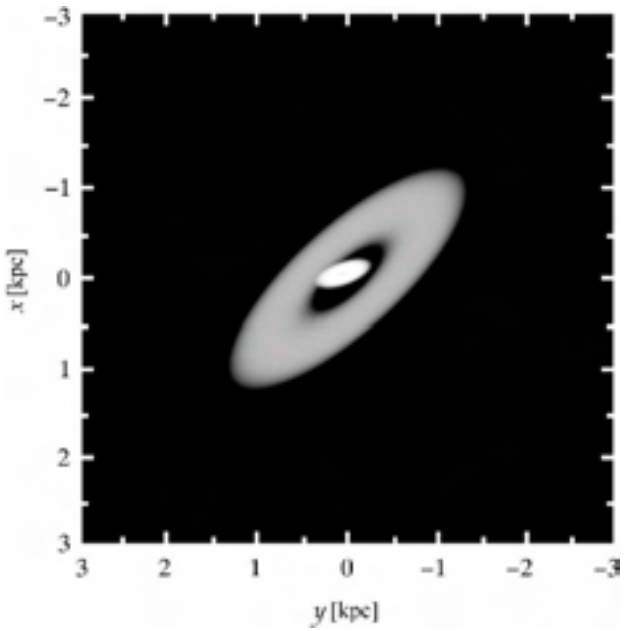
- Ionized gas (~ 83% warm & ~ 17% hot)
  - Widespread distribution throughout GB
    scale height ~ 1 kpc (warm) & ~ 2 kpc (hot)
  - Local concentration around GC
    radius ~ 120 pc & thickness ~ 40 pc

CMZ & GB disk (molecular gas)

Projection onto p.o.s



Face-on view



Cosmic rays

- Near the Sun
  Voyager 1 CR data
  $e_{\mathrm{CR}} \simeq 1.8$ eV cm^{-3}
- Radial distribution
  γ-ray intensity maps
  $L_{\mathrm{CR}} \sim 13$ kpc
- Vertical distribution
  CR propagation models + measured CR elemental composition
  $H_{\mathrm{CR}} \lesssim 3$ kpc
- Global distribution
  Synchrotron emission measurements

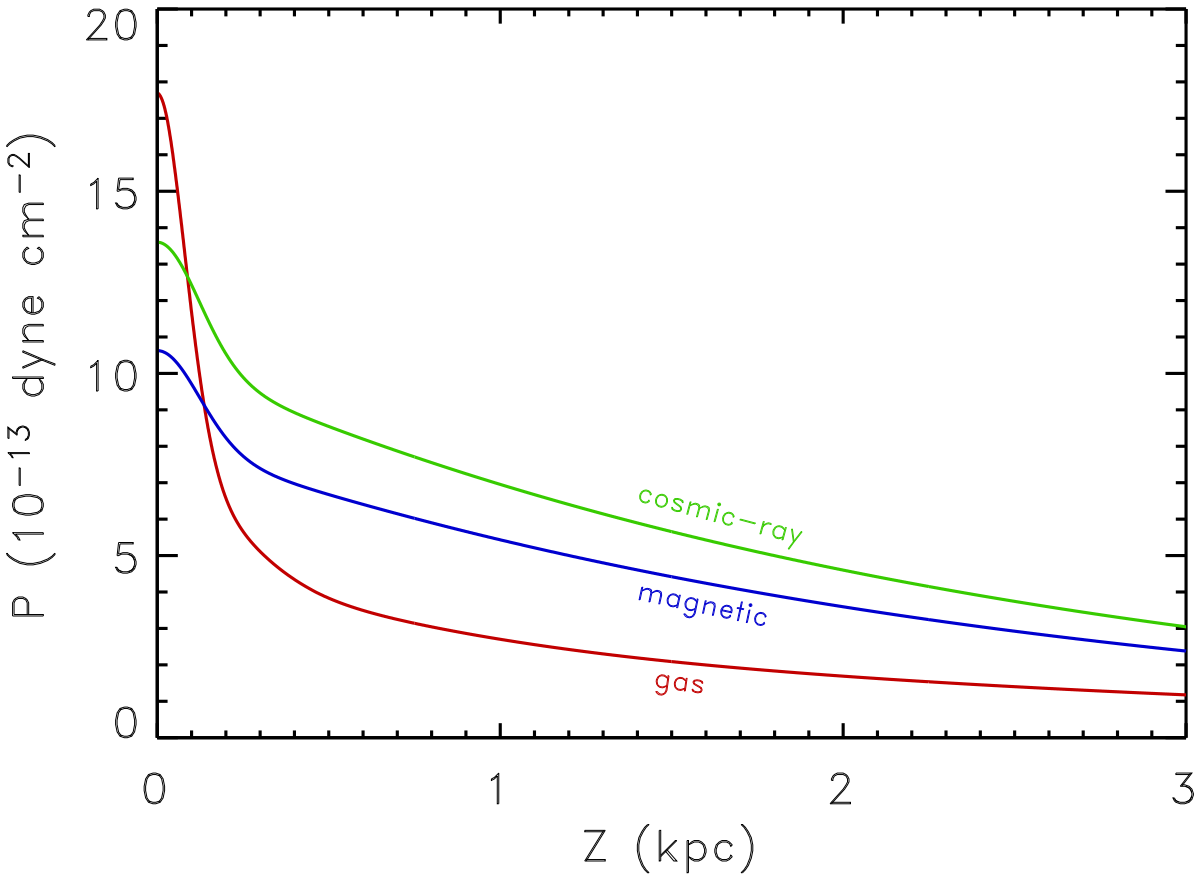
Magnetic fields

- Near the Sun
  Measured polarization of starlight
  $\vec{B}$ is horizontal & nearly azimuthal (angle $\simeq 7°$)
- In neutral regions
  Zeeman splitting measurements
  - In atomic clouds : $B \sim$ a few μG
  - In molecular clouds : $B \sim (10 - 3000)\ \mu$G
- In ionized regions
  Faraday rotation measurements
  - $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm turb} \sim 5\ \mu$G near $\odot$
  - $\vec{B}_{\rm reg}$ is nearly horizontal & predominantly azimuthal away from the GC
  - Reversals in B_Φ in the disk ($\Rightarrow$ spiral structure ?)
- In general ISM
  Synchrotron emission measurements
  - $B_{\rm tot} \sim 5\ \mu$G near $\odot$ $\rightarrow$ $B_{\rm tot} \sim 7\ \mu$G in MR
  - Global spatial distribution ($L_{\rm B} \sim 12$ kpc & $H_{\rm B} \sim 4.5$ kpc)

Near the Galactic Center

- Non-thermal radio filaments
  - ∗ *Morphology & radio (synchrotron) polarization measurements*
    $\vec{B}$ ∥ filaments ⇒ $\vec{B} \perp$ GP
  - ∗ *Dynamical argument*
    No distortion ⇒ $B \gtrsim 1$ mG
  - ∗ *Radio (synchrotron) intensity measurements*
    $B_{\rm equip} \sim (50 - 200)\ \mu$G
- In general ISM
  Diffuse synchrotron intensity measurements
  $B_{\rm equip} \sim 10\ \mu$G
- In dense molecular clouds
  FIR/submm (dust thermal emission) polarization measurements
  $\vec{B}$ is nearly ∥ GP

Interstellar pressures near the Sun



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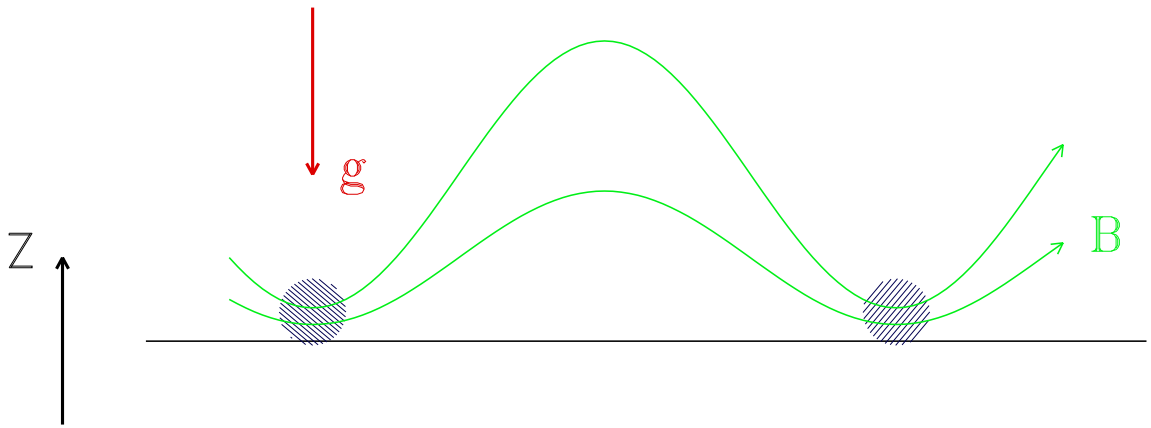
Role played by magnetic fields

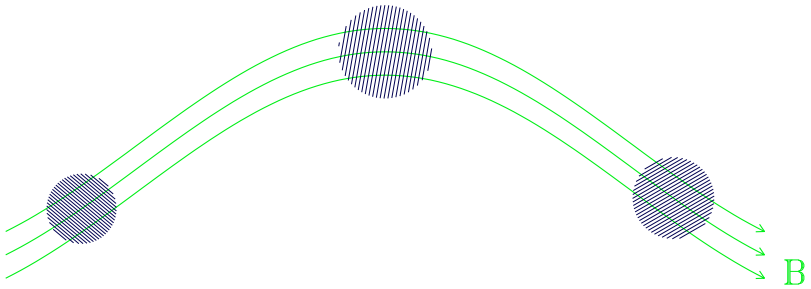
- Dynamic effects
  - ∗ *In general*
    - Couple the cosmic rays to the gas
    - Stiffen the ISM
  - ∗ *At large scales*
    - Partake in the hydrostatic balance
      - Support the gas against gravity
      - Confine cosmic rays to the Galactic disk
    - Give rise to the Parker instability
  - ∗ *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

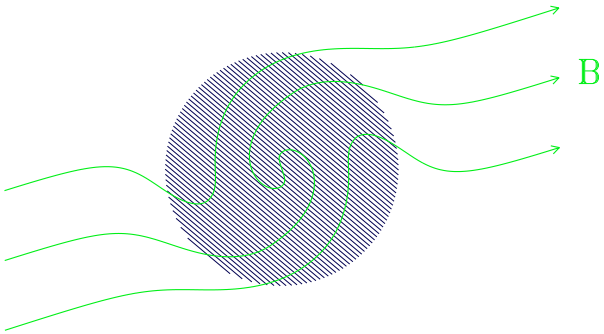


Effects of magnetic fields on cloud motions

- Translational motions



- Rotational motions



Role played by magnetic fields

- Energetic effects
  - Suppress thermal conduction & other diffusion processes
  - Heat up the gas through magnetic reconnection
  - Accelerate cosmic rays

Role played by cosmic rays

- Dynamic effects
  - *In general*
    - Exert their full pressure on the gas
  - *At large scales*
    - Contribute to the hydrostatic balance
    - Affect the Parker instability
  - *At small scales*
    - Oppose the expansion of SNRs and SBs
    - Help to support molecular clouds
- Energetic effects
  - Ionize the gas
  - Heat up the gas through ionizing collisions
    Coulomb collisions
    damping of self-excited waves

Role played by the gas

- For cosmic rays
  - Provides a reservoir of energetic particles
  - Fermi accelerates cosmic rays through its turbulent motions
  - Confines cosmic rays to the Galactic disk

- For magnetic fields
  - Amplifies magnetic fields through its (ordered + turbulent) motions
    → *Galactic dynamo*
  - Confines magnetic fields to the Galactic disk

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Role played by stars

- Stellar radiation field (UV photons)
  - Dissociates molecules
  - Ionizes the IS gas $\rightarrow$ H II regions & WIM
  - Heats up the IS gas
- Stellar winds
  - Source of enriched matter for the ISM
  - Same dynamical effects as supernovae
- Supernova explosions
  - Source of enriched matter for the ISM
  - Forge the structure of the ISM $\rightarrow$ hot cavities & expanding shells
  - Accelerate cosmic rays
  - Amplify magnetic fields
- Other effects
  - Generate low-energy cosmic rays
  - Produce seed magnetic fields (?)

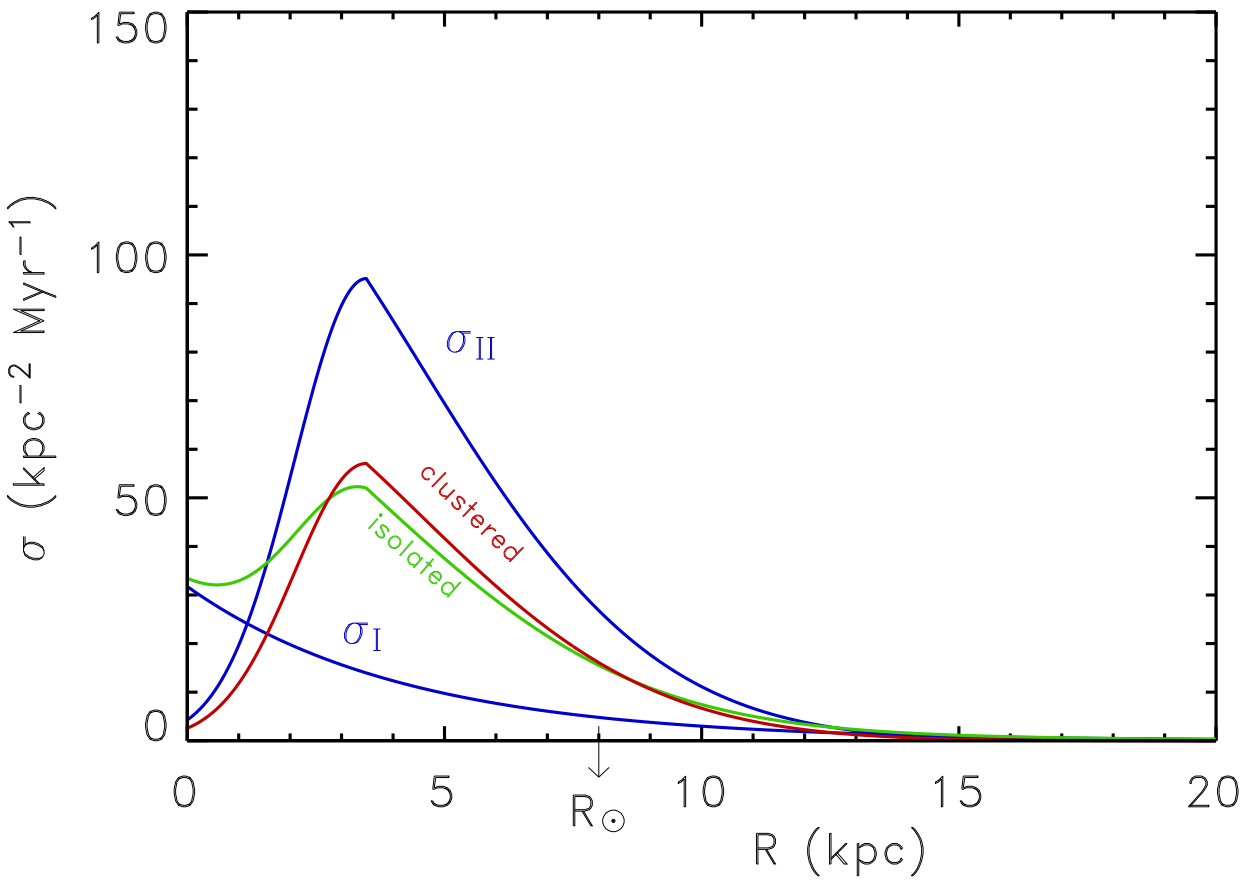
Supernovae and superbubbles

- Type I supernovae
  - From old, degenerate stars
  - Galactic frequency $\simeq 1/250\,\mathrm{yr}$
  - All isolated

- Type II supernovae
  - From young, massive stars
  - Galactic frequency $\simeq 1/60\,\mathrm{yr}$
  - $40\,\%$ isolated

    $60\,\%$ clustered $\rightarrow$ superbubbles $(\langle N \rangle \simeq 30)$

Supernova rates



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ISM science with the SKA

- Molecular gas

  - CO 2.6 mm
    Not observable in MW, but observable in galaxies with $z \gtrsim 4$

  - Strong lines : H_2CO 6 cm, OH 18 cm, NH_3 1.3 cm ...
    Observable in galaxies out to several 100 Mpc @ resol. $\sim$ 10 mas
    $\rightarrow$ Study of protostellar sites @ sub-pc resolution

  - Weak lines : CH 10 cm ...
    Observable in nearby galaxies @ resol. $\sim 10''$
    $\rightarrow$ Imaging of large molecular clouds

  - Lines @ (0.6 - 1.5) cm : CS, SO, HC_3N ...
    Observable in galaxies with $z \gtrsim 1$
    $\rightarrow$ - Complement to CO studies
    - Physical conditions in molecular gas
    - Chemical evolution at early epochs

  - OH, H_2O masers in external galaxies
    $\rightarrow$ Probes of extragalactic star formation

ISM science with the SKA

- Atomic gas

  H I 21 cm line

  - Powerful tracer of H I from very young to present-day galaxies
    → Galaxy formation & evolution

  - Detailed spatial structure & kinematics of H I
    - Resolve individual H I clouds in external galaxies out to $\sim$ 20 Mpc
    - Detailed properties of H I clouds / shells across MW and in MCs
    - Continuous turbulent spectrum in MW from $\gtrsim$ 1 kpc → a few 10 AU

  - HVCs in galactic halos
    → - Disk-halo interactions (galactic fountain vs. infall of EG gas)
      - Physical conditions in MW halo

  - Comparisons between emisson & absorption measurements
    → Distinction between cold & warm H I

ISM science with the SKA

- Warm ionized gas

  - *Radio continuum emission*
    → - Physical parameters (T, n, ϕ) of H II regions / WIM
      - Tracer of massive star formation → star formation history ...

  - *Radio recombination lines* of H, He, C ...
    → - Kinematic imaging of ionized gas
      - Info on T, n, ionization state & abundances in H II regions / WIM
      - Tracers of massive star formation

  - *Pulsar dispersion measures & EGCS scattering measures*
    - Greatly expanded sample of pulsars & EGCSs
    - Both effects scale as λ^2

ISM science with the SKA

- Other drivers

  - Connections between ISM phases & phase changes in gas → stars
    (diffuse ISM → atomic clouds → molecular clouds → protostellar cores)

  - Stellar feedback on ISM structure, dynamics & composition
    H II regions & SNRs

  - Disk-halo interactions
    Impact of star formation & galactic environment