

# The Interstellar Medium

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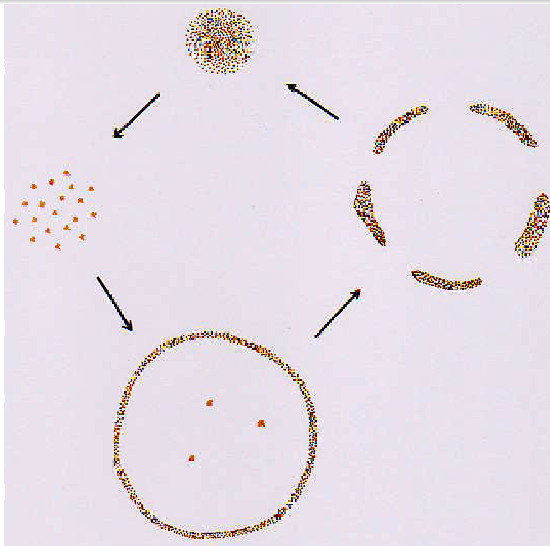
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# Outline

- 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 $\rightleftharpoons$ Stars



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# The 3 basic constituents of the ISM

- Ordinary matter (gas & dust)

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

- Cosmic rays

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

- Magnetic fields

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

# Ordinary matter

- Mass

~ 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 %

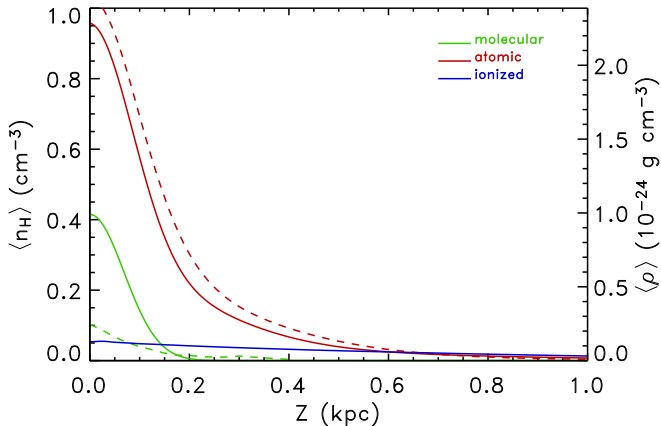
- Gas components

Component	$T$ (K)	$n_{\text{H}}$ (cm <sup>-3</sup> )
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	~ 8 000	0.1 – 0.3
Hot ionized	~ $10^6$	0.003 – 0.01

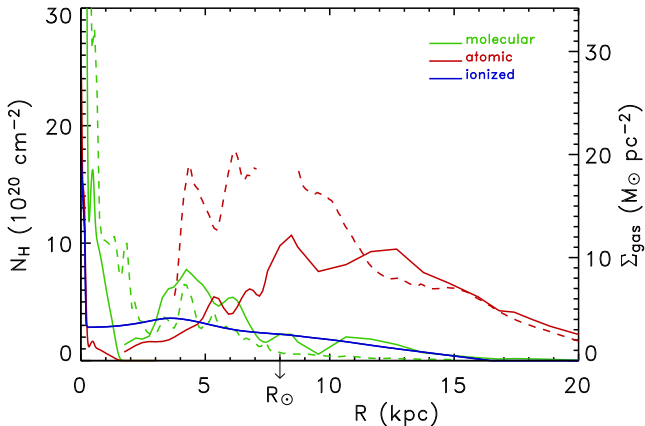
# Detection methods

- **Molecular gas**
  - *Optical* & *UV* absorption lines
  - *Radio* emission lines (CO  $J = 1 \rightarrow 0$  line @ 2.6 mm)
- **Atomic gas**
  - *UV* absorption lines (H $\text{I}$  Ly $\alpha$  line @ 1216 Å)
  - *Radio* H $\text{I}$  21 cm line (emission & absorption)
- **Warm ionized gas**
  - *Radio* continuum emission
  - *Optical*, *IR* & *radio* emission lines (H $\alpha$  recombination line @ 6563 Å)
  - Pulsar dispersion measures
- **Hot ionized gas**
  - *UV* absorption lines of high-stage ions (O $\text{VI}$ , N $\text{V}$ )
  - *Soft X-ray* thermal emission

# Space-averaged density near the Sun



# Surface density

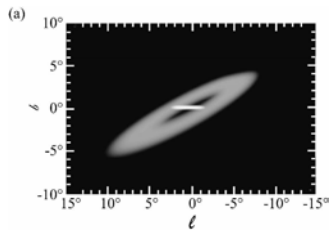


## In the Galactic Bulge

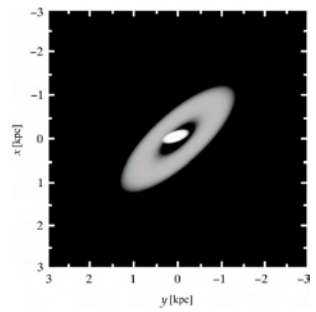
- **Neutral gas** (~ 91% molecular & ~ 9% atomic)
  - \* *Central molecular zone (CMZ)*
    - Thin sheet of gas – ~ parallel to GP – displaced from GC
    - Projected radius ~ 200 pc
    - Thickness ~ 30 pc (molecular) & ~ 90 pc (atomic)
  - \* *Galactic Bulge (GB) disk*
    - Thicker layer of gas – 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*

$$e_{\text{CR}} \approx 1.8 \text{ eV cm}^{-3}$$

- Radial distribution

*$\gamma$ -ray intensity maps*

$$L_{\text{CR}} \sim 13 \text{ kpc}$$

- Vertical distribution

*CR propagation models + measured CR elemental composition*

$$H_{\text{CR}} \lesssim 3 \text{ kpc}$$

- Global distribution

*Synchrotron emission measurements*

# Magnetic fields

- Near the Sun

*Measured polarization of starlight*

$\vec{B}$  is horizontal & nearly azimuthal (angle  $\simeq 7^\circ$ )

- In neutral regions

*Zeeman splitting measurements*

- In atomic clouds :  $B \sim$  a few  $\mu\text{G}$

- In molecular clouds :  $B \sim (10 - 3000) \mu\text{G}$

- In ionized regions

*Faraday rotation measurements*

-  $B_{\text{reg}} \simeq 1.5 \mu\text{G}$  &  $B_{\text{turb}} \sim 5 \mu\text{G}$  near  $\odot$

-  $\vec{B}_{\text{reg}}$  is nearly horizontal & predominantly azimuthal away from the GC

- Reversals in  $B_\Phi$  in the disk ( $\Rightarrow$  spiral structure ?)

- In general ISM

*Synchrotron emission measurements*

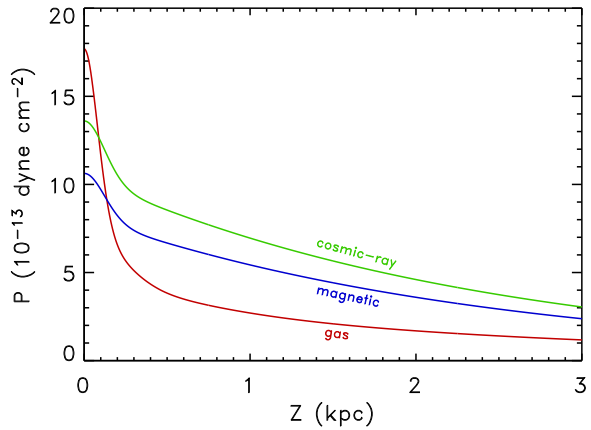
-  $B_{\text{tot}} \sim 5 \mu\text{G}$  near  $\odot \rightarrow B_{\text{tot}} \sim 7 \mu\text{G}$  in MR

- Global spatial distribution ( $L_B \sim 12 \text{ kpc}$  &  $H_B \sim 4.5 \text{ kpc}$ )

## Near the Galactic Center

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

# 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

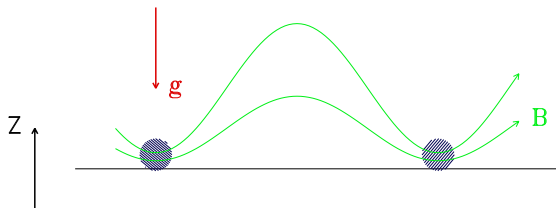
- \* *At large scales*

- 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*

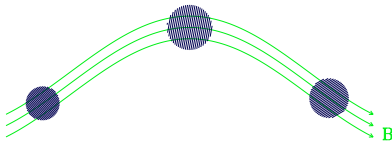
- Oppose the expansion of SNRs and SBs
    - Constrain the random motions of IS clouds
    - Brake the rotation of molecular clouds
    - Support molecular clouds against self-gravity
    - Control star formation

# Parker instability

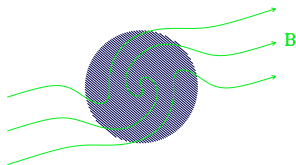


# Effects of magnetic fields on cloud motions

- 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 → H<sub>II</sub> 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 → hot cavities & expanding shells
  - Accelerate cosmic rays
  - Amplify magnetic fields
- **Other effects**
  - Generate low-energy cosmic rays
  - Produce seed magnetic fields (?)

# Supernovae and superbubbles

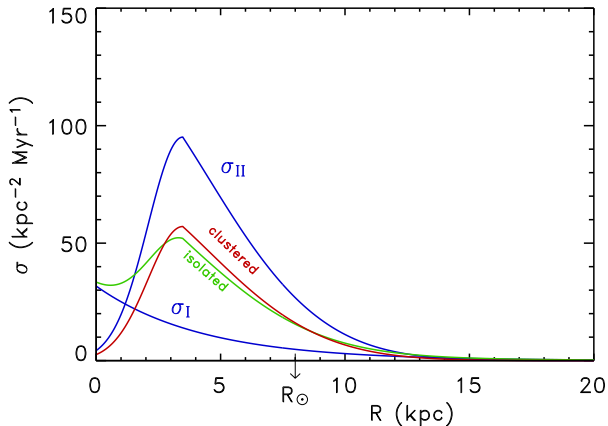
- Type I supernovae

- From old, degenerate stars
- Galactic frequency  $\approx 1/250 \text{ yr}$
- All isolated

- Type II supernovae

- From young, massive stars
- Galactic frequency  $\approx 1/60 \text{ yr}$
- 40 % isolated
- 60 % clustered  $\rightarrow$  superbubbles ( $\langle N \rangle \approx 30$ )

# 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<sub>2</sub>CO 6 cm, OH 18 cm, NH<sub>3</sub> 1.3 cm ...

Observable in galaxies out to several 100 Mpc @ resol.  $\sim 10$  mas

→ Study of protostellar sites @ sub-pc resolution

### - Weak lines : CH 10 cm ...

Observable in nearby galaxies @ resol.  $\sim 10''$

→ Imaging of large molecular clouds

### - Lines @ (0.6 - 1.5) cm : CS, SO, HC<sub>3</sub>N ...

Observable in galaxies with  $z \gtrsim 1$

→ - Complement to CO studies

- Physical conditions in molecular gas

- Chemical evolution at early epochs

### - OH, H<sub>2</sub>O masers in external galaxies

→ Probes of extragalactic star formation

# ISM science with the SKA

## ● Atomic gas

### H<sub>I</sub> 21 cm line

- Powerful tracer of H<sub>I</sub> from very young to present-day galaxies  
→ Galaxy formation & evolution
- Detailed spatial structure & kinematics of H<sub>I</sub>
  - Resolve individual H<sub>I</sub> clouds in external galaxies out to ~ 20 Mpc
  - Detailed properties of H<sub>I</sub> 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 emission & absorption measurements  
→ Distinction between cold & warm H<sub>I</sub>

# ISM science with the SKA

## ● Warm ionized gas

### - *Radio continuum emission*

- - Physical parameters ( $T, n, \phi$ ) 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  $\lambda^2$

# 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