The interstellar magnetic field near the Galactic center

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Magnetic fields on scales from kilometres to kiloparsecs: properties and origin

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Outline

1. The old picture
2. New ingredients
3. Conclusions
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Non-thermal radio filaments (NRFs) $\perp$ GP

* Morphology & radio polarization measurements
  $\vec{B} \parallel$ filaments $\Rightarrow \vec{B} \perp$ GP at low $|z|$ $\Rightarrow \vec{B}$ poloidal in general

* Dynamical argument
  No/little bending of NRFs $\Rightarrow P_{mag} > P_{ram}$ $\Rightarrow B \gtrsim 1 \ mG$ inside NRFs

* Pressure balance argument
  Confinement of NRFs $\Rightarrow B_{out} \sim B_{in}$ $\Rightarrow B \gtrsim 1 \ mG$ everywhere

☞ *Pervasive strong ($\gtrsim 1 \ mG$) & poloidal $\vec{B}$*
Non-thermal radio filaments

(Nord et al., AJ, 128, 1646, 2004)

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Problems in derivation of mG field

**Dynamical argument**

No/little bending of NRFs \( \Rightarrow P_{\text{mag}} > P_{\text{ram}} \Rightarrow B \gtrsim 1 \text{ mG} \) inside NRFs

*Potential problems* :
- Some NRFs are significantly distorted
- Only a fraction of the NRFs are actually colliding with clouds
- Condition \( P_{\text{mag}} \gtrsim P_{\text{ram}} \) probably too stringent
  
  More adequate condition : \( V_A \gg v_{\text{cloud}} \Rightarrow B \gg 10 \mu \text{G} \) inside NRFs

**Pressure balance argument**

Confinement of NRFs \( \Rightarrow B_{\text{out}} \sim B_{\text{in}} \Rightarrow B \gtrsim 1 \text{ mG} \) everywhere

*Other possibilities* :
- Confinement by thermal pressure of very hot gas
- Confinement by magnetic tension
- No confinement at all : NRFs are transient or dynamic structures
  
  (e.g., turbulent enhancements in \( B \), magnetic wakes behind clouds ... )
Non-thermal radio filaments

Fig. 29. Schematic diagram of all the identified radio filaments labeled in this survey. The position of Sgr A* is presented by a star. The light background circles show the angular size of the surveyed region. There is also a NRF G358.85+0.47 extending for ~7° in its length and running along the Galactic plane (Lang et al. 1999). This NRF was not covered by our survey but is shown in this diagram.

Other problems with pervasive mG field

- **Magnetic energy**
  
  If $B \approx 1$ mG throughout volume $\sim (300$ pc$)^2 \times 150$ pc $\Rightarrow E_{\text{mag}} \sim 10^{55}$ ergs

  $\sim$ energy released by $10^4$ supernova explosions

  $\sim$ rotational kinetic energy in CMZ

  $\gg$ turbulent kinetic energy in CMZ

  $\geq$ thermal energy of very hot gas

- **Synchrotron lifetimes**

  If $B \approx 1$ mG

  * $t_{\text{syn}} \sim 3 \times 10^4$ yrs at $\nu \sim 1.5$ GHz
    
    $\nless$ CR $e^-$ cannot travel entire length of longest NRFs

  * $t_{\text{syn}} \sim 1.2 \times 10^5$ yrs at $\nu \sim 74$ MHz
    
    $\nless$ CR $e^-$ need to be injected/re-accelerated at implausibly high rate
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Recent radio observations

- **Radio continuum (synchrotron) emission**
  - Inside NRFs: \( B_{\text{equip}} \sim (50 - 200) \mu G \)
  - In large-scale diffuse ISM: \( B_{\text{equip}} \sim (6 \mu G) (k/f)^{2/7} \rightarrow (6 - 80) \mu G \)

- **Radio (synchrotron) + X-ray / \gamma\text{-ray} (Inverse-Compton / bremsstrahlung)**
  - In X-ray filament: \( B \sim (30 - 130) \mu G \)
  - In large-scale diffuse ISM:
    - Downward break in radio spectrum at \( \sim 1.7 \text{ GHz} \) \( \Rightarrow B \gtrsim 50 \mu G \)
Other recent observations

- **FIR/submm (dust thermal emission) polarization**
  * In dense molecular clouds: \( \mathbf{B} \sim \parallel \) GP

- **Faraday rotation**
  * In diffuse ionized medium: \( |B_\parallel| \sim 10 \, \mu \text{G} \)
    
    If \( \mathbf{B} \sim \perp \) GP \( \Rightarrow \) \( B \gg 10 \, \mu \text{G} \)

- **Zeeman splitting**
  * In dense neutral clouds: \( |B_\parallel| \lesssim (0.1 - 1) \, \text{mG} \)
    
    If \( \mathbf{B} \sim \parallel \) GP \( \Rightarrow \) consistent with \( B \sim 1 \, \text{mG} \)
Problems with equipartition field

- **Equipartition assumption**

  *No theoretical justification*

  - In GD & in external galaxies (at large scales)
    
    \[ \vec{B} \parallel \vec{GP} \Rightarrow \text{- CRs injected into ISM tend to be magnetically confined} \]
    
    \[ - \text{When } P_{\text{CR}} \gtrsim P_{\text{mag}} \Rightarrow \text{Parker instability } \Rightarrow \text{CRs escape} \]
    
    Self-regulating mechanism

  - In GC
    
    \[ \vec{B} \perp \vec{GP} \Rightarrow \text{CRs injected into ISM directly escape along field lines} \]
    
    No self-regulating mechanism, like Parker instability

- **Proton-to-electron energy ratio**

  *Very uncertain value*

  - In GD & in external galaxies: \( k \approx 100 \)
  
  - In GC, in extragalactic jets & in galaxy clusters: \( k \approx 1 \)
Other theoretical considerations

- **Inside NRFs**
  
  Apparent rigidity & organized structure
  \[ \Rightarrow \text{NRFs are magnetically dominated} \]
  \[ \Rightarrow B > B_{\text{equip}} \sim 100 \mu G \]

- **Dynamo scenario**
  
  If dynamo amplification & saturation
  \[ \Rightarrow P_{\text{mag}} \sim P_{\text{turb}} \]
  \[ \Rightarrow B \sim 200 \mu G \]

  (everywhere or in localized filaments only)
Conclusions

- In large-scale diffuse intercloud medium
  - $\vec{B} \sim$ poloidal
  - *inward advection from GD, outflows from GC, local dynamo*
  - $B \gtrsim 50 \mu G$ (??)

- Filamentary structures (NRFs)
  - $\vec{B} \sim$ poloidal
  - $B > 100 \mu G \rightarrow B \gtrsim 1 \text{ mG}$ in some NRFs
  - turbulent enhancements in $B$, magnetic wakes behind clouds

- In dense molecular clouds
  - $\vec{B} \sim$ horizontal
  - shearing of initially poloidal $\vec{B}$ by cloud motions or tidal forces, decoupling from intercloud $\vec{B}$ due to cloud rotation
  - $B \sim 1 \text{ mG}$