Dynamics of millicharged dark matter in supernova remnants

Jung-Tsung Li
UC San Diego

Collaborator: Tongyan Lin
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Millicharged Dark Matter (mDM)

Model 1: Dirac fermion DM with hypercharge $Q = Q_x$

Model 2: Dark fermion couples to ultralight ($< 10^{-14} \text{eV}$) dark photon $A'$

Motivation

- Freeze-in abundance can make up the entire DM abundance and evade current bounds.
- Direct detection from polar materials looking for sub-GeV dark matter.
- Coulomb-type scattering explains the EDGES 21-cm result nicely.
- Charged DM interact with magnetic fields in Galactic disk and supernova.
  - Can mDM gain energy from supernova?
  - An mDM cosmic ray?
Rankine-Hugoniot condition

- Connects upstream (ahead of shock) and downstream (behind shock) states.
- Conserving mass, momentum, and energy.
  - Upstream bulk kinetic energy is dissipated at shock front and becomes heat.
  - Downstream flow speed $= \frac{v_{sh}}{4}$
  - Downstream thermal speed $\sim v_{sh}$
Supernova collisionless shock

1. Shock is linked to the increase of entropy. Upstream bulk kinetic energy is dissipated to heat at the shock zone.
   - Collisional: fluid viscosity (e.g., sonic boom)
   - Collisionless: plasma instability (e.g., astro shocks)

2. Collisionless shock dissipates upstream bulk kinetic energy to heat through wave-particle interaction.
   - Fluctuations come from counter-streaming ion instability.

3. The thickness of shock: several proton Larmor radius.
   \[ r_{L_X} \sim \frac{m_X}{Q_X} \gg r_{L,\text{proton}} \]
   No interaction to mDM at shock front!

Burgess & Scholer 2015
Plasma instabilities from mDM

- A relative velocity between shocked interstellar medium (ISM) and unshocked mDM can excited plasma waves.
- Plasma waves backscatter on mDM from wave-particle interaction.
- mDM particles are isotropized in the shocked ISM frame. The shocked gas sweeps up DM.
Zoo of plasma: choose representative plasma instabilities

| Instability            | Type | Beam direction | Wave direction | Frequency        | Instability                      |
|------------------------|------|----------------|----------------|------------------|----------------------------------|
| Ion-acoustic           | ES   | $V_0 \parallel B_0$ | $k \parallel B_0$ | $< \omega_{pi}$  | No (ion Landau damping)          |
| Langmuir               | ES   | $V_0 \parallel B_0$ | $k \parallel B_0$ | $> \omega_{pe}$   | No ($V_0 <$ velocity threshold)  |
| Lower-hybrid           | ES   | $V_0 \perp B_0$    | $k \perp B_0$    | $\sim \sqrt{|\Omega_i\Omega_e|}$ | No (ion Landau damping)          |
| beam-firehose          | EM   | $V_0 \parallel B_0$ | $k \parallel B_0$ | $\lesssim |\Omega_X|$            | Yes                             |
| Weibel                 | EM   | $V_0 \perp B_0$    | $k \parallel B_0$ | $\lesssim |\Omega_X|$            | Yes                             |

Parallel shock

![Parallel shock diagram](image)

Perpendicular shock

![Perpendicular shock diagram](image)
Electrostatic waves and instabilities: suffer Landau damping

- Ion acoustic wave: a sound wave of ions, $\mathbf{B}_0 \parallel v_{\text{sh}}$
- Langmuir wave: fast electron oscillation, $\mathbf{B}_0 \parallel v_{\text{sh}}$
- Lower hybrid wave: ion oscillation across B field, $\mathbf{B}_0 \perp v_{\text{sh}}$

1. Small $Q_x/m_X$, effectively low-density plasma
2. mDM beam speed $\sim$ proton thermal speed $\sim \psi_{\text{sh}}$

Proton/electron plasma

mDM beam (gentle bump)

Blandford and Thorne 2017

Francis Chen 1984
EM wave: firehose instability in parallel shock

\[ 0 = D^\pm (k, \omega) = c^2 k^2 - \omega^2 - \sum_{j=\pm} \frac{\omega^2}{k v_{th,j}} \left( \frac{\omega}{k v_{th,j}} \right) Z(\xi_j) - \sum_{s=\pm} \frac{\omega^2}{k v_{th,\chi}} \left( \frac{\omega - k V_0}{k v_{th,\chi}} \right) Z(\xi_s) \]

(main plasma)            (Doppler shifted mDM)

Solve \( \omega = \omega_r + i \gamma \). Positive \( \gamma \) means a growing instability mode.
EM wave: Weibel instability in perpendicular shock

Dispersion relation

\[ 0 = D^\pm = \varepsilon^2 k^2 - \omega^2 - \sum_{j = i^+, e^-} \omega_{pj}^2 \left( \frac{\omega}{k v_{th,j}} \right) Z(\xi_j) - \sum_{s = \chi^+, \chi^-} \omega_{ps}^2 \left[ \left( \frac{\omega}{k v_{th,s}} \right) Z(\xi_s) + \left( \frac{V_0}{v_{th,s}} \right)^2 (1 + \xi_s Z(\xi_s)) \right] \]

\[ \begin{align*}
\omega_r & = 2000 \text{ km/s} \\
\omega_r & = 1000 \text{ km/s} \\
\omega_r & = 500 \text{ km/s} \\
\omega_r & = 300 \text{ km/s}
\end{align*} \]
Saturation of instability

1. mDM beam is isotropized in the downstream plasma in one instability timescale. Then we say instability is saturated

   \[ \text{instability time } \sim \frac{1}{\gamma} \sim \frac{1}{\Omega_\chi} \]

2. Saturation length be smaller than supernova shock size:

   \[ L_{\text{sat}} \sim \frac{v_{\text{sh}}}{\gamma_\chi} < R_{\text{SN}} \]

But another issue is shock expands….

Adiabatic decompression!
Adiabatic decompression

- mDM scatters on plasma waves as the shock remnants expands
  a) Density argument: when shocked ISM density equals ambient ISM density, decompression stops
  b) Pressure argument: when shocked ISM pressure equals ambient ISM pressure, decompression stops

Adiabatic decompression cools mDM back to ambient DM thermal distribution, or even colder!
Conclusion

- mDM interacts with shocked hot electron/proton plasma through plasma instabilities. It is a wave-particle interaction.

- The same plasma effect also adiabatically decompresses downstream mDM. The final mDM velocity distribution returns to ~ ambient mDM distribution, or even colder!

- Plasma physics plays important role to dark cosmic ray formation.