Using Optical and UV Spectra of SNRs as a Probe of Collisionless Shock Physics

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High Mach Number Collisionless shocks

- By jump conditions, $T_e << T_i$; $T_{i1} / T_{i2} = m_{i1} / m_{i2}$

- ISM: $n \sim 0.01 - 100 \text{ cm}^{-3}$, $V_S \sim 100 - 10,000 \text{ km s}^{-1}$

- $1 \text{ AU} < \ell_{\text{mfp}} < 300 \text{ pc}$; collisionless plasma

- MHD waves, turbulence assume the role of collisions in shock transition

STREAM K.E. $\rightarrow$ PLASMA INSTABILITIES $\rightarrow$ WAVES $\rightarrow$ HEATING

- Shock front thickness $\sim R_L (i)$

- Solar CME, May 17, 2005
Properties of Collisionless Shocks

- Ions have most of the flow energy, so plasma waves resonant mostly with ions, heating is anisotropic \((T_\parallel \neq T_\perp)\) (Kennel 1985)

- Wave heating intrinsically non-thermal \(\rightarrow\) \(f_e(V), f_i(V)\) non-Maxwellian close to the shock front

- Degree of collisionless heating sensitive to shock parameters: \((V_s, \theta_B - n, \beta)\), quasi-\(\perp\) shock structures very different from quasi-\(\parallel\) ones; complicated

- Degree of electron-ion / ion-ion temperature equilibration at shock front is a free parameter, so \(m_1 / m_2 \leq (T_1 / T_2)_0 \leq 1\) (a fundamental problem of plasma physics)

- If \((T_1 / T_2)_0 = m_1 / m_2\), then \(T_1\) and \(T_2\) evolve downstream from the shock via Coulomb equilibration:

\[
t_{eq}(1 - 2) = 5.7 \times 10^4 \frac{A_1 A_2}{n_1 Z_1^2 Z_2^2 \ln \Lambda_1 - 2} V_{1000}^3 (sh) \quad (yrs)
\]

- \(t_{eq} \geq t_{SNR}\), so for minimal equilibration at the shock, the ion temperatures will remain different: occurs for adiabatic (non-radiative) shocks found in SNRs
Collisionless, non-radiative shocks in the solar wind: Earth’s bow shock, interplanetary shocks ($V_s \sim 400 \text{ km s}^{-1}$, $n \sim 1 \text{ cm}^{-3}$) are similar to non-relativistic, non-radiative SNR shocks

SNR shocks usually characterized as fast-mode, quasi-$\perp$ shocks, characterized by the magnetosonic Mach number, $M_s$:

$$M_s \equiv \frac{V_{sh}}{\sqrt{V_A^2 + C_S^2}}$$

BIG difference: SW fully ionized, $T \sim 10^5 \text{ K} \rightarrow 1.5 < M_s < 3.0$, while SNRs propagate through ISM ($T \sim 10^4$, $B \sim 3 \mu\text{G}) \rightarrow 20 < M_s < 300$

Shock transition is highly turbulent and unsteady, ions reflected upstream ahead of shock play important role in determining shock structure (Tidman & Krall 1971)
Non-radiative SNRs as Collisionless shock laboratories

- Optical, UV, X-ray spectroscopy of fast non-radiative shocks are best tools for measuring \((T_e/T_i)_0\), \((T_{i1}/T_{i2})_0\) ... and for departures of line profiles from Maxwellian distributions

- Postshock gas hot \((T_{av} \geq 10^7 \text{ K})\), heavy ions fully stripped, no cooling. Forbidden line optical, UV emission negligible. Coulomb collisions infrequent, so shock structure retains ‘memory’ of initial collisionless heating...

- Observations require the isolation of plane-parallel segments of SNR blast waves (i.e., objects must be local: Galactic or LMC/SMC)

- Trace the evolution of line ratios, line widths as a function of postshock distance in the optical, UV and X-rays to gauge the equilibration

- Relatively insensitive to the evolutionary history of the SNR (unlike X-ray obs.)
Non-radiative shocks in partially neutral gas produce optical spectra that are excellent probes of collisionless shock physics.

H I crosses downstream unaffected by MHD turbulence at shock transition.

- Slow, ambient H I rapidly ionized away in a thin ionization zone ($d \leq 5 \times 10^{15}$ cm).
- A second, fast population of H I forms by charge exchange.
- Collisional excitation of fast and slow neutrals produces broad and narrow Balmer lines (Chevalier et al. 1980).

Compression of gas $\leq 4$ in emitting zone, so optical/UV emission from these shocks is faint ($\leq 5 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$).
Diagnostic Utility of Balmer-Dominated spectra

- Optical spectra are dominated by Balmer lines of H (lines of He, O, N, S,... down by ~ 50-100)

- FWHM of broad Balmer lines $\propto T_p, V_s$

$$\frac{I_B}{I_N} \propto \frac{\langle \sigma_{ex} v \rangle}{\langle \sigma_i v \rangle} \propto V_{sh}, (T_e/T_p)_0$$

- Shape of the broad Balmer reflects velocity distribution of protons at the shock front

- Broad Balmer line is shifted to bulk velocity of postshock gas; magnitude of shift gives viewing angle to shock ($\Delta v = v_b \cos \Theta$)

![Diagram of edge-on and face-on shock spectra]
Measurement of $T_e / T_p$ in Balmer-Dominated SNRs

- 2-step procedure to simultaneously determine $(T_e / T_p)_0$ and $V_{sh}$ (Ghavamian et al. 2001):
  - Measure FWHM of broad Hα line to narrow range of $V_{sh}$ first between limits of minimum, maximum equilibration
  - Model $I_B / I_N$ over the range of shock speeds, match to the observed $I_B / I_N$

<table>
<thead>
<tr>
<th></th>
<th>NE Cygnus Loop</th>
<th>RCW 86</th>
<th>Tycho’s SNR</th>
<th>SN 1006</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_S$ (km s⁻¹)</td>
<td>300 - 400</td>
<td>600 - 650</td>
<td>1950 - 2300</td>
<td>2900</td>
</tr>
<tr>
<td>$(T_e / T_p)_0$</td>
<td>0.8 - 1.0</td>
<td>0.25 - 0.3</td>
<td>≤ 0.1</td>
<td>≤ 0.07</td>
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Same result obtained from combined optical/X-ray analysis of Balmer-dominated blast wave in DEM L 71 (Rakowski et al. 2003; see talk by C. Rakowski)

Electrons receive a smaller and smaller fraction of total shock energy as shock speed increases!

Chevalier et al. (1980); Ghavamian et al. (2001)
**Electron-ion/ion-ion Equilibration in the FUV I.**

- Diagnostic lines available in the 900 Å - 2000 Å range:

  O VI $\lambda\lambda 1032, 1038$, broad Ly $\beta$, Ly $\gamma \rightarrow$ (FUSE/HST/HUT)

  C IV $\lambda\lambda 1548, 1550$, N V $\lambda\lambda 1238, 1243$, He II $\lambda 1640 \rightarrow$ (HST/HUT)

- Simultaneously probe $e^-$ - ion and ion-ion equilibration:

  First, constrain $V_s$ via modelling Balmer line profiles (if present) and/or proper motion studies (if D is known)

  - Trace spatial variation in ion line emissivity behind shock front $\rightarrow$ get $T_e$

  **Unquilibrated:** $v_{FWHM}(1) = v_{FWHM}(2)$

  **Equilibrated:** $v_{FWHM}(1) = \sqrt{\frac{m_2}{m_1}} v_{FWHM}(2)$

- FUSE obs. of NE Cygnus Loop give $1 < T_O / T_p < 2.5$, $V_s = 350$ km s$^{-1}$, while spatial variation in O VI emission gives $T_e / T_O \sim 1$, so $T_e \sim T_p \sim T_O$ (nearly full equilibration!) (Raymond et al. 2003)
Non-Maxwellian Ion Distributions in Non-Radiative Shocks

- In situ obs. of solar wind plasma (0.3-1.5 AU) always show e- velocity distributions w/nearly Maxwellian cores and non-thermal tails (Feldman et al. 1983, Zouganelis 05, Maksimovic 05,...) or flat-topped distributions (Feldman et al. 1983)

- Energetic tails on e- and ion dist. can enhance collisional ionization, excitation rates (Porquet et al. 2001)

- In non-radiative SNR shocks,
  \[ t_{eq}(e-e) \ll t_{SNR} \]

  \[ t_{eq}(p-p), t_{eq}(i-i) > t_{SNR} \]

- So broad ionic lines in UV/optical should show some non-Maxwellian deviations

- Broad Ha lines in Balmer-dominated SNRs are very well fit by Gaussians; further obs. at higher S/N may show otherwise
Optical probes: the case of SN 1006

- Remnant of Type Ia explosion, 40' across, located in low extinction region above Galactic plane

- Bright X-ray synchrotron along W, E rims, TeV e⁻s implicated (Koyama et al. 1996)

- Prominent Balmer-dominated rim on NW, much fainter in rest of SNR (Winkler & Long 1997)

- Model of Balmer-dominated spectra gives $T_e/T_p \leq 0.07$, $V_S = 2900 \text{ km s}^{-1}$ (Ghavamian et al. 2002)
Observations of SN 1006 with HUT and FUSE have allow us to compare proton, He, C, N and O line widths directly (Laming et al. 1996, Korreck et al. 2004)

Results suggest that the amount of heating (or conversely, the amount of energy lost) by the ions in the shock front varies with the mass of the ion... a clue to the nature of the shock front turbulence.
Four Balmer-dominated Type Ia SNRs in the LMC are excellent candidates for ion-ion equilibration study: $E(B-V) \sim 0.11$

- Known distance (50 kpc), allows good constraints on shock speed from proper motion measurements ($V_S \geq 2000$ km s$^{-1}$)

**FUSE observations (Ghavamian et al. 2006)**

- **0519-69.0:**
  - $V_{\text{FWHM}}$ (Ly$\beta$) = 3130 ± 155 km s$^{-1}$
  - $V_{\text{FWHM}}$ (OVI) = 4975 ± 1830 km s$^{-1}$
  - $T_O / T_p \approx 16$

- **0509-67.5:**
  - $V_{\text{FWHM}}$ (Ly$\beta$) = 3710 ± 400 km s$^{-1}$
  - $V_{\text{FWHM}}$ (OVI) ≈ 3500-3700 km s$^{-1}$
  - $T_O / T_p \approx 16$

- **DEM L 71:**
  - $V_{\text{FWHM}}$ (Ly$\beta$) = 1140 ± 30 km s$^{-1}$
  - $V_{\text{FWHM}}$ (OVI) = 740 ± 45 km s$^{-1}$
  - Multiple shocks along L.O.S.
Conclusions and Future Directions

- As the shock speed increases, the thermal energy of the shock is distributed less and less effectively between different particle species, asymptotically approaching mass-proportional heating. This is a fundamental property of fast ISM shocks.

- Anti-correlation between \((T_e/T_p)_0\) and \(V_{sh}\) seen in Balmer-dom. SNRs is very similar to the anti-correlation observed between \((T_e/T_p)_0\) and \(M_A\) in solar wind shocks (Schwartz et al. 1988). Do shocks in fully ionized gas follow the same trend?

- As best we can tell, the broad Balmer and Ly \(\beta\) profiles are Maxwellian. What does this imply about the plasma turbulence at the shock front?

- UV observations of shocks in SN 1006 suggest that for the given shock speed, the energy lost by the ions varies in proportion to the ion mass, contrary to what is seen in solar wind shocks (Korreck et al. 2004)

- What does this imply about the cosmic ray injection mechanism in collisionless shocks?

- Can we calibrate \((T_e/T_p)_0\) vs. \(M_S\)?