Electron-Ion Thermal Equilibration in Collisionless Shocks

Parviz Ghavamian

(Towson University, Maryland, U.S.A.)
Shock Basics
Balmer-Dominated Shocks

- Non-radiative shocks in partially neutral gas produce optical spectra dominated by Balmer lines of H

- Slow, ambient H I rapidly ionized away

- Fast H I forms by charge exchange (pickup ions also formed)

Collisional excitation of fast and slow H I produces broad and narrow Balmer lines

\[ I_{H\alpha} = 0.2 \frac{h \nu_{H\alpha}}{4\pi} n_{HI} V_{SH} \]

\[ I_{H\alpha} \sim 5 \times 10^{-6} \left( \frac{n_{HI}}{1 \text{ cm}^{-3}} \right) \left( \frac{V_{sh}}{1000 \text{ km/s}} \right) \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]

(faint!)
How Are Electrons Heated Relative to Ions?

\[ kT_2 = \frac{3}{16} m_j v_{sh}^2 \]

strong shock jump conditions for ideal gas
Slow Coulomb Equilibration

Example: $V_{SH} = 2500 \text{ km/s}$, $\beta \equiv T_e/T_p = m_e/m_p$

$f_{HI} = 0.5 \quad n = 1 \text{ cm}^{-3}$
van Adelsberg et al. (2008)
Ghavamian et al. (2002) filament, for a good sky subtraction. It is virtually identical to the position used by KWC87. We obtained 4 exposures at this location, with a total exposure time of 8400 s, which we combined into a single two-dimensional spectrum following initial reduction.

The data were reduced using standard IRAF procedures of bias subtraction, flat fielding, and illumination correction. Spectra of a HeNeAr lamp taken at the beginning and end of the series of object frames were used for wavelength calibration. We subtracted the night sky contribution from the two-dimensional spectrum using emission from the two ends of the slit. The $\text{H}/\text{C}_11$ line profiles (both broad and narrow components) were nearly constant along the observed filament; therefore, we integrated the emission along the slit to obtain a single high signal-to-noise ratio spectrum from a 51.500 section of the filament (Figs. 2 and 3). Exposures of several spectrophotometric standard stars from Hamuy et al. (1994) were used for flux calibration. We estimate an absolute photometric accuracy of 20% for our quoted emission line fluxes.

3. DETECTED EMISSION LINES

Among the most interesting new features in our optical data are the detection of broad $\text{H}/\text{C}_12$ and $\text{He}/\text{C}_21$. To our knowledge, this is the first detection of the $\text{He}/\text{C}_21$ line in a pure nonradiative shock. The neutral He atoms passing downstream are unaffected by the electromagnetic turbulence at the shock front. Therefore, neutral He atoms remain cool throughout the shock and produce narrow emission lines unresolved in our data. On the other hand, since $\text{He}/\text{C}_21$ is an ion, it is heated at the shock front by the same collisionless processes that heat the electrons and ions. Therefore, we expect the $\text{He}/\text{C}_21$ line to be broad and more difficult to detect than the $\text{He}/\text{C}_21$ line. There is a hint of the $\text{He}/\text{C}_21$ line at a low (1.5) statistical significance.

The surface brightnesses of the detected emission lines from northwest SN 1006 appear in Table 1. We have used $E(B-V) = 0.11$ (Schweizer & Middleditch 1980) to obtain dereddened line intensities from our measured spectra.

Fig. 1.—Narrowband $\text{H}/\text{C}_11$ image of northwest SN 1006, acquired from the CTIO 0.9 m telescope in 1998 June, shortly before the spectroscopy reported here. The location and P.A. of the 2000/50 RC Spectrograph slit is marked. North is at the top; east is to the left.

Fig. 2.—Full one-dimensional spectrum of the northwest SN 1006 Balmer filament. Narrow emission lines of $\text{H}/\text{C}_11$, $\text{H}/\text{C}_12$, and possibly $\text{H}/\text{C}_13$. The sharp feature near the middle of the spectrum is an artifact of the sky subtraction.

Fig. 3.—Close-up view of the northwest SN 1006 Balmer spectrum. No smoothing has been applied. Among the newly detected lines is $\text{He}/\text{C}_21$. There may also be a weak detection of the $\text{He}/\text{C}_21$ line.
Observables in Balmer-Dominated Spectra

\[ \Delta V_{\text{broad}}(H\alpha, H\beta, \ldots) \propto T_p, V_{SH}, \varepsilon_{CR} \]

\[ \frac{I_b}{I_n} \propto \frac{\langle \sigma_{cx} v \rangle}{\langle \sigma_i v \rangle} \rightarrow (\beta_{up}, \beta_{down}, V_{SH}, \varepsilon_{CR}) \]

\[ (\varepsilon_{CR} \equiv P_{CR} / \rho_0 V_{SH}^2) \]

(Smith et al. 1991; G01, G02, G07, G13, van Adelsberg et al. 2008; Blasi et al. 2012; Morlino et al. 2012, 2013)
Models
Latest Models Predict a THIRD Hα Component!

- **Neutral return flux** (NRF) upstream deposits energy ahead of shock, creating an intermediate width Hα component.

- Typical $\Delta V_{in} \sim 200-300$ km/s: *may be blended with narrow component at low spectral res observations* (Morlino et al 2012)

---

![Graph showing Intermediate Component Width](image)

- $\Delta V_{n} = 150$ km/s

---

Morlino et al. (2012)

Ghavamian et al. (2000)
$\Delta V \text{ vs } V_{SH}$ Plot Affected By NRF Too: SN 1006 Again

$\Delta V = 2400 \text{ km/s}$

**Morrino et al. (2013)**
The NRF Also Affects $I_b/I_n$

- Value of $\beta_{up}$ substantially affects $F(H\alpha)$: unexpected
- $I_b/I_n$ also strongly affected for low res spectra, where narrow and intermediate components are unresolved
Recent $I_b/I_n$ Calculations Include the Unresolved Intermediate Component

**Morrino et al. (2012):** NRF but not CR modification

**Winkler et al. (2003):**

![Diagram showing $I_b/I_n$ versus $V_{sh}$ with SN 1006 $I_b/I_n = 0.77$ and range of $V_{SH}$ for NW from Chandra proper motions (Katsuda et al. 2013).]

Katsuda et al. (2013)
Trends in $T_e/T_p$
Observing Many Balmer SNRs Gives $\beta_{\text{down}} \sim V_{\text{SH}}^{-2}$

van Adelsberg et al 2008; G13

Does $T_e/T_p$ curve change above 2000 km/s?
A possible explanation may lie in the CR precursor. 

\[
\frac{T_e}{T_p} = \frac{3}{16} m_e v_{sh}^2 + \Delta E_e
\]

\[
\approx \frac{\Delta E_e}{\frac{3}{16} m_p v_{sh}^2}
\]

\[
\propto \frac{1}{v_{sh}^2}
\]

- A constant heating \(\Delta E_e\) would reproduce what we see.
- Suggests a \(\Delta E_e\) occurs ahead of the shock...

With CRs/Reflected Ions

\[\approx \kappa_{CR} / V_{SH}\]
How to Get this Trend?
One Possibility: Lower Hybrid (LH) in the CR Precursor

LH waves:
\[ k_{\parallel}/k_{\perp} = \frac{m_e}{m_p} \]
\[ \omega_{LH} = \left( \Omega_e \Omega_p \right)^{1/2} \]

- LH waves can bulk heat e^-s parallel to \( \delta B \)
- \( \Delta E_e = \frac{1}{2}m_e\Delta v_e^2 \propto \Omega_e \kappa_{CR} \sim \text{constant} \) (for \( \kappa \propto 1/B \))
  \( \Delta E_e \sim 0.3 \text{ keV (const)} \)
\( \beta_{\text{down}} \) at Saturn’s Bow Shock From Cassini

Masters et al. (2011)

mostly \( \perp \) shocks

mostly quiet solar wind

\( M_A = \frac{v_{\text{SH}}}{v_A} \)

\( \Delta T_e \propto \frac{1}{M_A} \frac{1}{2 m_p v_n^2} \)

(Schwartz et al. 1988)

(Ghavamian et al. 2013)
New Observations
New Observations of Balmer-Dominated Filaments in the Cygnus Loop

- Comparison to shock models indicates $\beta_{\text{down}} \sim 1$
- These $I_b/I_n$ cannot be matched by any existing models, and haven’t even been calculated in the latest ones (e.g., van Adelsberg et al. 2008, Morlino et al. 2012, 2013)

$\Delta V \sim 300 \text{ km/s}$
$I_b/I_n \sim 0.65$

$\Delta V \sim 270 \text{ km/s}$
$I_b/I_n \sim 0.9$

$\Delta V \sim 140 \text{ km/s}$
$I_b/I_n \sim 0.34$

Medina et al. (2014)
First Detection of Broad Hα in the Galactic SNR G156.2+5.7

Hα image: Gerardy & Fesen (2007)

MMT Blue Channel slit positions

Hα 0.1-2.4 keV X-rays
WISE 22 µm

X-ray 'shadow'

Balmer-dominated shocks

Radiative shocks
First Detection of Broad H$\alpha$ in the Galactic SNR G156.2+5.7

- $\Delta V_{1+2} = 490$ km/s; $I_b/I_n = 0.65$
- $\Delta V_6 \sim 235$ km/s; $I_b/I_n = 1.2$
- Positions 1+2: Measured $I_b/I_n$ too low for shock models
  
  
  $470 \leq V_{SH} \leq 600$ km/s

  (Agrees w/$V_{SH}$ from H$\alpha$ proper motion: Katsuda et al 2016)

- Position 6: $\beta_{down} = 1; V_{SH} = 300$ km/s
G156.2+5.7 in WISE 22 μm Dust Emission

Work by Towson U. undergrad Jason Powell

Ghavamian & Powell (2016, in prep)
Conclusions

• Balmer-dominated shock models have become much more sophisticated, including momentum feedback from NRF, CR back pressure,...

• This also muddles the picture a bit on measuring $T_e/T_p$, though it seems $\varepsilon_{CR} \lesssim 0.2$ can be accommodated

• $I_b/I_n$ predictions have not yet been published for NRF + CR modification

• $I_b/I_n$ for $V_{SH} < 1000$ km/s have not been attempted since G01. Crucial for interpretation of Balmer spectra in Cygnus Loop, G156.2+5.7,...

• $I_b/I_n$ are problematic at low shock speeds. Often too low.

• Does the equilibration-shock speed trend hold for fully ionized shocks too? Need proper motions for SNRs in FULLY PRE-IONIZED gas with well-determined distances (LMC/SMC) to get $V_{SH}$, along with X-ray spectroscopy ($T_e$) and UV spectra ($T_e$ and $T_i$)

• Ion-ion equilibration studies sorely needed too. Needs UV.
Tycho’s SNR

H$_\alpha$
0.3-1.0 keV
3.0-5.0 keV

Ghavamian et al. (2013)

(P. F Winkler)
(S. Park et al. 2007)
Additional Methods of Estimating $\frac{T_e}{T_p}$
In Situ Solar Wind Measurements

Optical data give broad Hα FWHM, limiting range of $V_{SH}$

X-ray spectra at sequence of positions behind shock gives evolution of $T_e$ due to Coulomb collisions + adiabatic expansion (Rakowski et al. 2003)
First Measurement of $T_e/T_i$ in an Ejecta Shock (Yamaguchi et al. 2014)

Tycho’s SNR

- Result: $T_e/T_i \sim 0.01$ (!)
- $V_{rev} \sim 4000$ km/s; Mach number should be $\sim 100$
- No significant magnetic field expected in expanding Fe-rich ejecta