USING OPTICAL AND UV SPECTRA OF SNRs AS A PROBE OF COLLISIONLESS SHOCK PHYSICS

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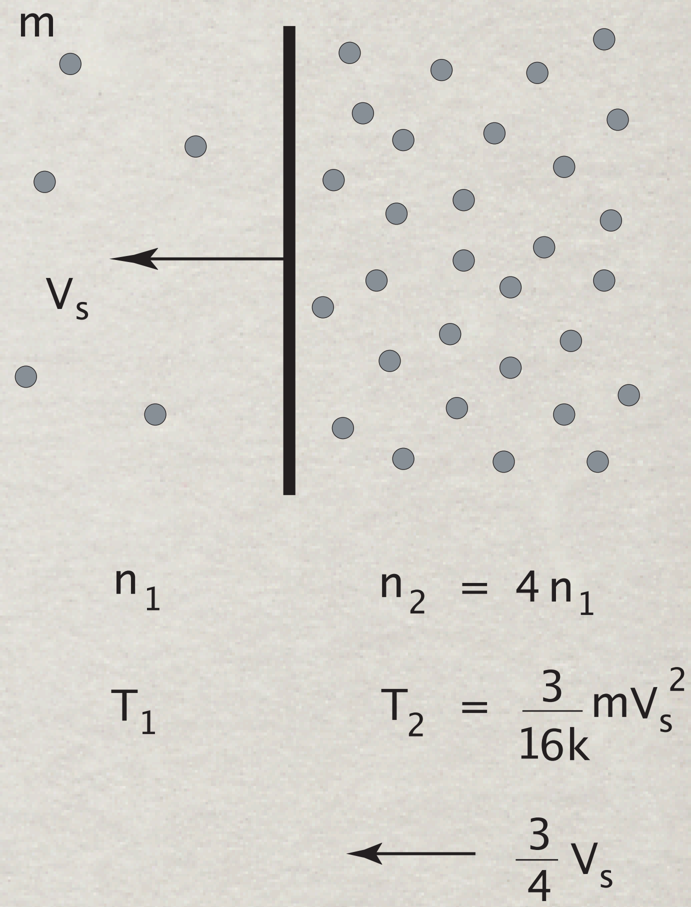
HIGH MACH NUMBER COLLISIONLESS SHOCKS



n_1 $\quad n_2 = 4 n_1$

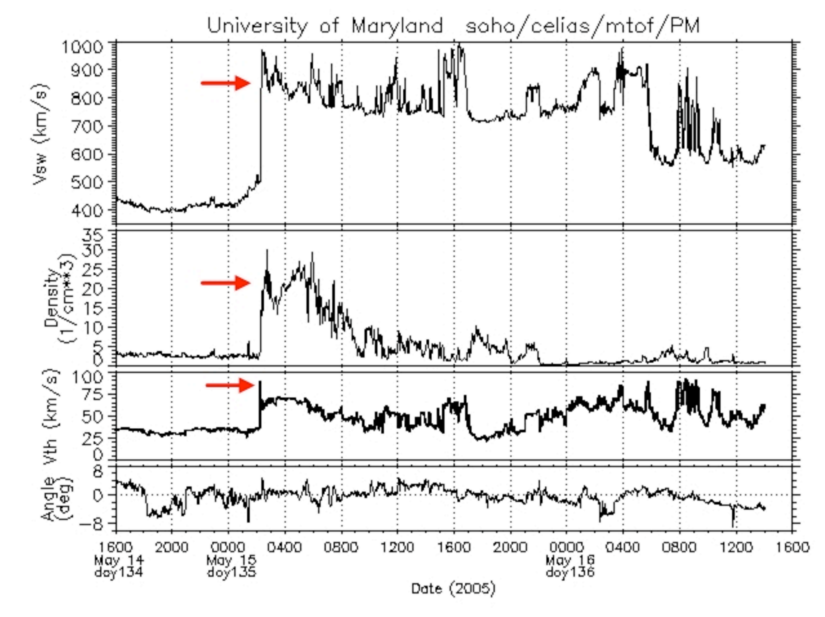
T_1 $\quad T_2 = \frac{3}{16k} m V_s^2$

$\frac{3}{4} V_s$

- 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 AU < ℓ_{mfp} < 300 pc; collisionless plasma
- MHD waves, turbulence assume the role of collisions in shock transition

STREAM K.E. → PLASMA INSTABILITIES → WAVES → HEATING

- Shock front thickness ~ 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 → $f_e(V)$, $f_i(V)$ non-Maxwellian close to the shock front

- Degree of collisionless heating sensitive to shock parameters: (V_s, $\theta_{B\text{-}n}$, β), quasi-⊥ shock structures very different from quasi-|| 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:

$$t_{eq}(1-2) = 5.7 \times 10^4 \, \frac{A_1 A_2}{n_1 Z_1^2 Z_2^2 \; ln\, \Lambda_{1-2}} \, V_{1000}^3(sh) \qquad (yrs)$$ (Spitzer 1962)

- $t_{eq} \geq t_{SNR}$, so for minimal equilibration at the shock, the ion temperatures will remain different: occurs for adiabatic (non-radiative) shocks found in SNRs

SHOCK PARAMETERS: SOLAR WIND VS. ISM SHOCKS

- Collisionless, non-radiative shocks in the solar wind: Earth's bow shock, interplanetary shocks ($V_S \sim 400$ km s^{-1}, $n \sim 1$ cm^{-3}) are similar to non-relativistic, non-radiative SNR shocks

- SNR shocks usually characterized as fast-mode, quasi-⊥ shocks, characterized by the magnetosonic Mach number, M_S:

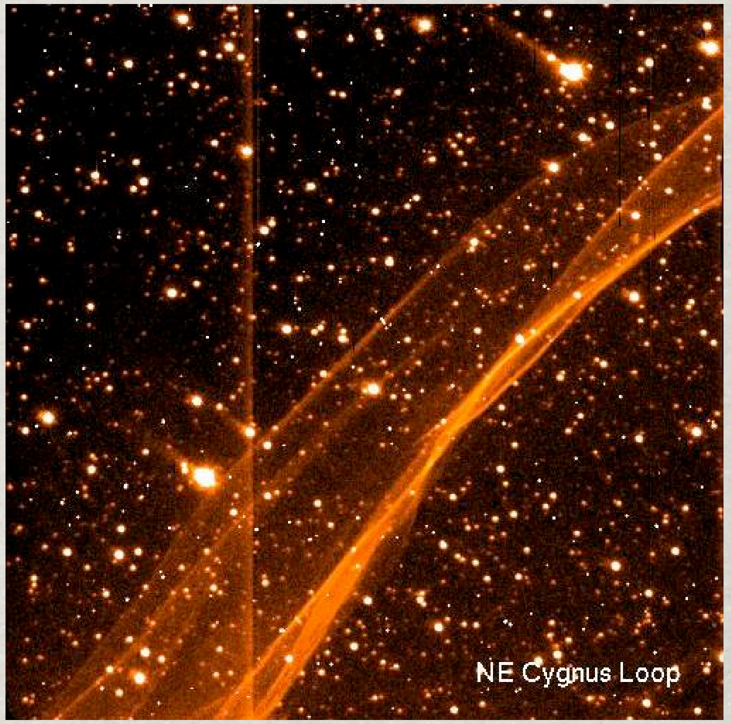
$$M_S \equiv \frac{V_{sh}}{\sqrt{V_A^2 + C_S^2}}$$

- BIG difference: SW fully ionized, $T \sim 10^5$ K → $1.5 < M_S < 3.0$, while SNRs propagate through ISM ($T \sim 10^4$, $B \sim 3$ μG) → $20 < M_S < 300$

- Shock transition is highly turbulent and unsteady, ions reflected upstream ahead of shock play important role in determing shock structure (Tidman & Krall 1971)

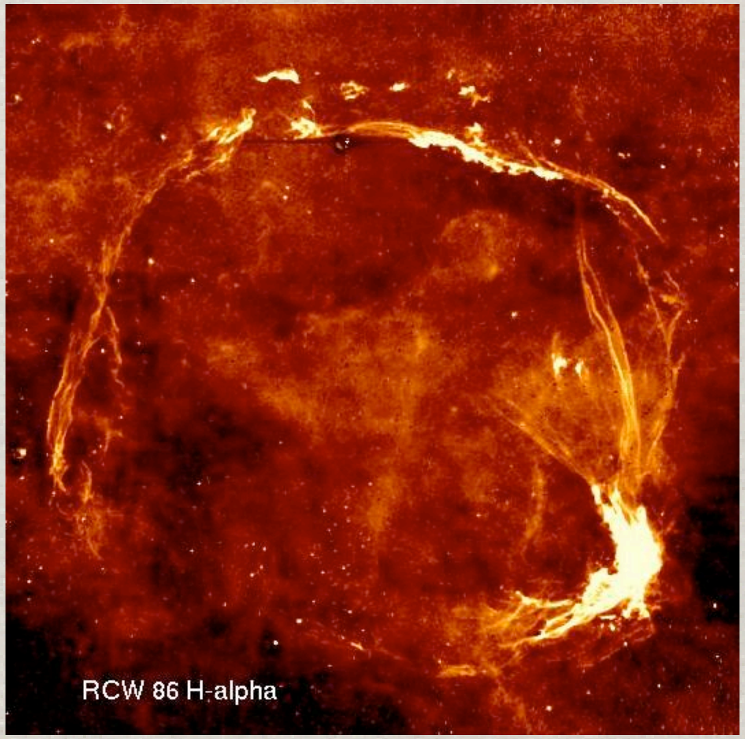
NON-RADIATIVE SNRS AS COLLISIONLESS SHOCK LABORATORIES

- 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 ($T_{av} \geq 10^7$ 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)



Smith (1997)

- 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.)

COLLISIONLESS SHOCKS IN PARTIALLY NEUTRAL GAS

- Non-radiative shocks in partially neutral gas produce optical spectra that are excellent probes of collisionless shock physics

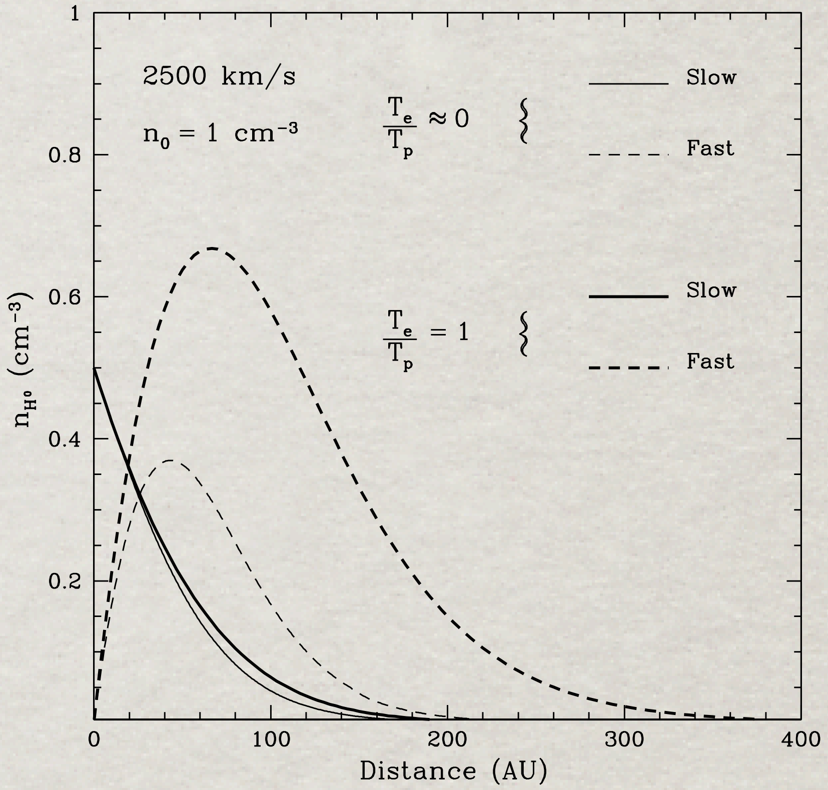
- H I crosses downstream unaffected by MHD turbulence at shock transition

- Slow, ambient H I rapidly ionized away in a thin ionization zone (d ≤ 5 × 10^{15} cm)

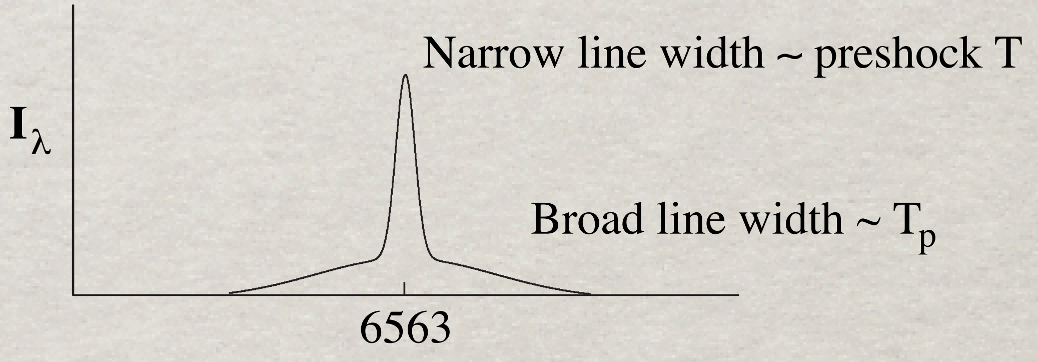
- A second, fast population of H I forms by charge exchange

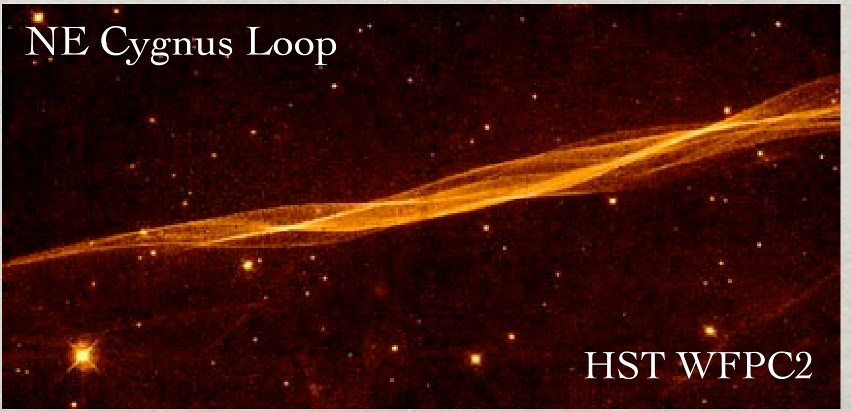
- Collisional excitation of fast and slow neutrals produces broad and narrow Balmer lines (Chevalier et al. 1980)

- Compression of gas ≤ 4 in emitting zone, so optical/UV emission from these shocks is <u>faint</u> (≤ 5 × 10^{-16} ergs cm^{-2} s^{-1} $arcsec^{-2}$)



Ghavamian et al. (2001)





Blair et al. (1999)

DIAGNOSTIC UTILITY OF BALMER-DOMINATED SPECTRA

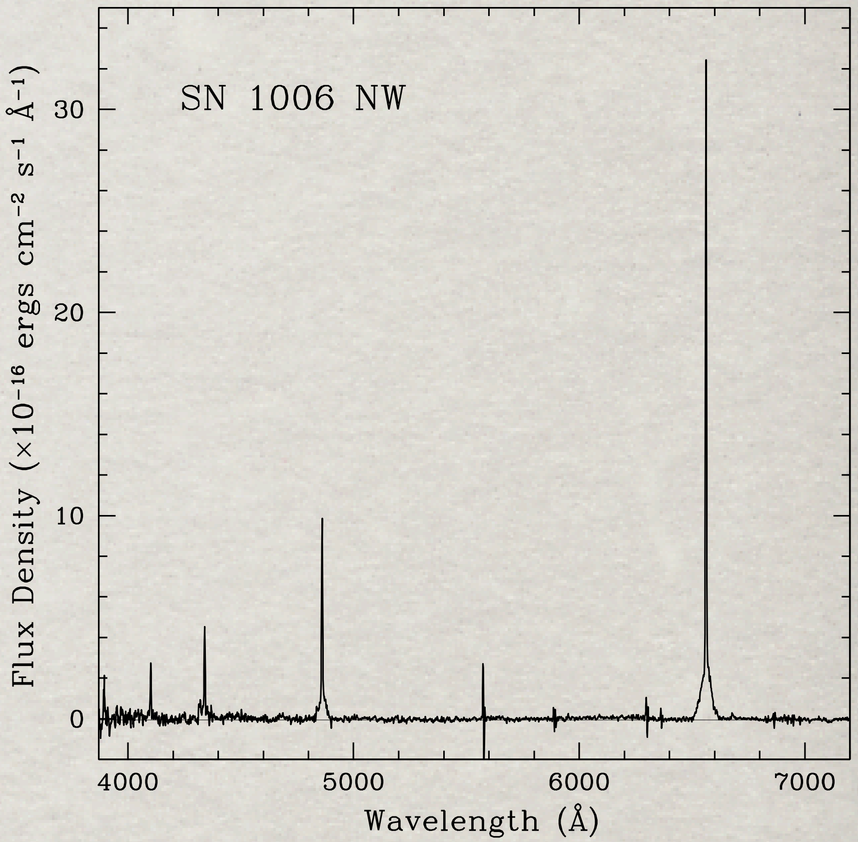
- Optical spectra are dominated by Balmer lines of H (lines of He, O, N, S,... down by ~ 50-100)

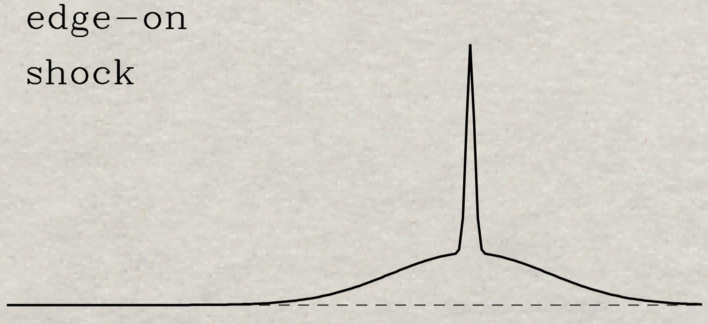
- FWHM of broad Balmer lines ∝ T_p , V_S

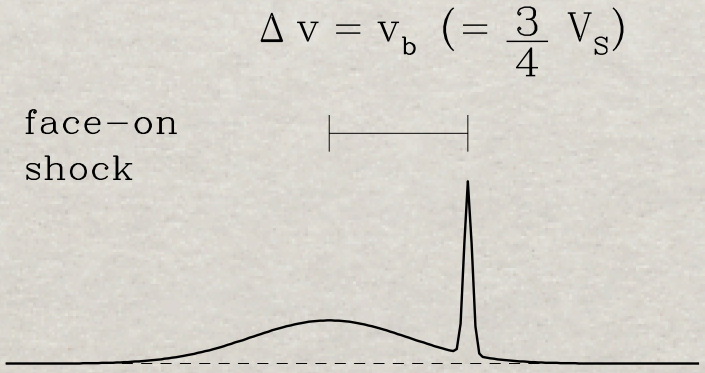
$$\frac{I_B}{I_N} \propto \frac{< \sigma_{cx}\, v >}{< \sigma_i\, v >} \propto V_{sh}\,, \;\; (T_e/T_p)_0$$

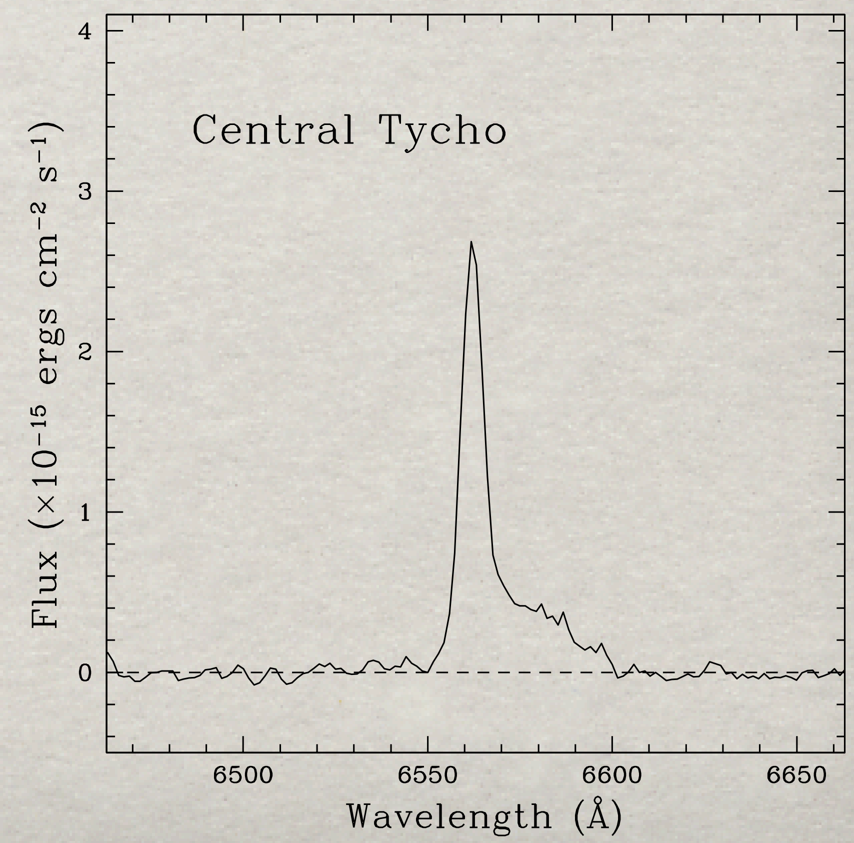
- Shape of the broad Balmer reflects velocity distribution of protons at the shock front

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







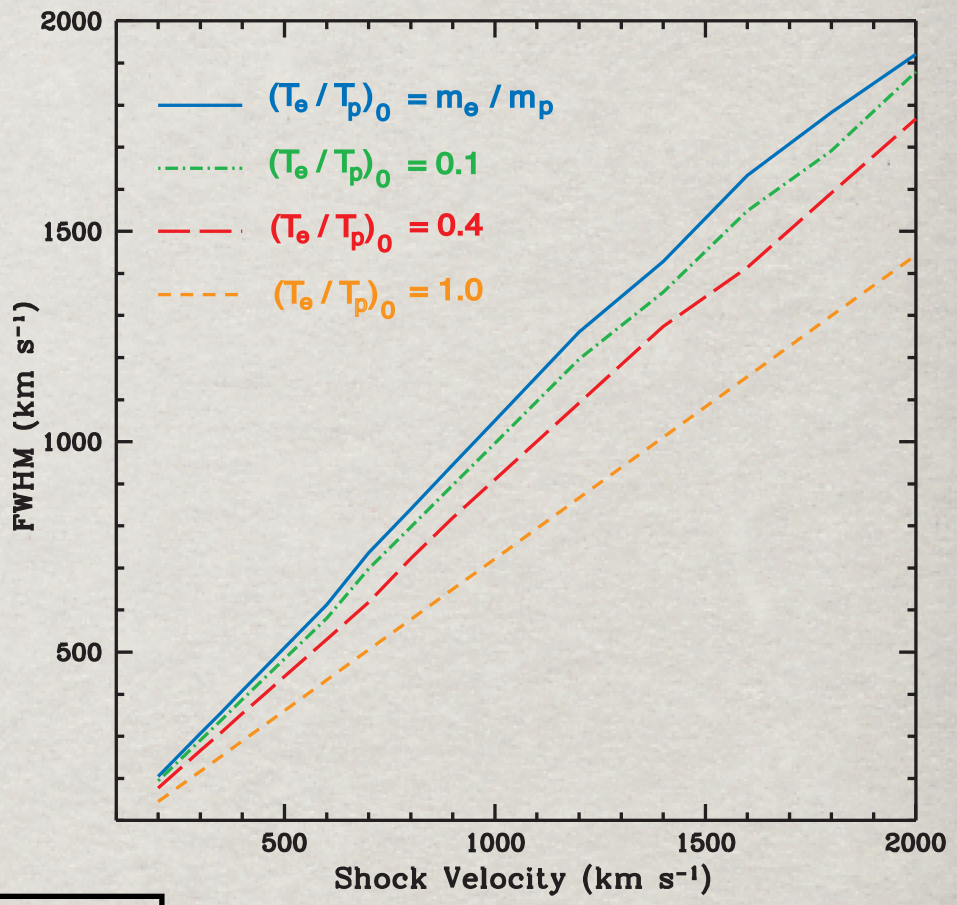


MEASUREMENT OF T_E/ T_P IN BALMER-DOMINATED SNRs

- 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



Chevalier et al. (1980); Ghavamian et al. (2001)

	NE Cygnus Loop	RCW 86	Tycho's SNR	SN 1006
V_S (km s $^{-1}$)	300 - 400	600 - 650	1950 - 2300	2900
$(T_e / T_p)_0$	0.8 - 1.0	0.25 - 0.3	≤ 0.1	≤ 0.07

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

- 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)

Electron-ion/ion-ion Equilibration in the FUV I.

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

O VI λλ1032, 1038, broad Ly β , Ly γ → (FUSE/HST/HUT)

C IV λλ1548, 1550, N V λλ1238,1243, He II λ1640 → (HST/HUT)

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

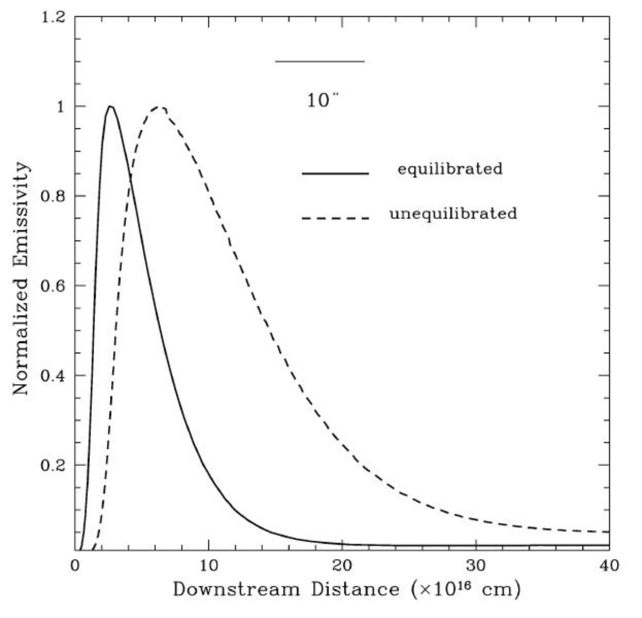
- First, constrain V_S via modelling Balmer line profiles (if present) and/or proper motion studies (if D is known)

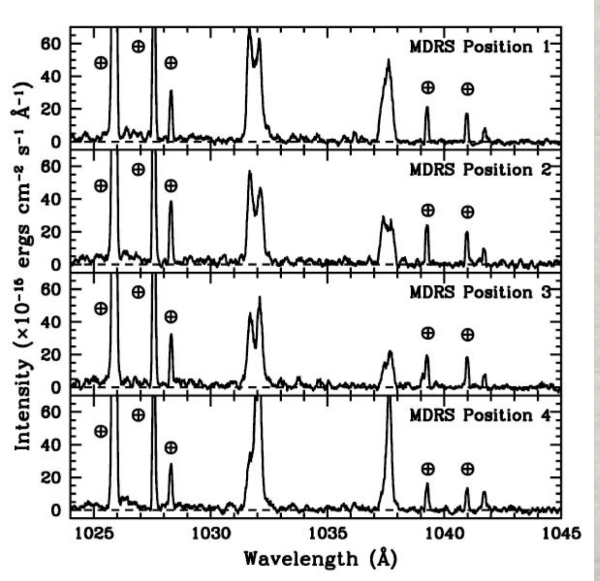
\- Trace spatial variation in ion line emissivity behind shock front → get T_e

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)





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,

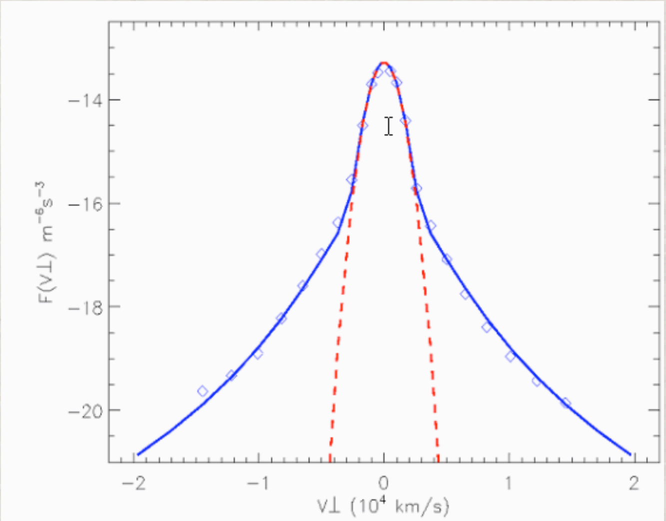
  $t_{eq}(e\text{-}e) \ll t_{SNR}$

  $t_{eq}(p\text{-}p),\ t_{eq}(i\text{-}i) > t_{SNR}$

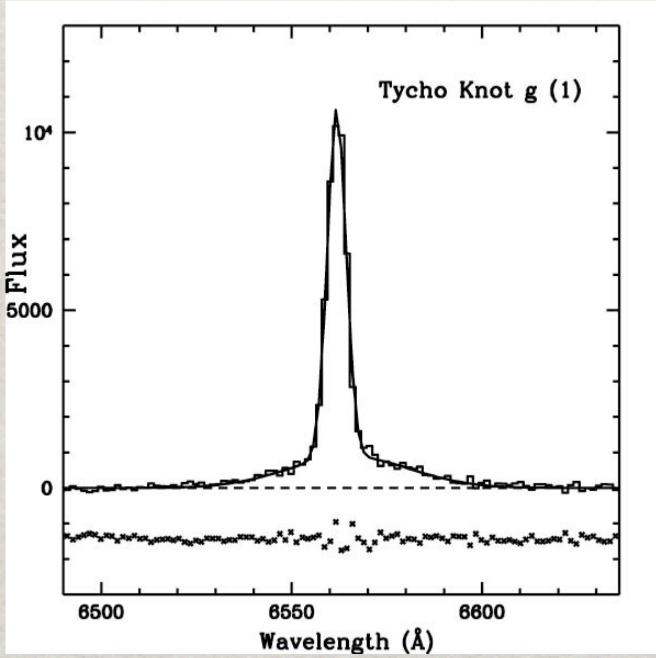
- So broad ionic lines in UV/optical should show some non-Maxwellian deviations

- Broad Ha lines in Balmer-dominated SNRs are very well fit by Gaussians; further obs. at higher S/N may show otherwise

Kappa dist. of solar wind e$^-$



Maksimovic et al. (2005)



Ghavamian (1999)

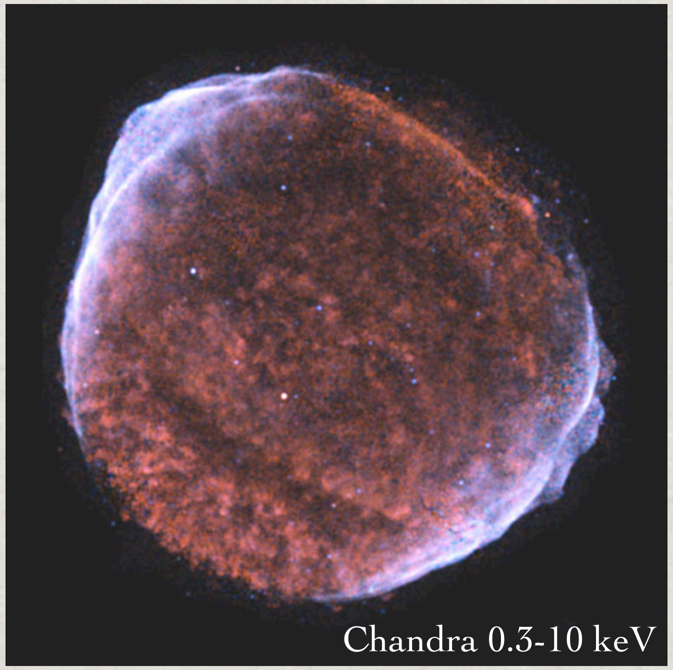
OPTICAL PROBES: THE CASE OF SN 1006

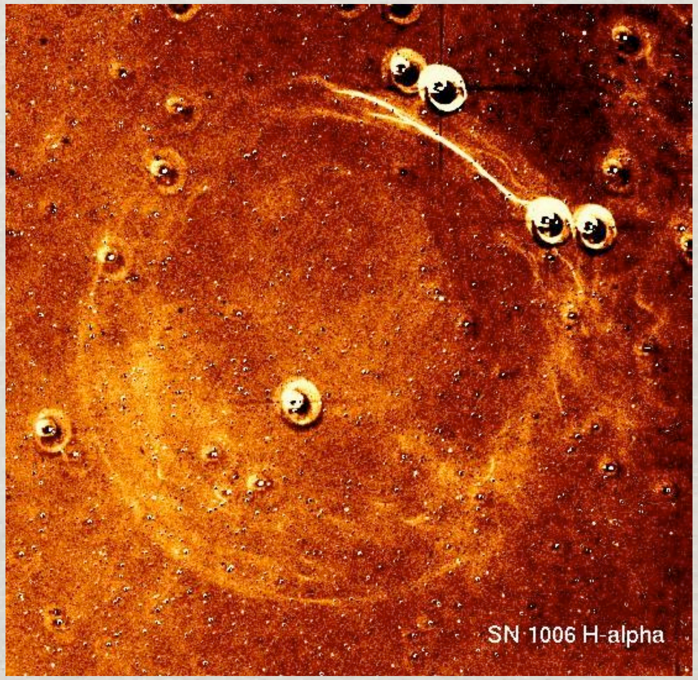
- Remnant of Type Ia explosion, 40' across, located in low extinction region above Galactic plane

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

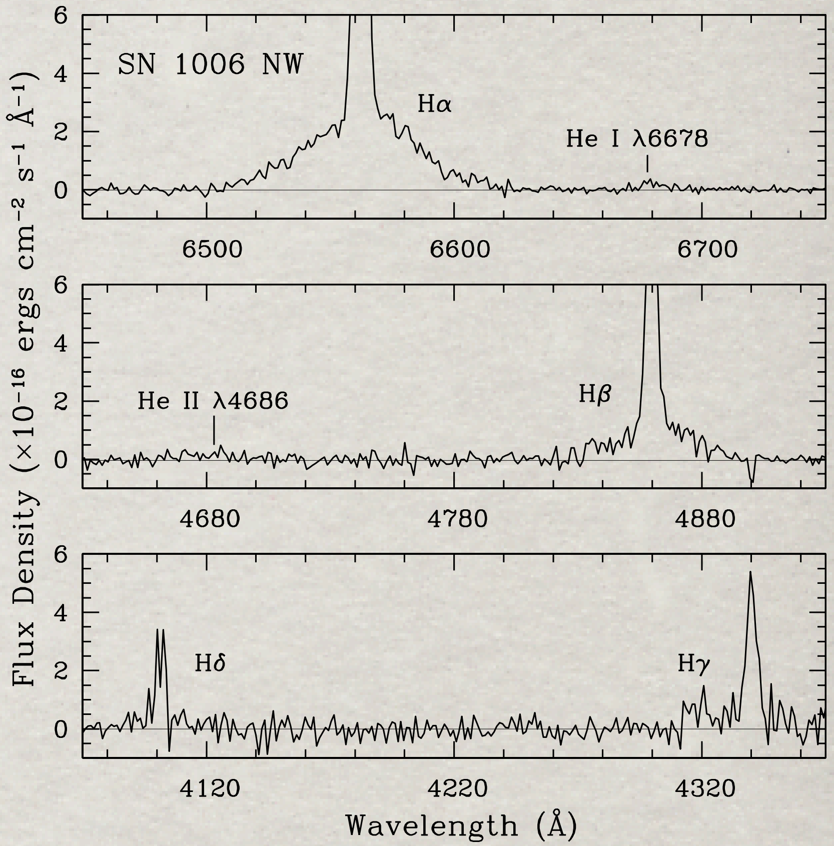
- Prominent Balmer-dominated rim on NW, much fainter in rest of SNR (Winkler & Long 1997)

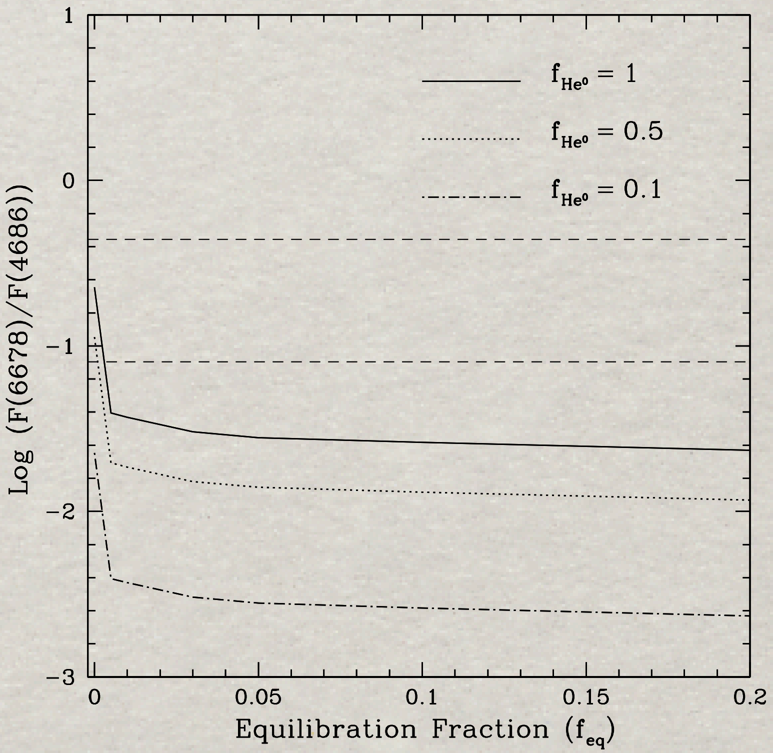
- Model of Balmer-dominated spectra gives $T_e/T_p \leq 0.07$, $V_S = 2900$ km s^{-1} (Ghavamian et al. 2002)


Chandra 0.3-10 keV



Winkler & Long (1997)

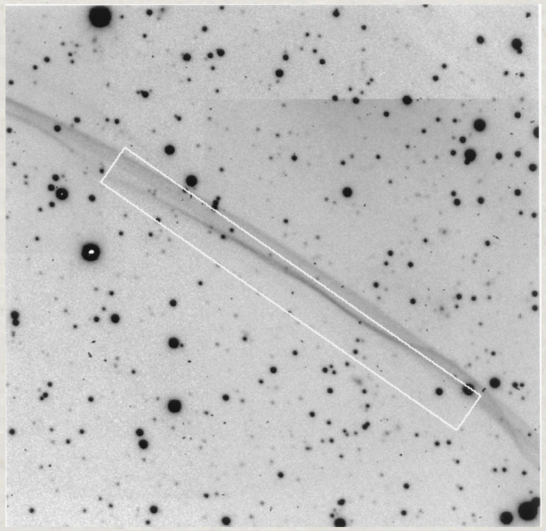




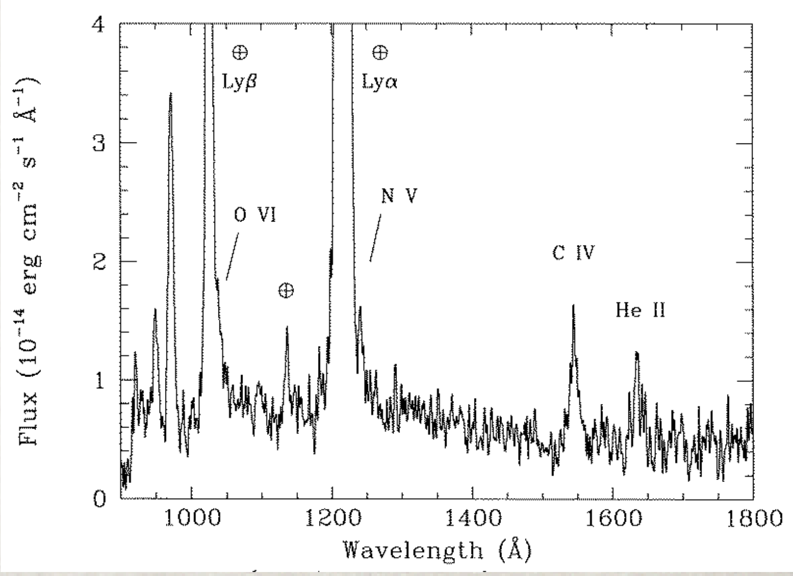
Ghavamian et al. (2002)

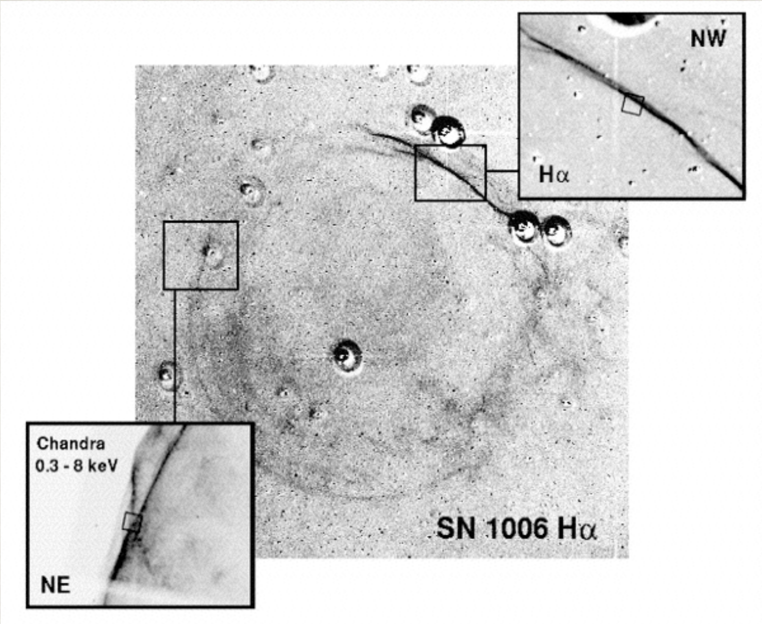
ION-ION EQUILIBRATION PROBES IN THE UV. I

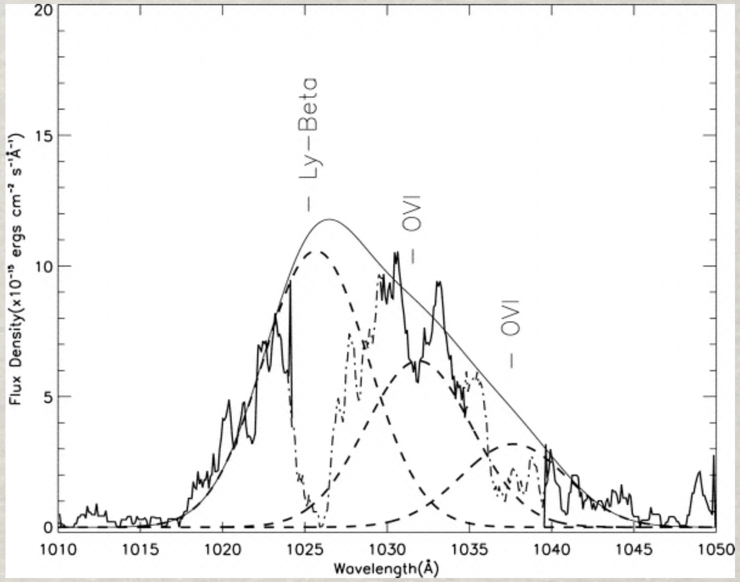
- Observations of SN 1006 with HUT and FUSE have allow us to compare proton, He, C, N and O line widths directly (Laming et al. 1996, Korreck et al. 2004)
- Results suggest that the amount of heating (or conversely, the amount of energy lost) by the ions in the shock front varies with the mass of the ion... a clue to the nature of the shock front turbulence.



Raymond et al. (1995)







Korreck et al. (2004)

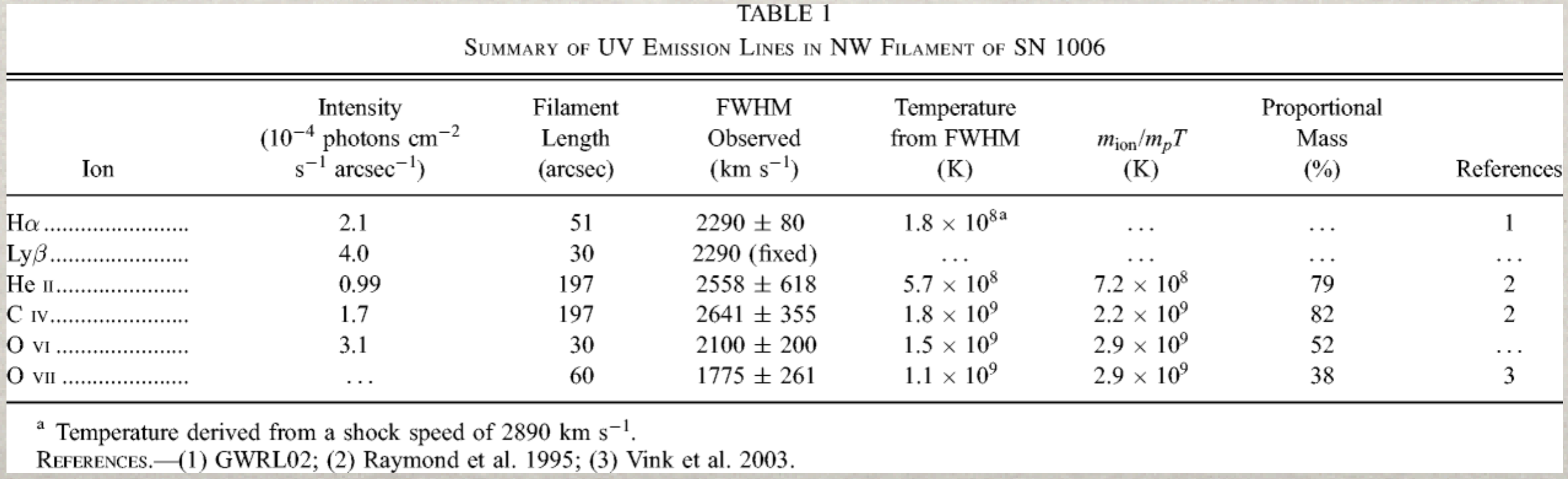


TABLE 1

SUMMARY OF UV EMISSION LINES IN NW FILAMENT OF SN 1006

Ion	Intensity (10^{-4} photons cm^{-2} s^{-1} arcsec^{-1})	Filament Length (arcsec)	FWHM Observed (km s^{-1})	Temperature from FWHM (K)	$m_{\rm ion}/m_p T$ (K)	Proportional Mass (%)	References
Hα	2.1	51	2290 ± 80	1.8×10^{8a}	...	...	1
Lyβ	4.0	30	2290 (fixed)	...	...	...	...
He II	0.99	197	2558 ± 618	5.7×10^8	7.2×10^8	79	2
C IV	1.7	197	2641 ± 355	1.8×10^9	2.2×10^9	82	2
O VI	3.1	30	2100 ± 200	1.5×10^9	2.9×10^9	52	...
O VII	...	60	1775 ± 261	1.1×10^9	2.9×10^9	38	3

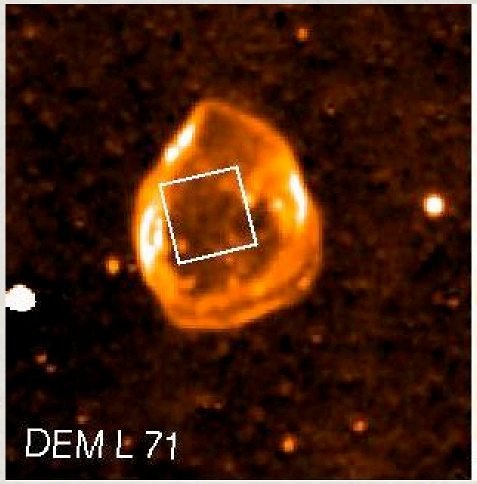
[a] Temperature derived from a shock speed of 2890 km s^{-1}.

REFERENCES.—(1) GWRL02; (2) Raymond et al. 1995; (3) Vink et al. 2003.

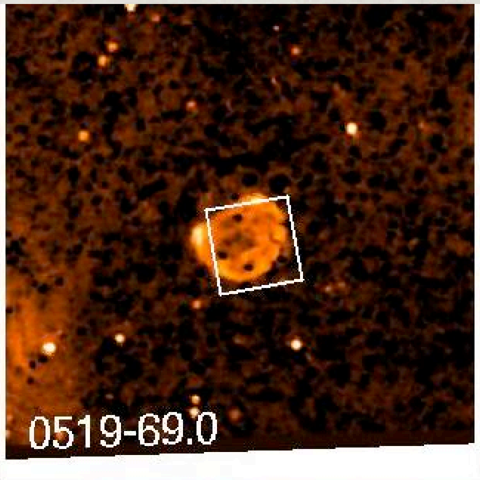
ION-ION EQUILIBRATION PROBES IN THE UV. II

- Four Balmer-dominated Type Ia SNRs in the LMC are excellent candidates for ion-ion equil. study: E(B-V) ~ 0.11

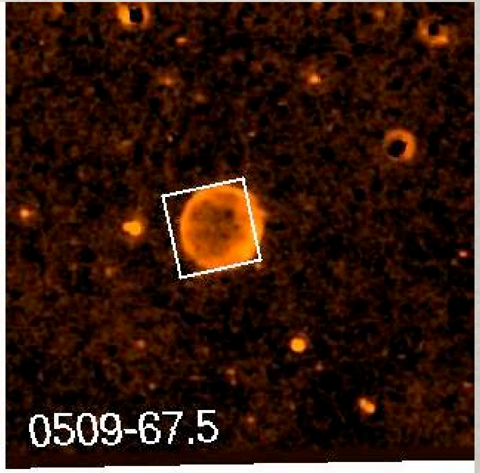
- Known distance (50 kpc), allows good constraints on shock speed from proper motion measurements ($V_S \geq 2000$ km s^{-1})



Age: 4500 yr
(Ghavamian et al. 2003)

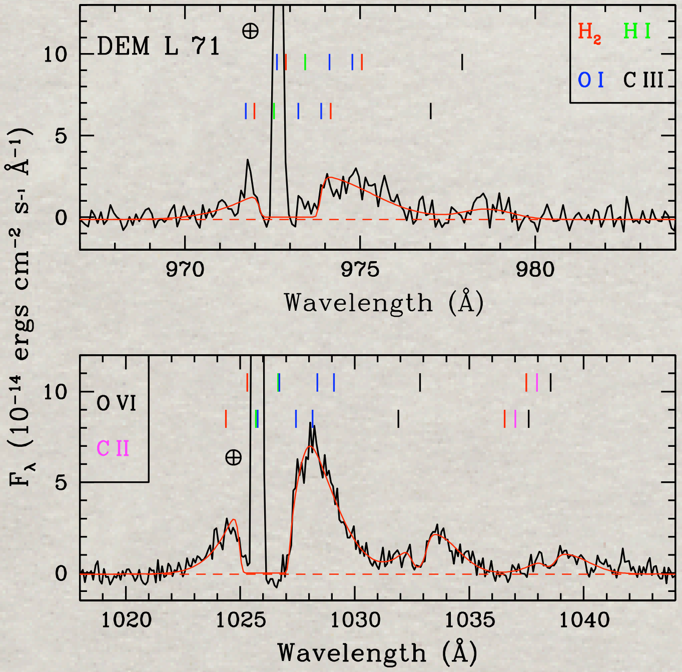


Age: 600 yr
(Rest et al. 2005)



Age: 400 yr
(Rest et al. 2005)

FUSE observations (Ghavamian et al. 2006)

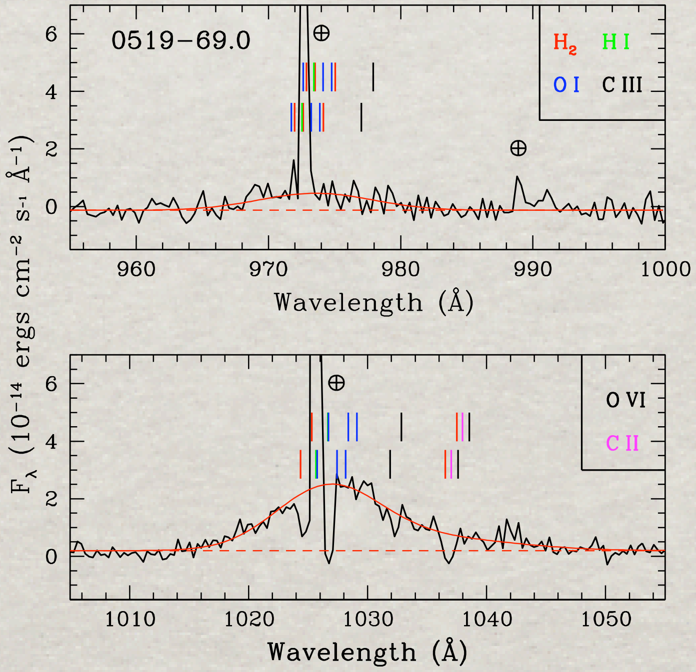


DEM L 71:

V_{FWHM} (Lyβ) = 1140 ± 30 km s^{-1}

V_{FWHM} (OVI) = 740 ± 45 km s^{-1}

Multiple shocks along L.O.S.

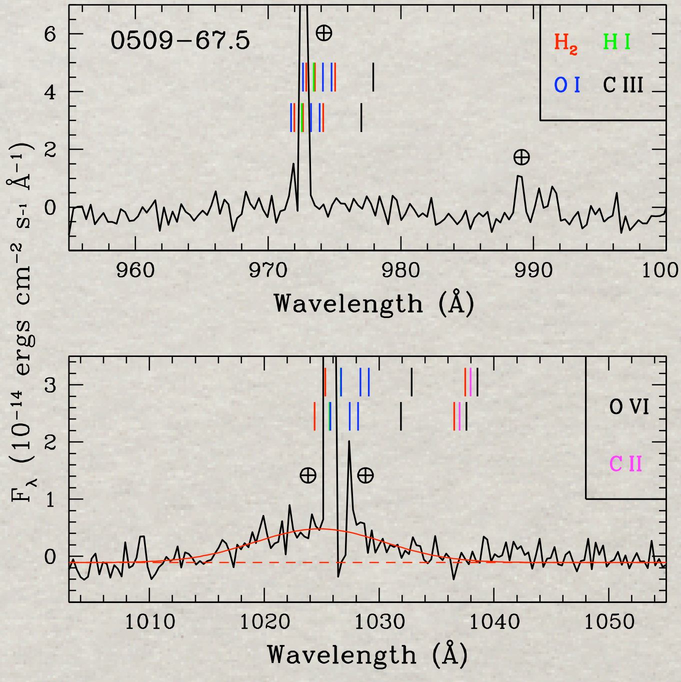


0519-69.0:

V_{FWHM} (Lyβ) = 3130 ± 155 km s^{-1}

V_{FWHM} (OVI) = 4975 ± 1830 km s^{-1}

T_O / T_p = 14 -16



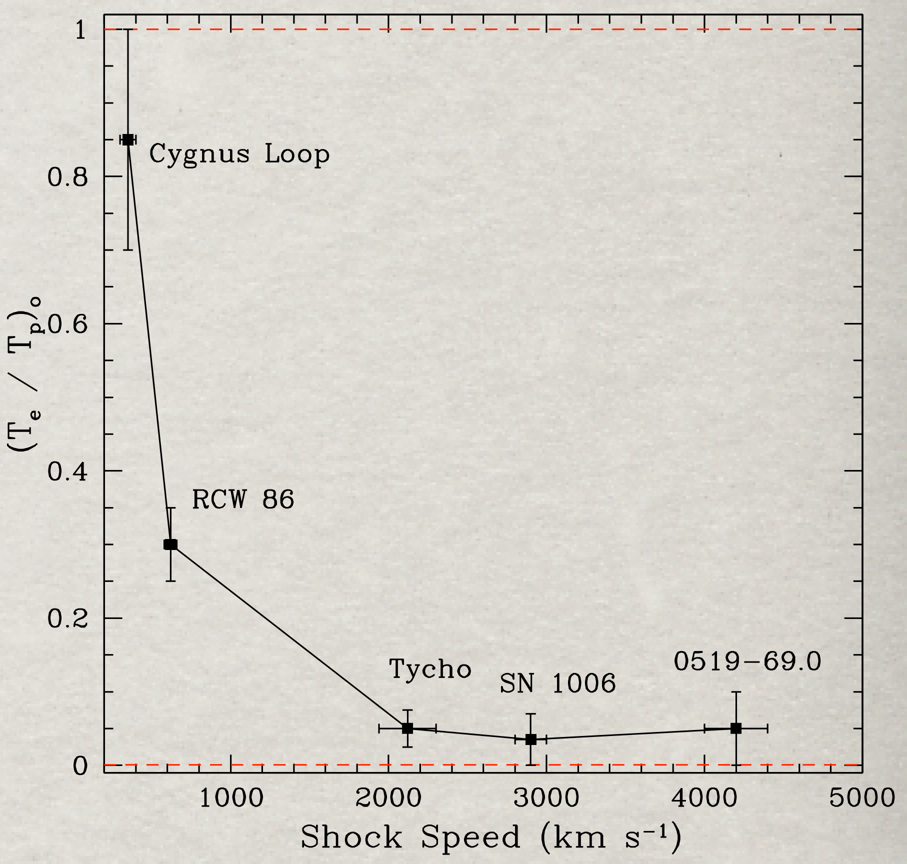
0509-67.5

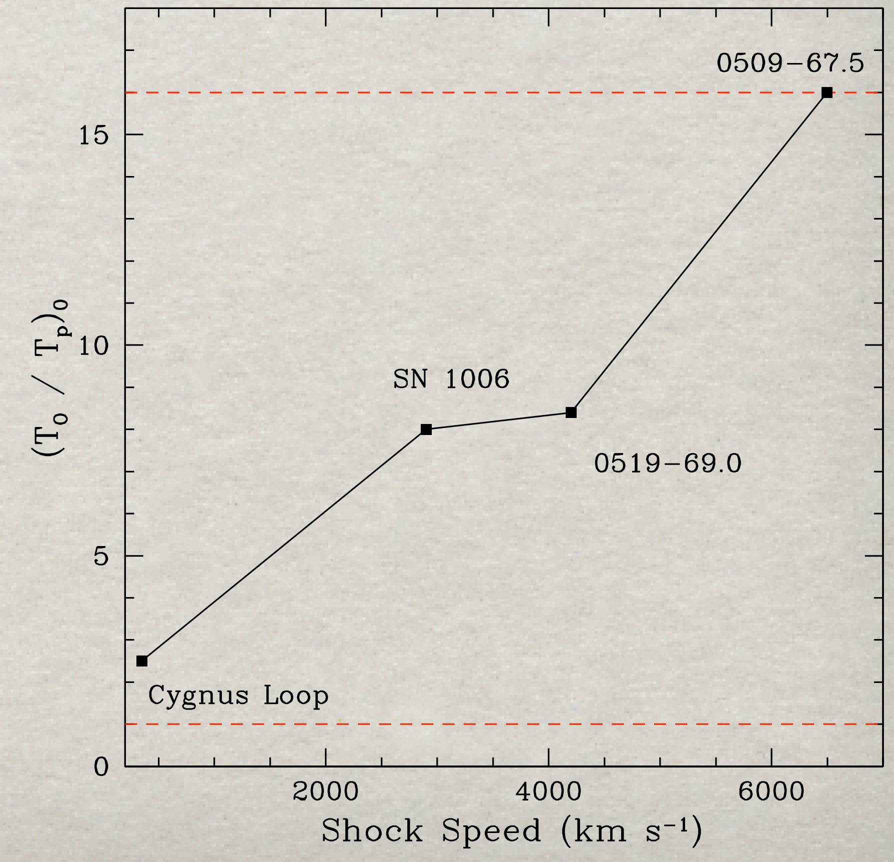
V_{FWHM} (Lyβ) = 3710 ± 400 km s^{-1}

V_{FWHM} (OVI) ≈ 3500-3700 km s^{-1}

T_O / T_p ≈ 16

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 β 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 ?