Electron Injection (and Heating) in SNR Shocks

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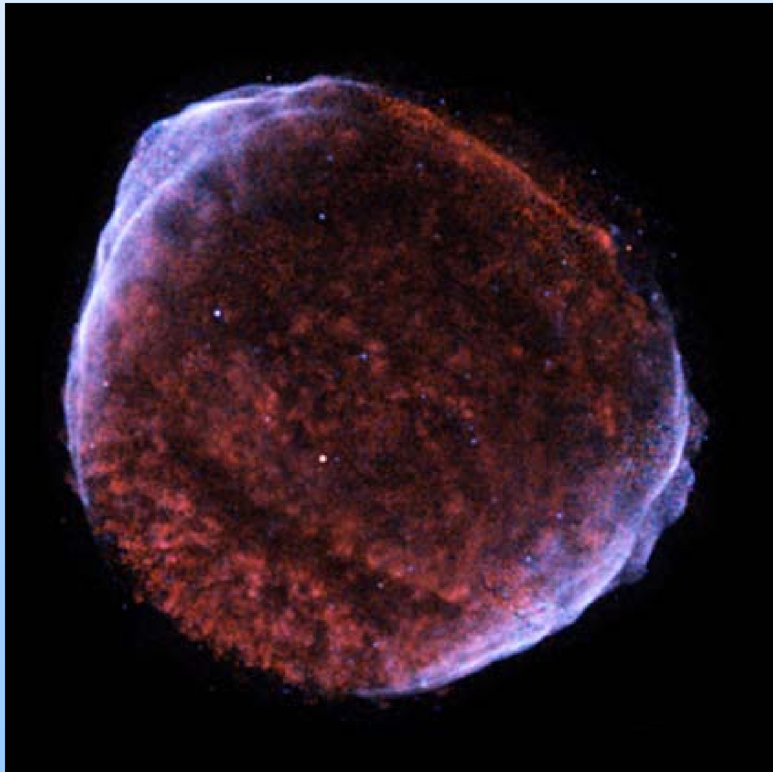
The Electron Injection Problem

- For ions, need $v_{inj} = 2v_{shock} – 10v_{shock}$ (Zank et al. 2006) for diffusive shock acceleration.
- Electrons of the same rigidity: $E \approx (2v_{shock}/c – 10v_{shock}/c)$GeV $\approx$ 30 -150 MeV

Injection mechanism(s) are unknown, but clearly must exist for electron acceleration. See SN 1006!

Injection must be related to electron heating, about which something is known because it can be observed.

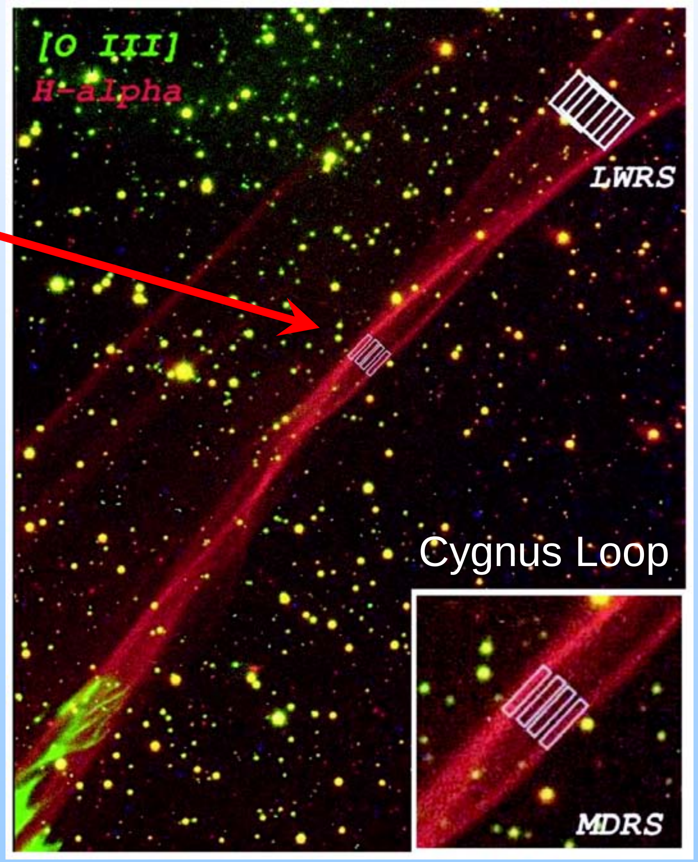


The Electron Heating Problem

- Rankine-Hugoniot jump conditions: postshock temperature $\propto$ mean particle mass
- Naïve application to a collisionless shock, (length scale << particle mean free path) → mass proportional particle temperatures?
- $T_e / T_p = 1/1836$??
- Coulomb equilibration happens, but is slow. Might some faster process heat electrons?
- Use spectroscopy to find out …

Hα emission from the shock front

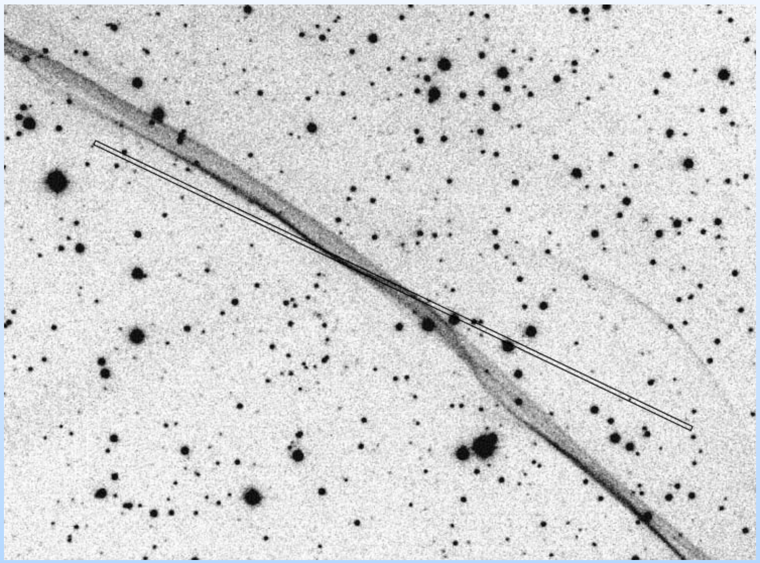
- Non-radiative shocks: primarily Hα emission from the immediate shock front
- Radiative shocks: show O III, N II, S II etc from recombination zone downstream

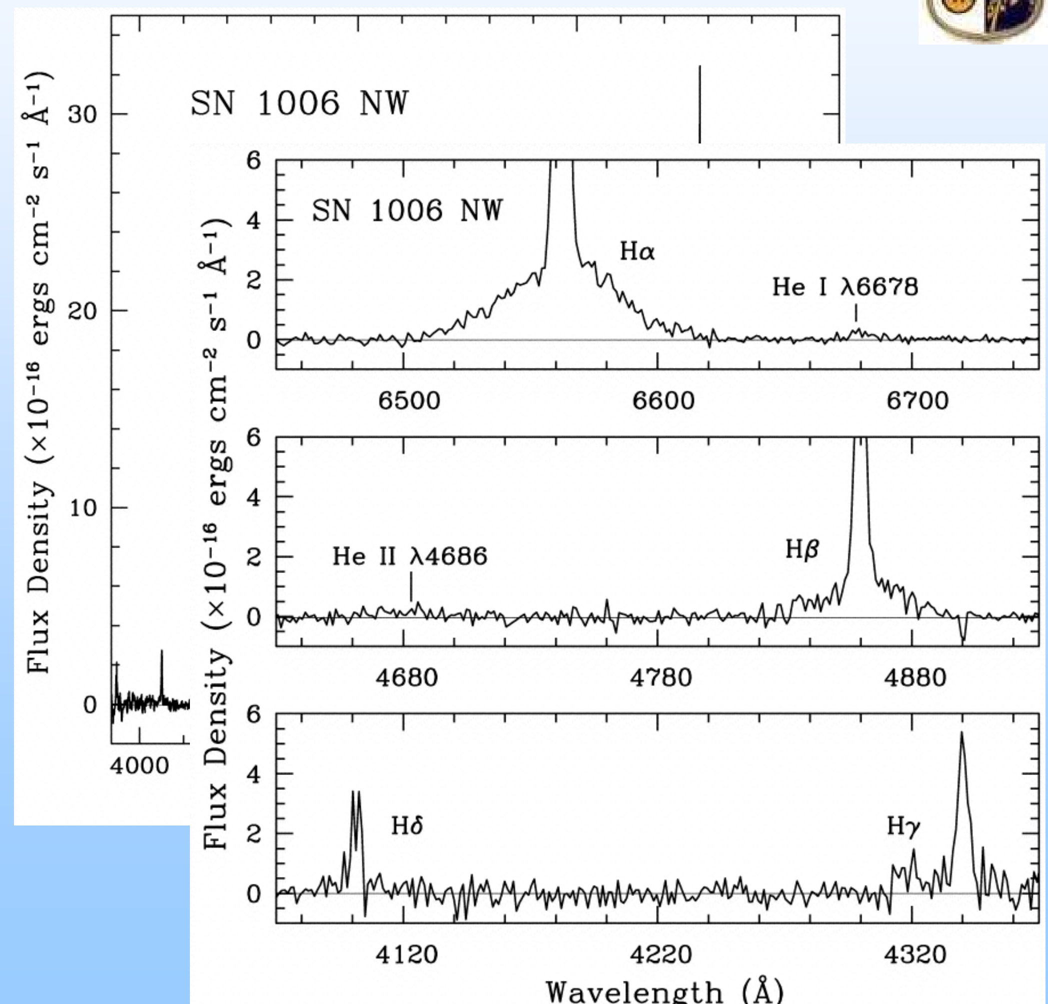


Raymond et al. 2003, ApJ 584, 770

Electron-Ion Equilibration: T_e/T_p from Optical Spectroscopy

(SN1006 from Ghavamian et al. 2002, ApJ, **572**, 888)





narrow Hα from preshock

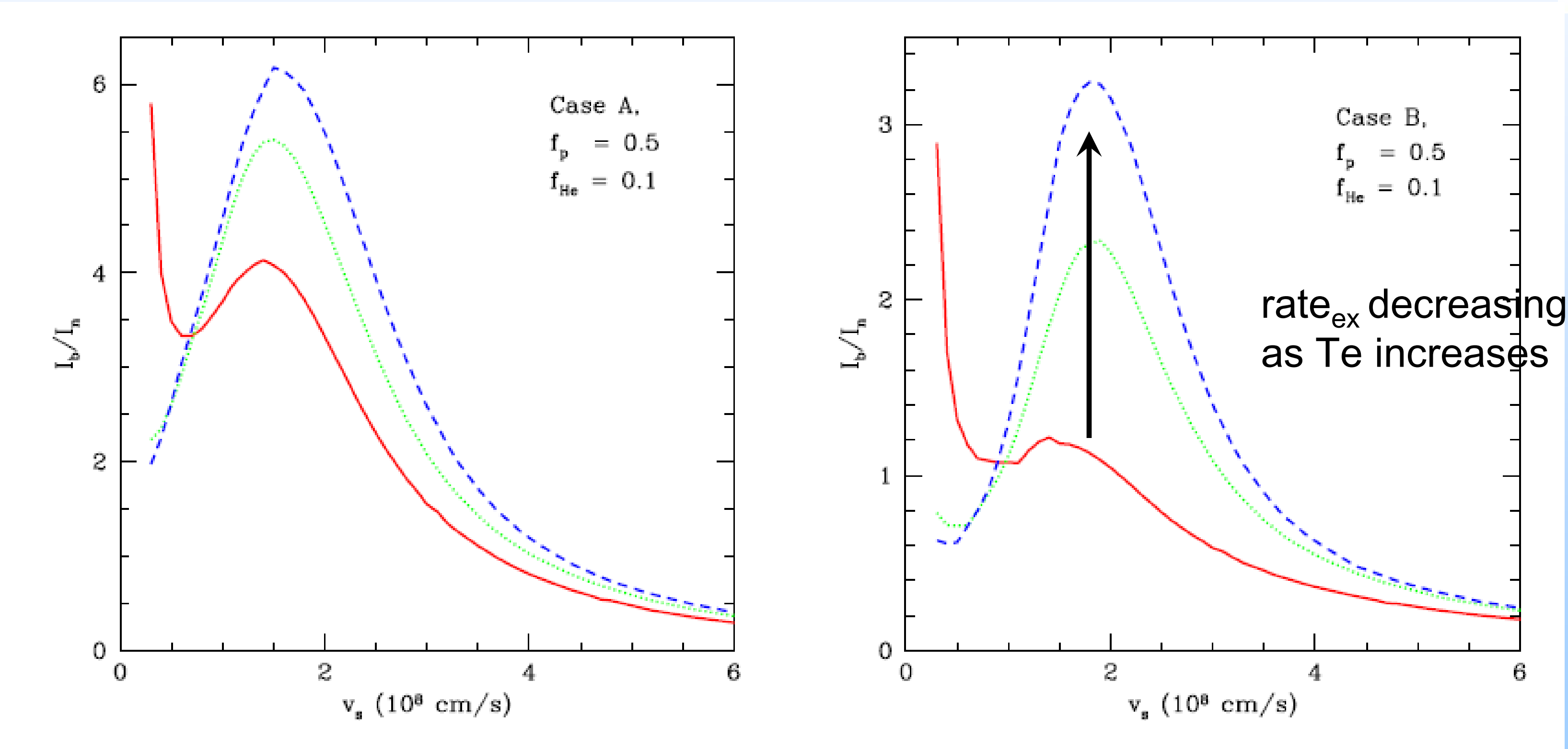
→ T_e

broad Hα from postshock

→ T_p

I_B/I_N (v_{shock})
(~$rate_{cx}/rate_{ex}$)

- $T_e/T_p = 0.1$ (solid red)
- $Te/Tp = 0.5$ (solid green)
- $Te/Tp = 1.0$ (dashed blue)

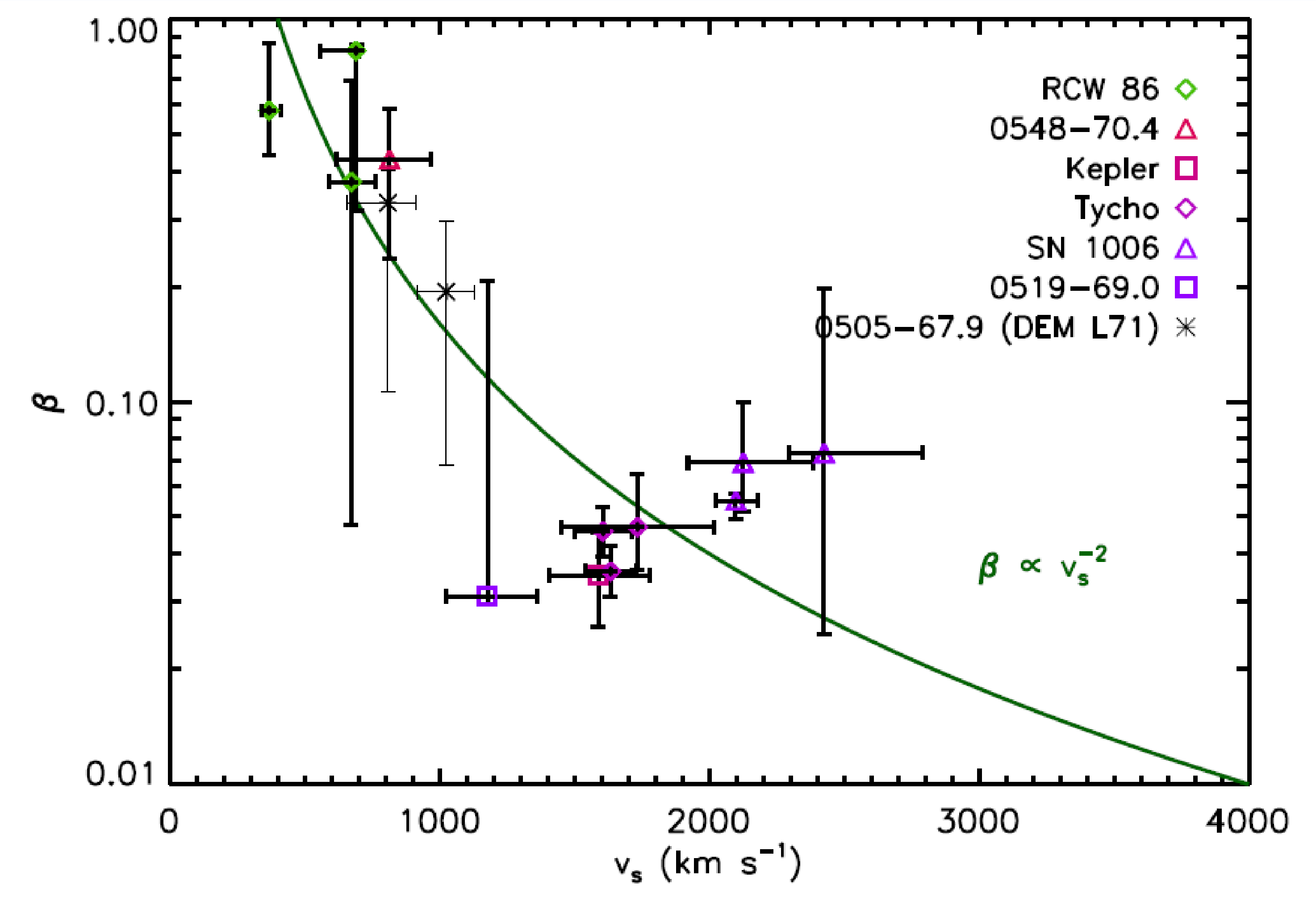


optically thin narrow Hα

optically thick narrow Hα

van Adelsberg, Heng, McCray & Raymond 2008, ApJ, **689**, 1089

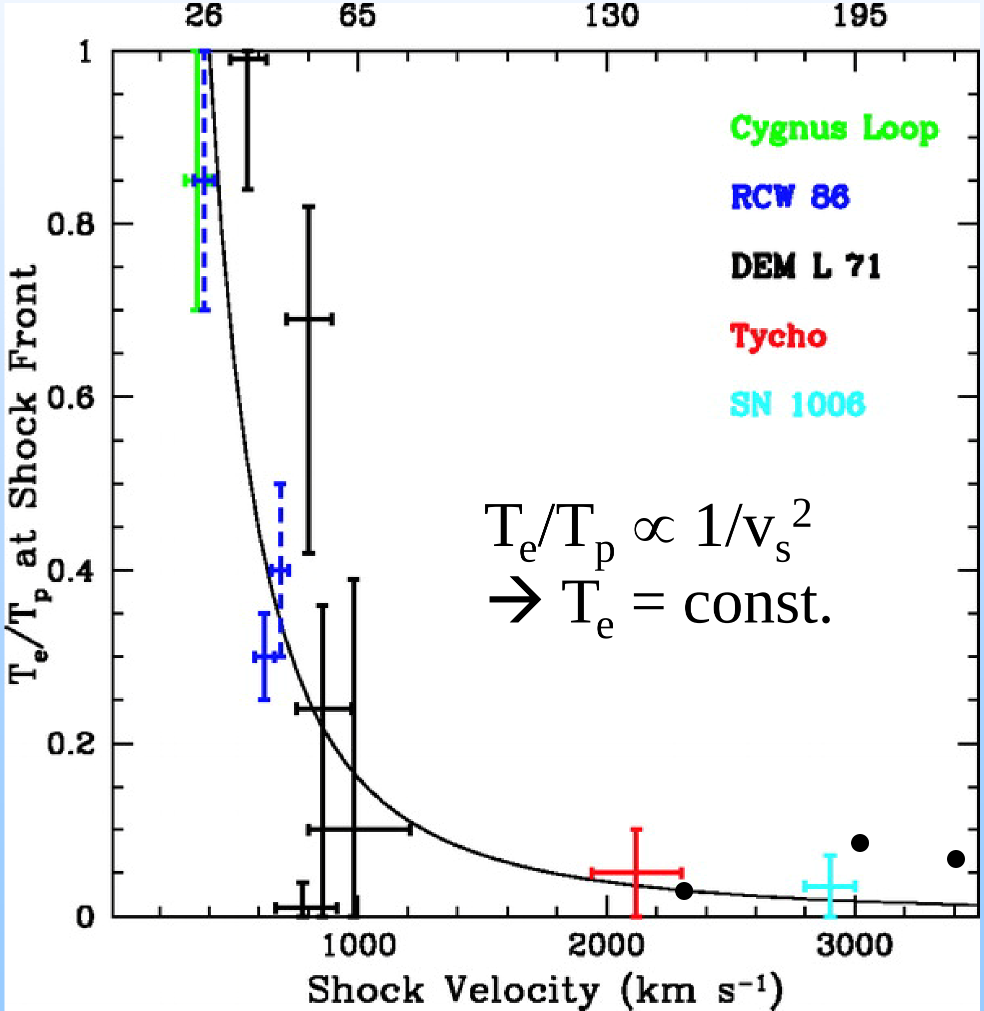
sophisticated treatment of cross sections and post-charge exchange distribution functions



van Adelsberg, Heng, McCray & Raymond 2008, ApJ, **689**, 1089

T_e/T_p Against Shock Velocity

(Ghavamian, Laming & Rakowski 2007, ApJ, **654**, L69)

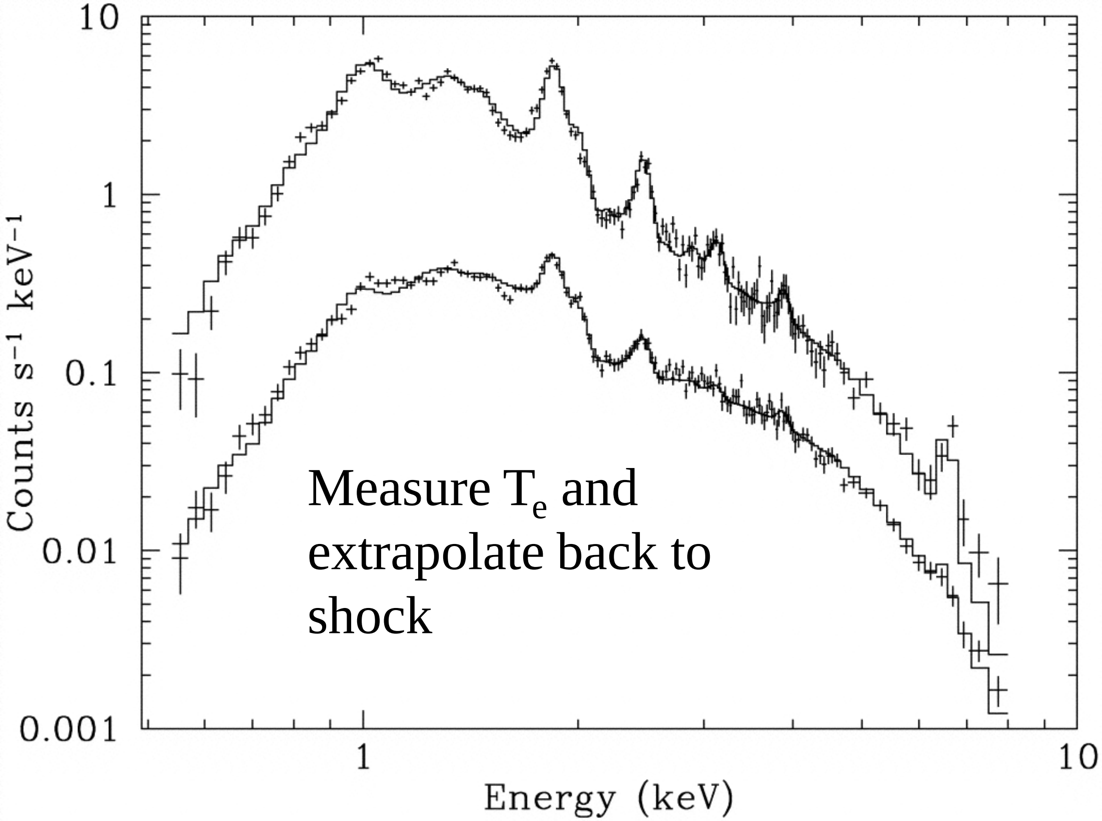


Other data points:

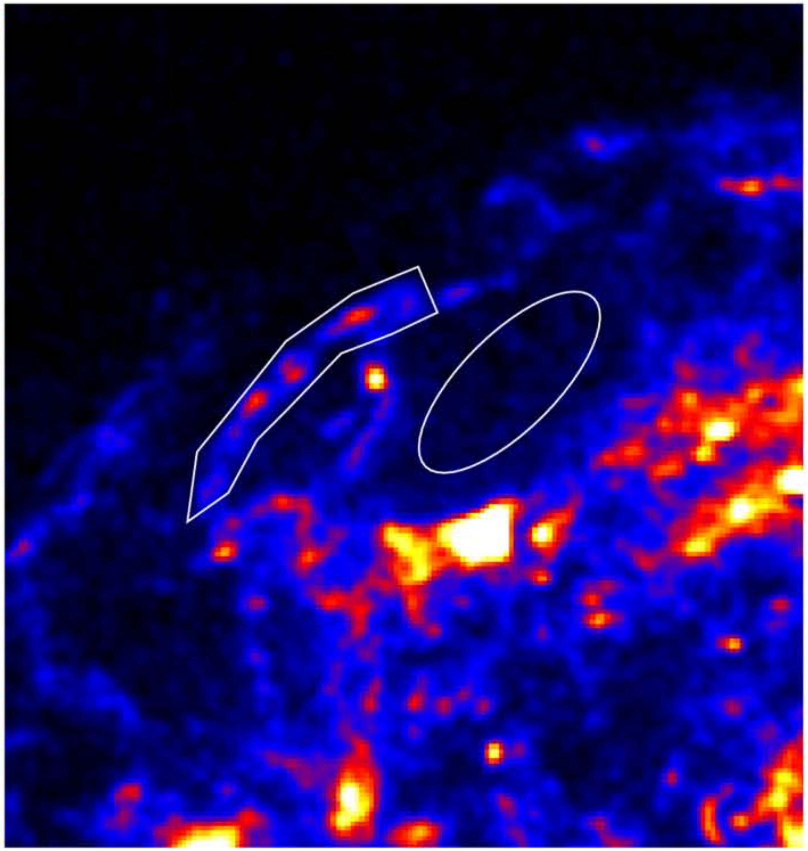
SN 1006 (Laming et al. 1996)
SN 1006 (Vink et al. 2003)
SN 1987A (Michael et al. 2002)
Tycho (Hwang et al. 2002)
Cas A (Vink & Laming 2003)
1E0102-72 (Hughes et al. 2000)
SN 1993J (Fransson, Lundqvist & Chevalier 1996; not shown)

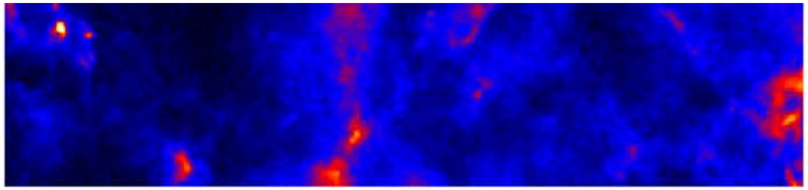
Diagnostics at The Forward Shock of Cas A from Vink & Laming (2003, ApJ, **584**, 758)

Chandra image in continuum, thin shell gives B ~ 100 μG



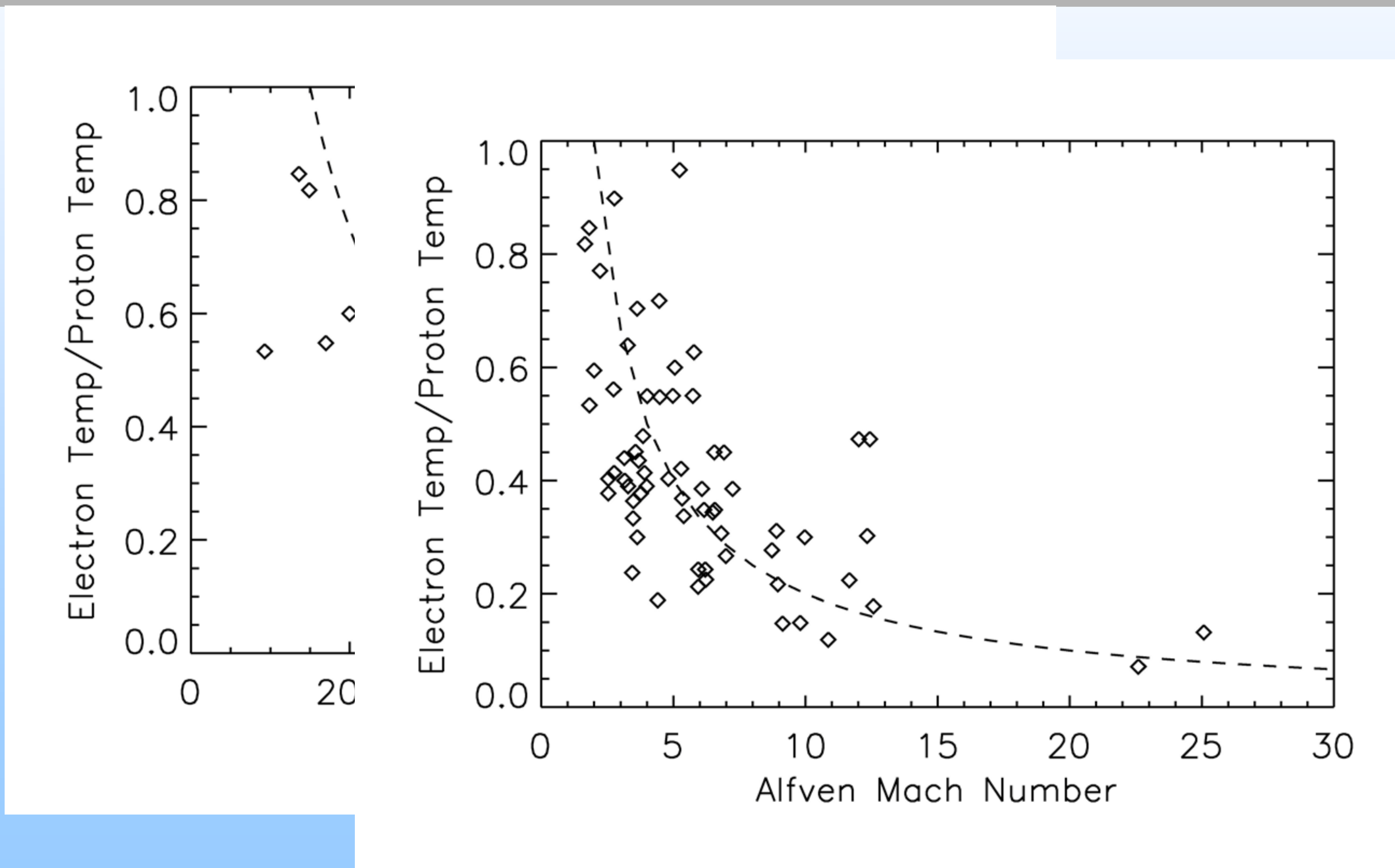
Measure T_e and extrapolate back to shock





… and in the Solar Wind …

(from Schwartz et al. 1988, JGR, **93**, 12923, $T_e/T_p \propto 1/v_s$, $1/M_A$)



The Models: Shock Reflected Ions Generate Electron Heating Turbulence …

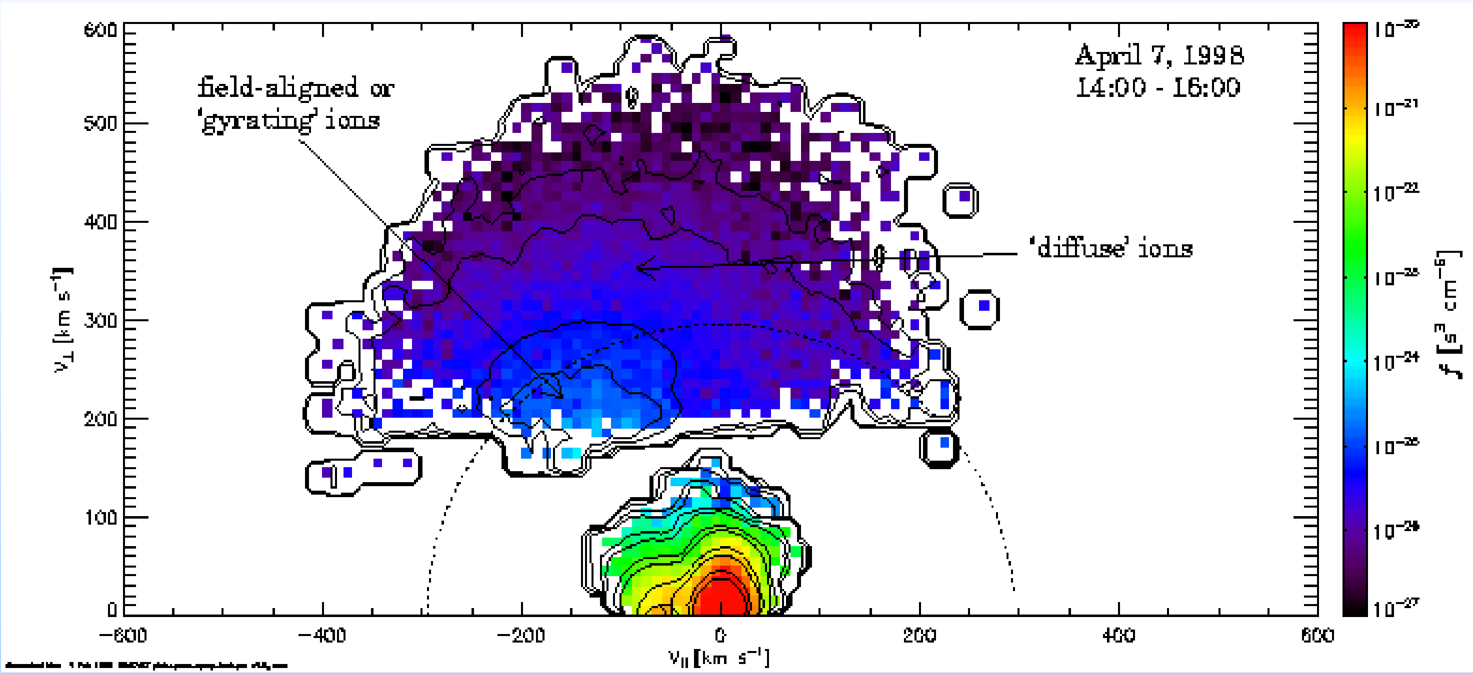
- Cargill & Papadopoulos 1988 1D hybrid code, T_e~$0.2T_i$
- Shimada & Hoshino 2000 1D PIC, similar result, as in …
- Amano & Hoshino 2007, 2009, 2D PIC moderate M_A~14, Umeda, Yamao & Yamazaki 2008, 2009, 2D PIC M_A~5
- Ohira & Takahara 2007, 2008, 2D PIC high M_A, reduced electron heating

Electron Injection: Schmitz, Chapman & Dendy 2002ab, McClements et al. 2001, Dieckmann et al. 2000, 2006

Parallel Shocks: Bykov & Uvarov 1999

Upstream shock reflected ions.

http://www.srl.caltech.edu/ACE/ACENews/ACENews34.html



- $1/2 m_e v_e^2 = 1/2 m_e D_{\|\|} t = 1/2 m_e D_{\|\|}/\Omega_i \sim v_s^2$ with $D_{\|\|} \sim (eE/m_e)^2/\omega \propto v_s^2$ so …
- T_e/T_i = constant with shock velocity → a problem!

Another Possible Solution?

- Assume electrons are heated by waves generated in cosmic ray precursor.

- $1/2 m_e v_e^2 = 1/2 m_e D_{\|\|} t$
- $= 1/2 m_e D_{\|\|} (L/v_s)$
- $\propto 1/2 m_e D_{\|\|} (K/v_s^2)$
- $D_{\|\|} \sim (eE/m_e)^2/\omega \propto B v_s^2$
- $K \sim 1/B$

- → B and v_s dependences cancel out for constant T_e!
- Some support in Rakowski, Ghavamian & Laming 2009, ApJ, **696**, 2195? (depleted I_B/enhanced I_N in DEM L71)
- $T_e/T_p \propto 1/v_s$ with nonrelativistic cosmic rays

Magnetic Field Amplification versus Electron Heating

Linear theory:

B-field growth $\gamma_B = n_{CR}M_Av_s/2n_ir_{g,inj}$, parallel shock
$= 0$, perpendicular (Bell 2004, MNRAS, **353**, 550)

LH-wave growth $\gamma_{LH} = 0.04n_{CR}\omega_{LH}/n_i$, perpendicular shock
$= 0$, parallel (Rakowski, Laming, & Ghavamian 2008, ApJ, **684**, 348)

High M_A, cosmic rays amplify B, low M_A, cosmic rays grow LH waves, heat electrons. Equality at $M_A \sim 6v_{inj}/v_s \sim$ 3-12? (depending on geometry and magnetic field saturation)

Comparison with solar wind → x 10-100 amplification of B in SNRs

Conclusions

- Cosmic Rays/Solar Energetic Particles are important!
- The Bell hypothesis on magnetic field amplification by CRs is supported by observations of SNRs
- An extension of this hypothesis to CR generated electrostatic lower hybrid waves appears to match measurements of T_e/T_p.
- Predicted CR shock precursor should have long region ($\sim K/v_s$) of B-field amplification followed by shorter region ($\sim 10^{16}$ cm to avoid ionizing H) of electron heating.
- Narrow Hα line width indicative of CR precursor? (Lee et al. 2007, ApJ, **659**, L133)
- Outstanding problem of CR electron injection!