X-ray Observations of Electron/Ion Heating in Supernova Remnant Shocks

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February 10, 2006

X-ray Observations of Collisionless Shocks in Supernova Remnants

- Provide a complementary view of the shock to compare with UV and optical T_p, T_{ion}.
- CCD observations allow spatial separation of post-shock region
- High spectral resolution allows precise determination of relative line fluxes
- interpreting spectra: T_e cannot be assumed equal to T_{shock}
- inverse correlation of electron heating and shock speed, but offset from solar relation in Mach number.

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Measuring temperatures

Ideally measure:

- expanding shock velocity, V_S
- thermal electron temperature, T_e
- thermal proton temperature, T_p
- thermal ion temperatures, T_{He}, T_C, T_O, T_N, …
- relativistic electron synchrotron radiation

Three basic methods:

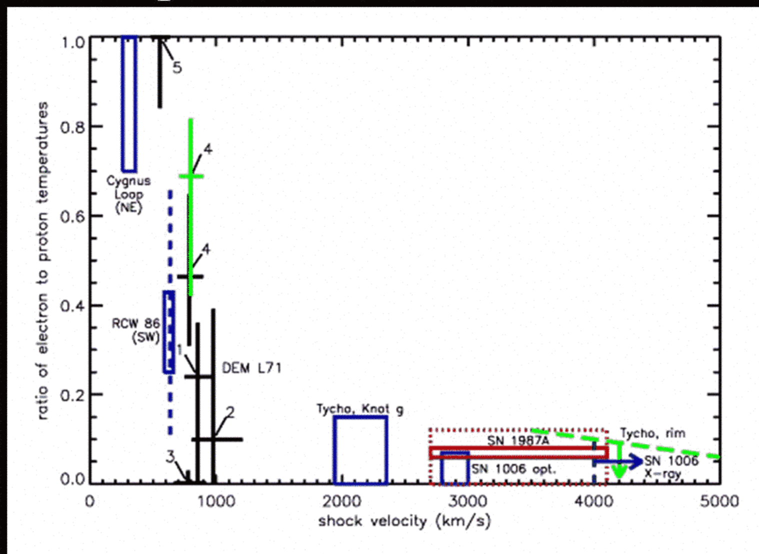
- Thermal broadening of line width
- Ratio of two lines
  - same element different ion
  - different elements
  - excited by different particles
  - use ion fractions
- Thermal bremsstrahlung continuum

Cautions:

- velocity, geometry factor in
- knowledge of ion fractions or relative abundances
- deduce initial T_e from ionization
- distinguish from other types of continuum emission

Methods:	Depends on:
Hα broad width, ion line widths	T_p, T_{ion}, geometry of v_{bulk}
Hα broad to narrow ratio	T_e, T_p, neutral fraction, precursor emission
Line ratios in a single element	Ion fractions, temp. of exciting particle
Line ratios between elements	Relative abundances, ratio of temps. of exciting particles (eg T_e /T_p)
Expansion measurements	V_{shock} , D
X-ray spectrum	T_e, $n_e t$, abundances, shock model …
Synchrotron radio/X-ray, radial brightness profiles…	

post-shock electron-proton temperature ratios in SNRs



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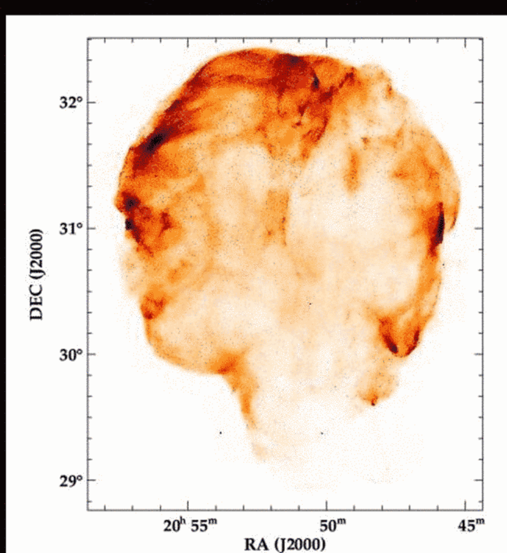
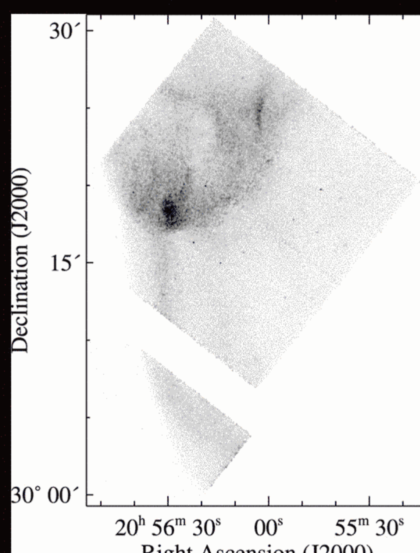
the Cygnus Loop ~ 350 km/s

ROSAT X-ray mosaic Cygnus Loop



N. Levenson

Chandra X-ray 0.3 -8.0 keV



Levenson and Graham 2005 ApJ 622, 366

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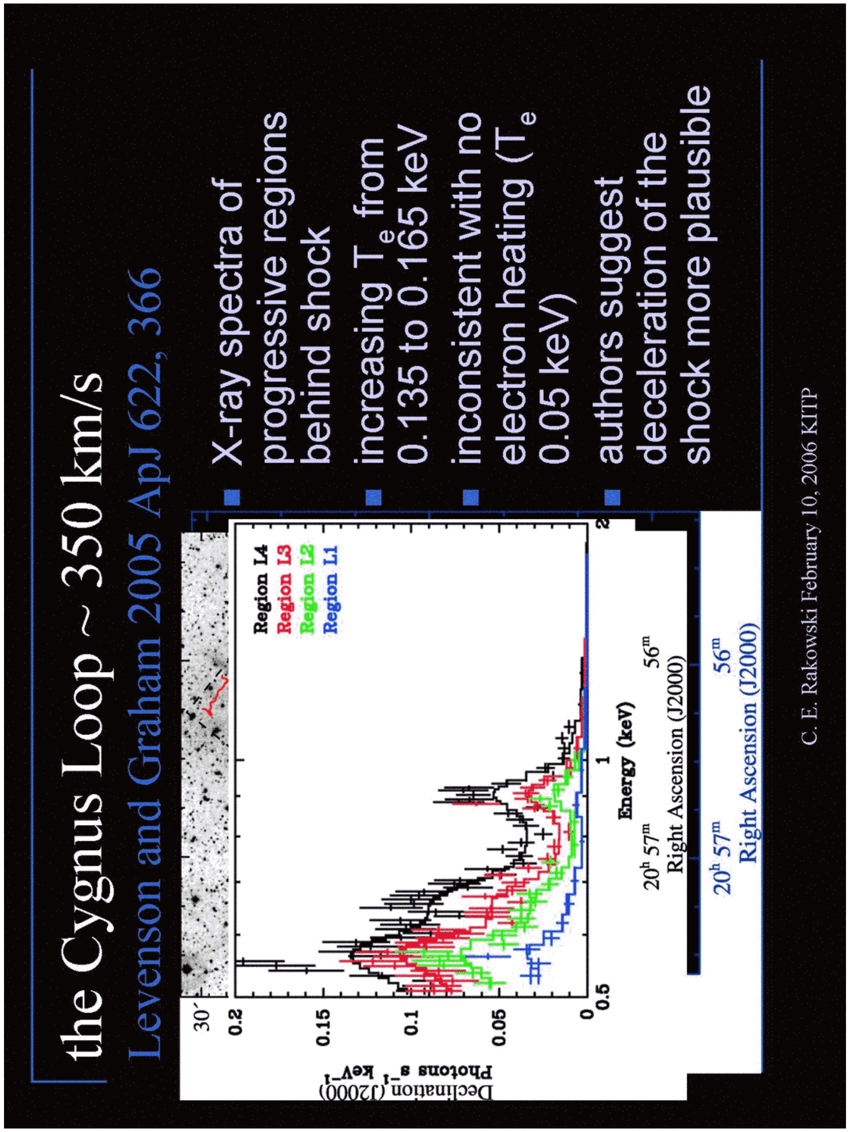
the Cygnus Loop ~ 350 km/s
Levenson and Graham 2005 ApJ 622, 366
X-ray spectra of progressive regions behind shock
increasing T_e from 0.135 to 0.165 keV
inconsistent with no electron heating (T_e 0.05 keV)
authors suggest deceleration of the shock more plausible
Region L4
Region L3
Region L2
Region L1
Energy (keV)
Photons s^{-1} keV^{-1}
Declination (J2000)
Right Ascension (J2000)
20h 57m
56m
30′
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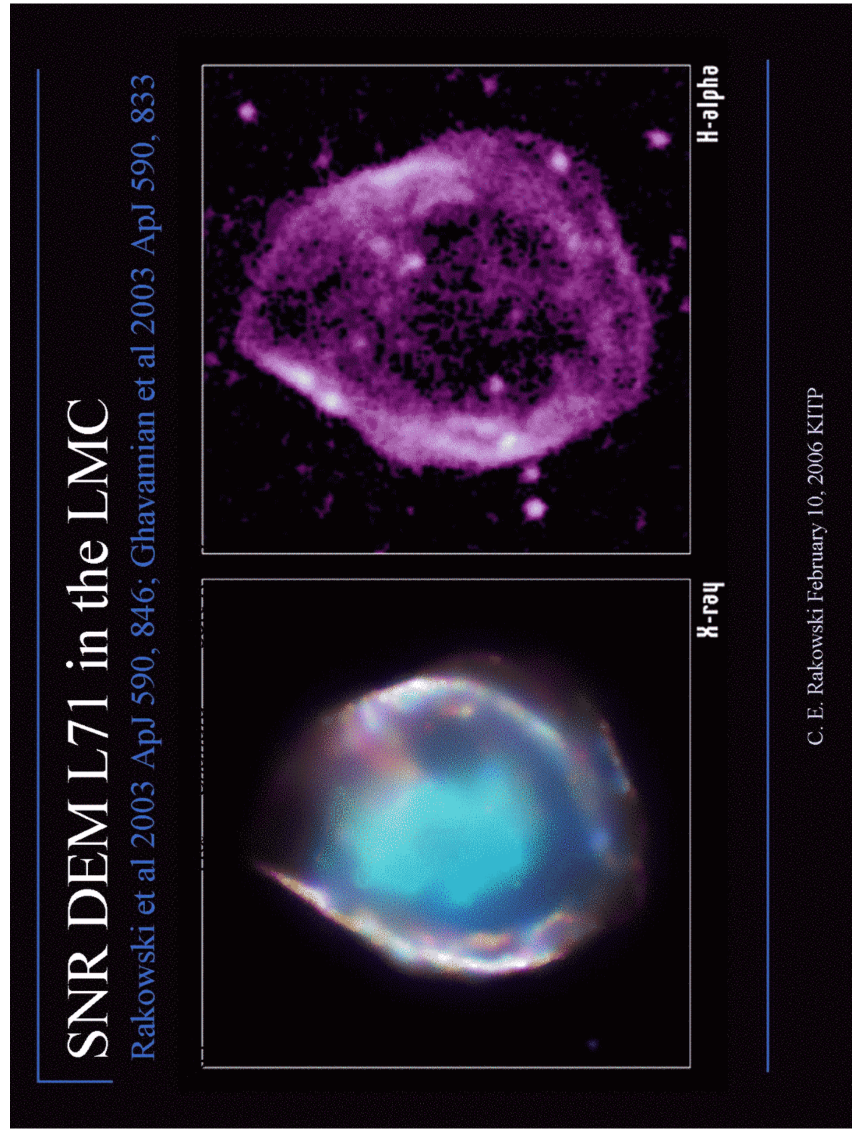
SNR DEM L71 in the LMC
Rakowski et al 2003 ApJ 590, 846; Ghavamian et al 2003 ApJ 590, 833
X-ray
H-alpha
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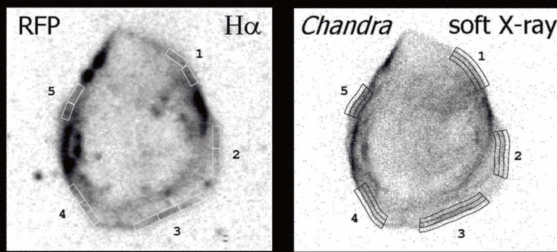

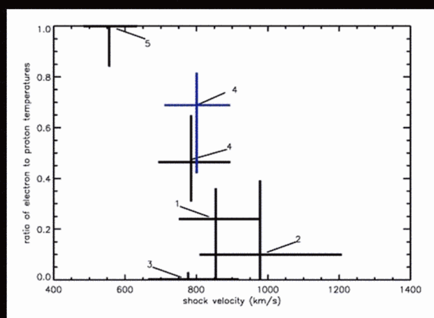

- DEM L71 has Hα filaments around its entire outer rim.
- Optically measure T_p at the shock
- X-ray – measure the evolution of T_e behind the shock with three nested regions.
- First results in black. Fit the three regions simultaneously for T_e/T_p in a planar shock with T_p, abundances and column density fixed.
- Deeper X-ray observations confirm evolution behind the shock.
- Can now fit for the abundances and column density within each aperture and obtain a more reliable result (Rakowski 2005).

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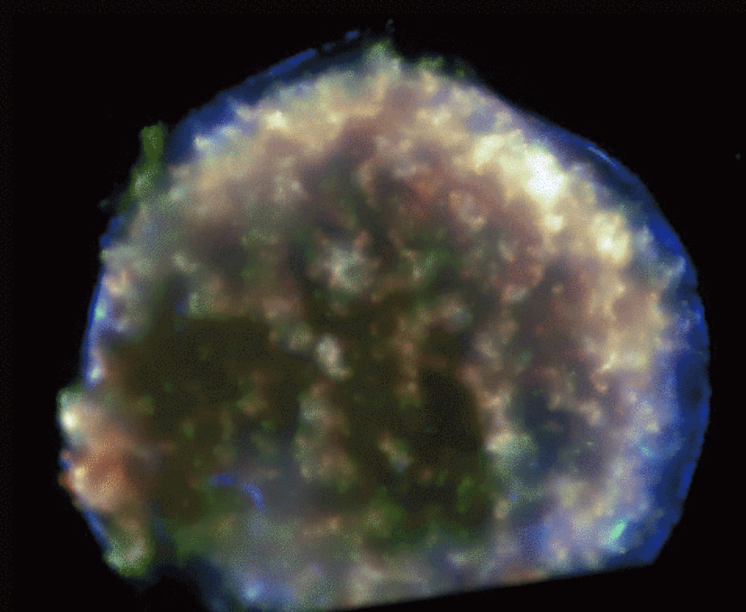
Tycho's SNR



credit: NASA/CXC/SAO

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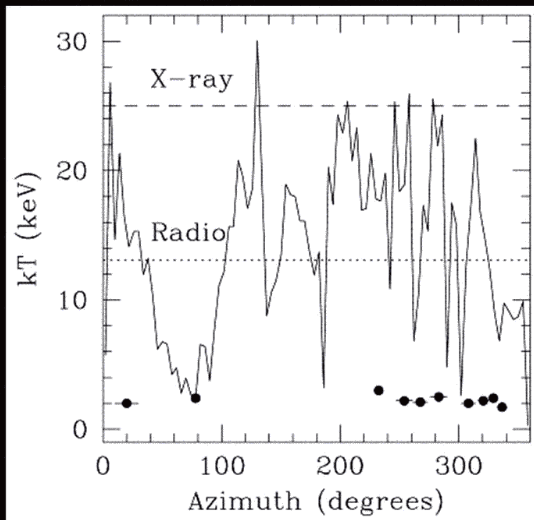
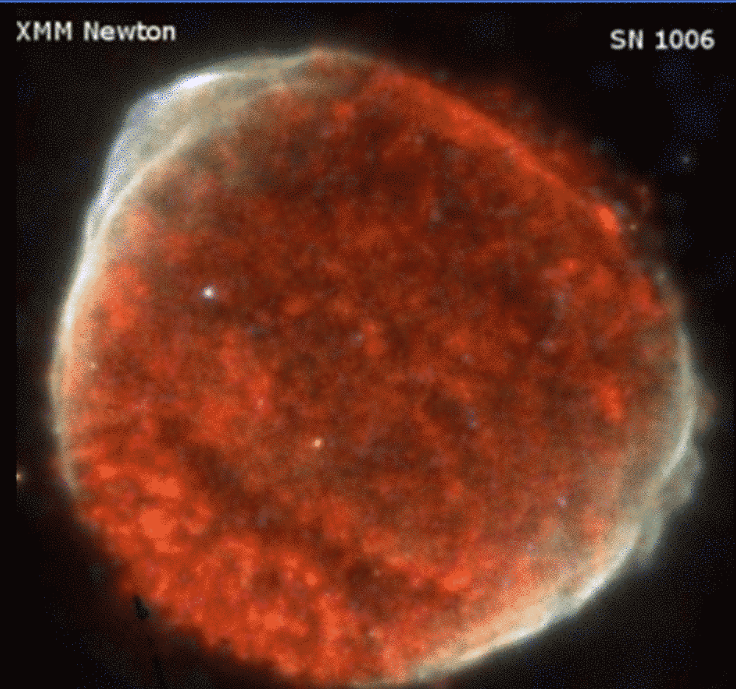
Tycho's SNR



- Ghavamian et al. 2001 ApJ 547, 995
  - Hα, Hβ broad to narrow ratios for bright optical knot in east.
  - Hβ ratio best match for v_s~2100 km s^{-1}, $T_e/T_p < 0.1$.
- Hwang et al. 2002 ApJ 581, 1101
  - Featureless X-ray spectra along N-NW rim. If thermal extremely low ionization timescale and $kT_e \sim 2$ keV
  - compared with mean radio expansion
    - $T_e/T_{mean} < 0.1$-0.2
    - $T_e/T_p < 0.03$ -0.10
  - Alternatively if X-ray cont. is synchrotron emission, then thermal component is even cooler.
- Warren et al. 2005 ApJ in press
  - Evidence for CR acceleration in ratio of radii of shocks and contact discontinuity



SN 1006 >2300 km s^{-1} fully unequilibrated shocks

4 lines of evidence for no equilibration between particles at the shock

- Raymond, et al. 1995 ApJ 454, L31
  - UV emission lines of H I, He II, C IV, N V, and O VI all display similar line widths consistent with a speed of 2300 km s^{-1}. Ion-ion equilibration ineffective
- Laming & Blair 1996 ApJ 472, 267
  - He II λ 1640 (electron excited) to C IV λ 1550 (proton excited) ratio indicates $T_e/T_i < 0.05$, assuming a factor of 2 carbon depletion onto grains. However, cannot rule out $T_e/T_i = 0.2$
- Ghavamian et al. 2002 ApJ 572, 888
  - He I to He II ratio indicates: $f_{eq} < 0.1$, $T_e/T_p < 0.03$
  - Hα, Hβ broad to narrow ratio and all line ratios consistent with $T_e/T_p < 0.07$.
- Vink et al. 2003 ApJ 587, L31
  - *XMM-Newton* X-ray grating spectrum of compact knot. Width of O V, O VI and O VII lines show $kT_{Oxygen} = 530 \pm 150$ keV, $v_s \geq 4000$ km s^{-1}.
  - CCD spectra show $kT_e \sim 1.5$ keV, implying $T_e/T_p \sim 0.05$ if no ion equilibration.

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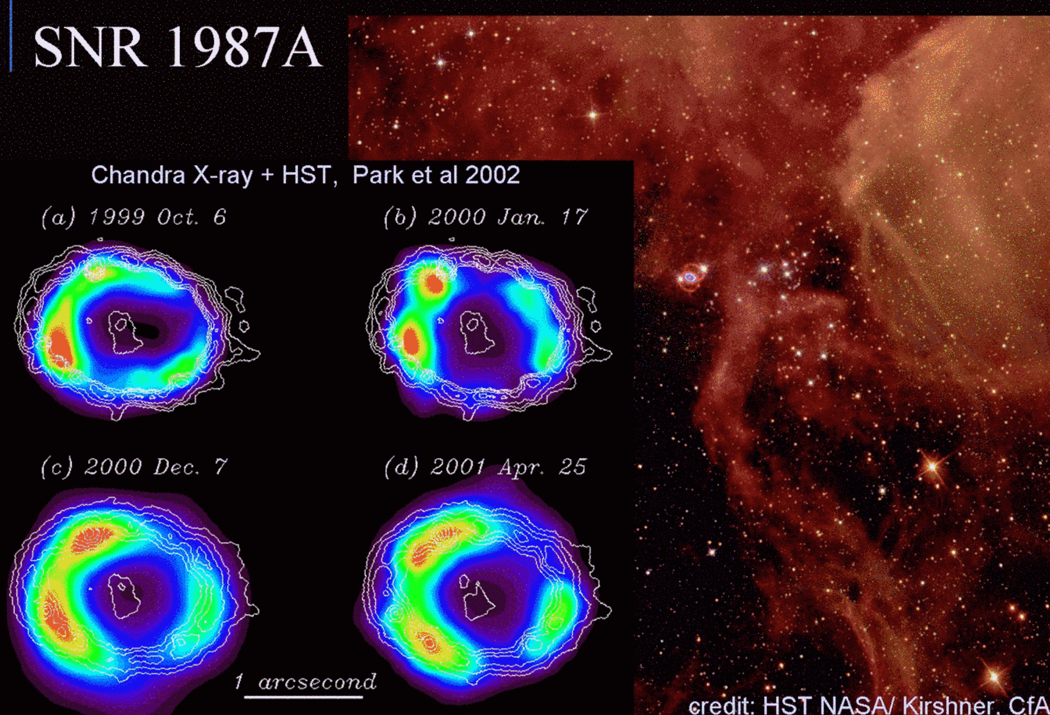
SNR 1987A



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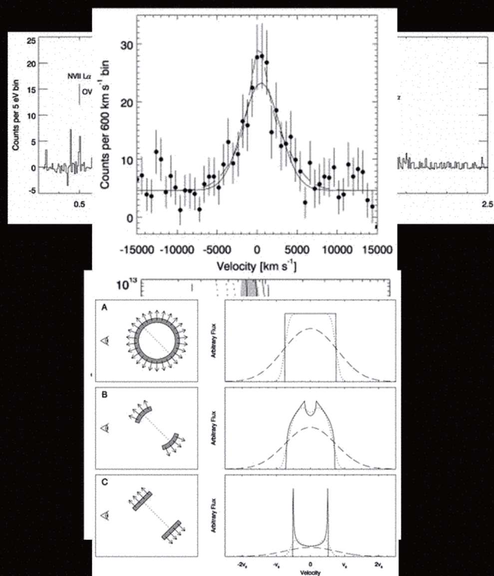
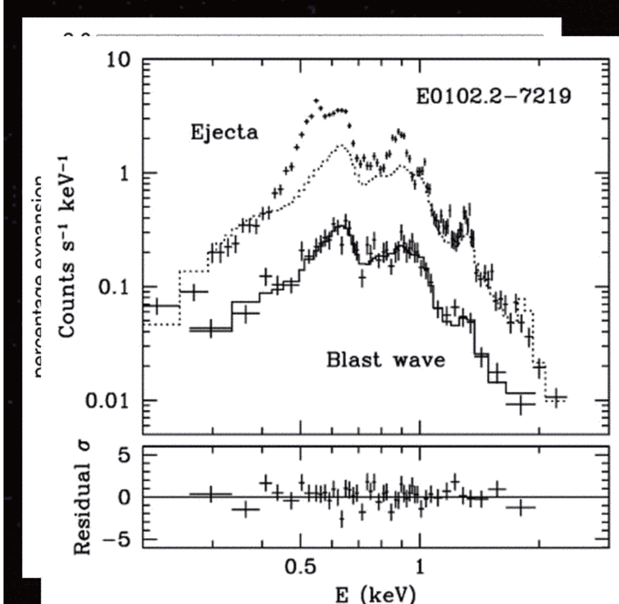
SNR 1987A X-ray grating and CCD spectra

Michael et al. 2002 ApJ 574 166

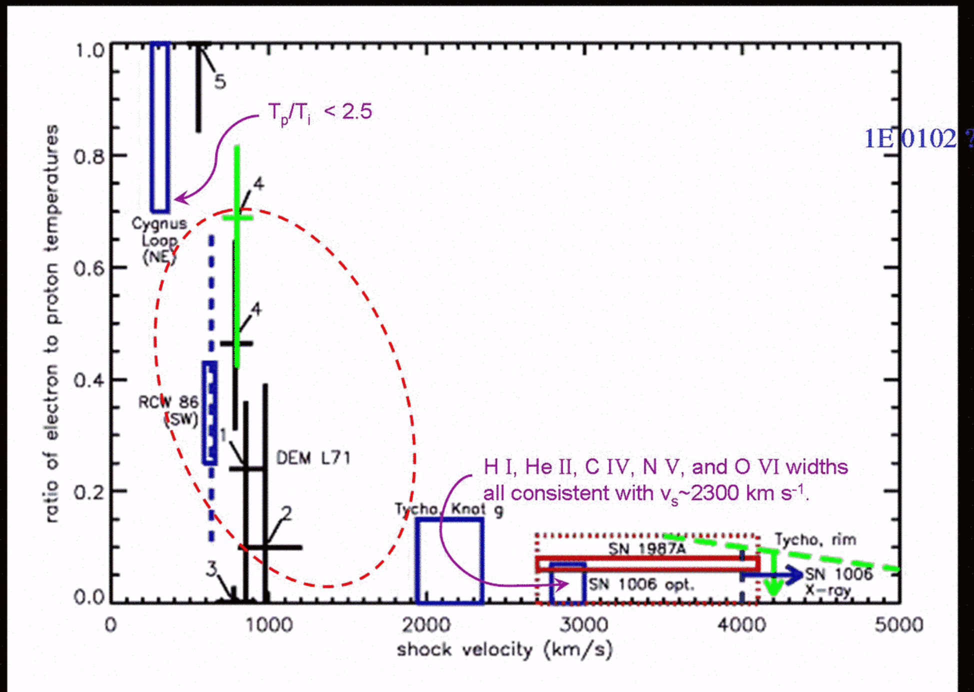


- *Chandra* HETG spectrum of SN1987A $K\alpha$ and $L\alpha$ lines of Ne, Mg, Si, N, O marked
- Constraints on kT_e and $n_e t$ from line ratios of individual elements.
  - Line ratios agree with CCD spectrum, $kT_e \approx 2.6$ keV, $n_e t \approx 6 \times 10^{10}$ cm^{-3} s.
- Combined X-ray line profile
  - Broadening includes both thermal velocity and bulk motion
- Line profiles produced by different geometries of the X-ray emitting plasma
  - solid line – equilibrated (implies faster shock, greater bulk motion contribution)
  - smoother dashed line – no temperature equilibration between the ions
- For no ion equilibration and equatorial geometries: $v_s = 3400 \pm 700$ km s^{-1}.
- If $v_s \approx 3500$ km s^{-1}, then CCD spectra fit by $T_e / T_p = 0.11 \pm 0.02$.

1E 0102-72 Hughes et al. 2000 ApJ 543, L61



- Measure V_s by the expansion of the SNR
  - 0.1% yr^{-1}
  - ~6000 km s^{-1}
  - kT_e 2.5 - 45 keV
- Measure kT_e from blast wave spectrum
  - < 1 keV
- Infer energy -> cosmic-ray production
- With efficient cosmic-ray acceleration the thermal populations may be equilibrated.



Rakowski 2005 AdvSpaceRes

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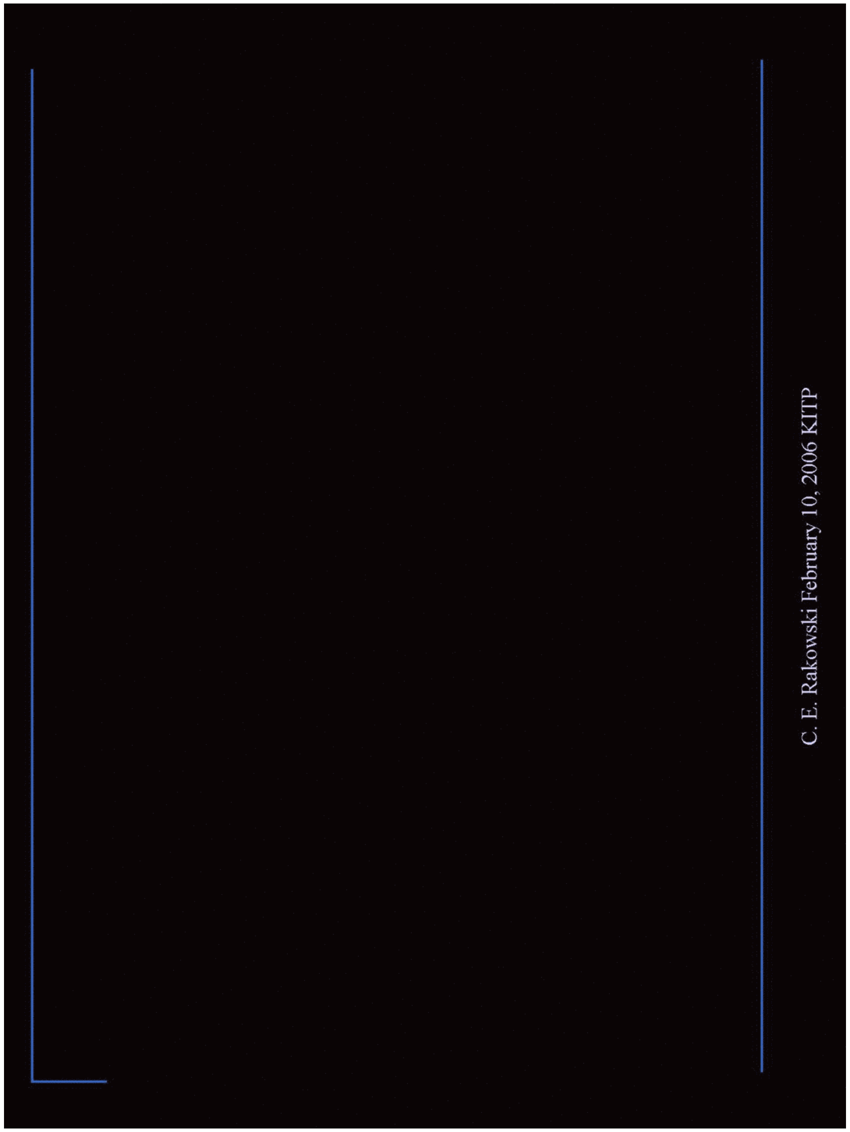
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