Ions Crossing the Contact Discontinuity in Astrophysical Shocks

Narrow Radiative Recombination Continua Detected in a Planetary Nebula

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- For more see: arXiv:0901.1039

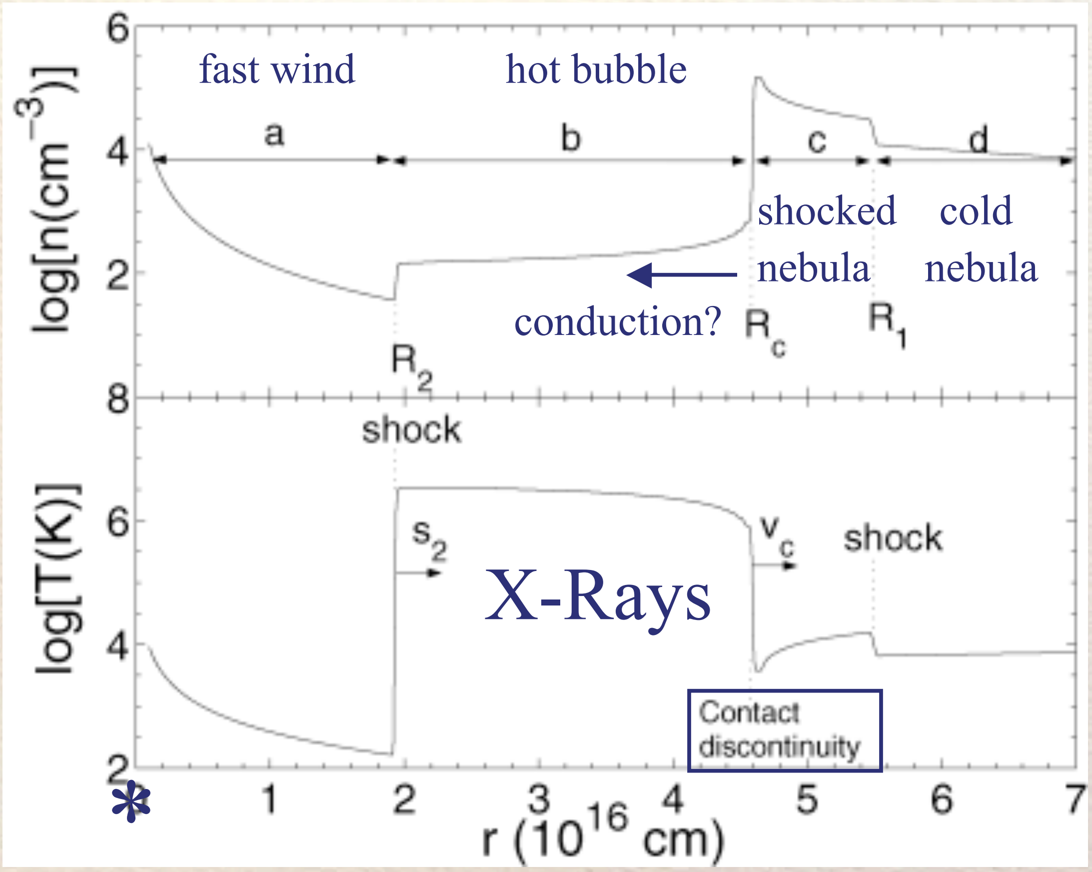
X-Rays from Planetary Nebulae

- Last evolution stages of low-mass stars 1-8$M_\odot$
- Ejected envelope is ionized by UV radiation of central star - a future white dwarf
- But X-rays?
  - Fast wind of ~10^{-7} $M_\odot$/yr UV driven to ~1,000 km/s slams into nebula
  - Reverse shock heats the fast wind to X-ray temperatures, creating the so-called Hot Bubble
  - Picture supported by X-ray images as hot bubble appears confined to the interior of the optical and IR nebula
  - Observed temperatures of 0.1 - 0.2 keV too low
    - Heat conduction / nebular evaporation into bubble?
    - Evolving wind

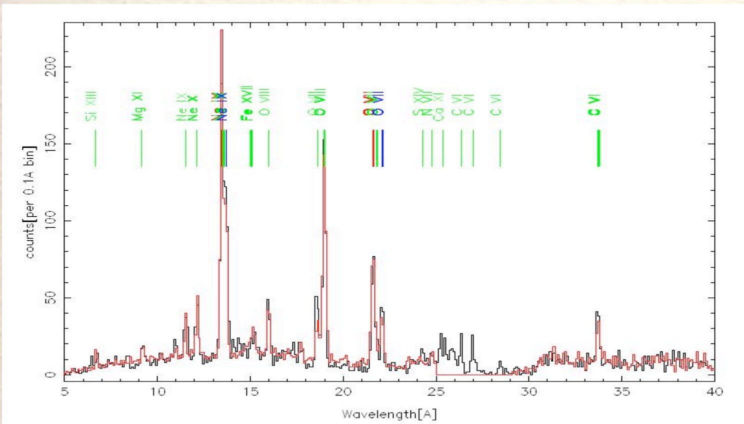
1D Radial Profiles

Density

Temp.



X-Ray Spectroscopy: Chemical Support for Shocked Fast Wind



- 300 ks Chandra / LETG Observation of BD+30°3639 <u>talk by Young Sam Yu</u>
- *2T* model *kT* = 160 eV, 260 eV
- Abundances match evolved WC9 wind and not nebula
- Argues against nebular evaporation

Mass fractions

Element	Wind *	X-Rays
H	--	--
He	42%	42%
C	50%	50%
N	< 0.2%	0.24%
O	5.9%	4.8%
Ne	2%	3.3%
Fe	0.05%	< 0.2%

* UV absorption (Marcolino et al. 2007)

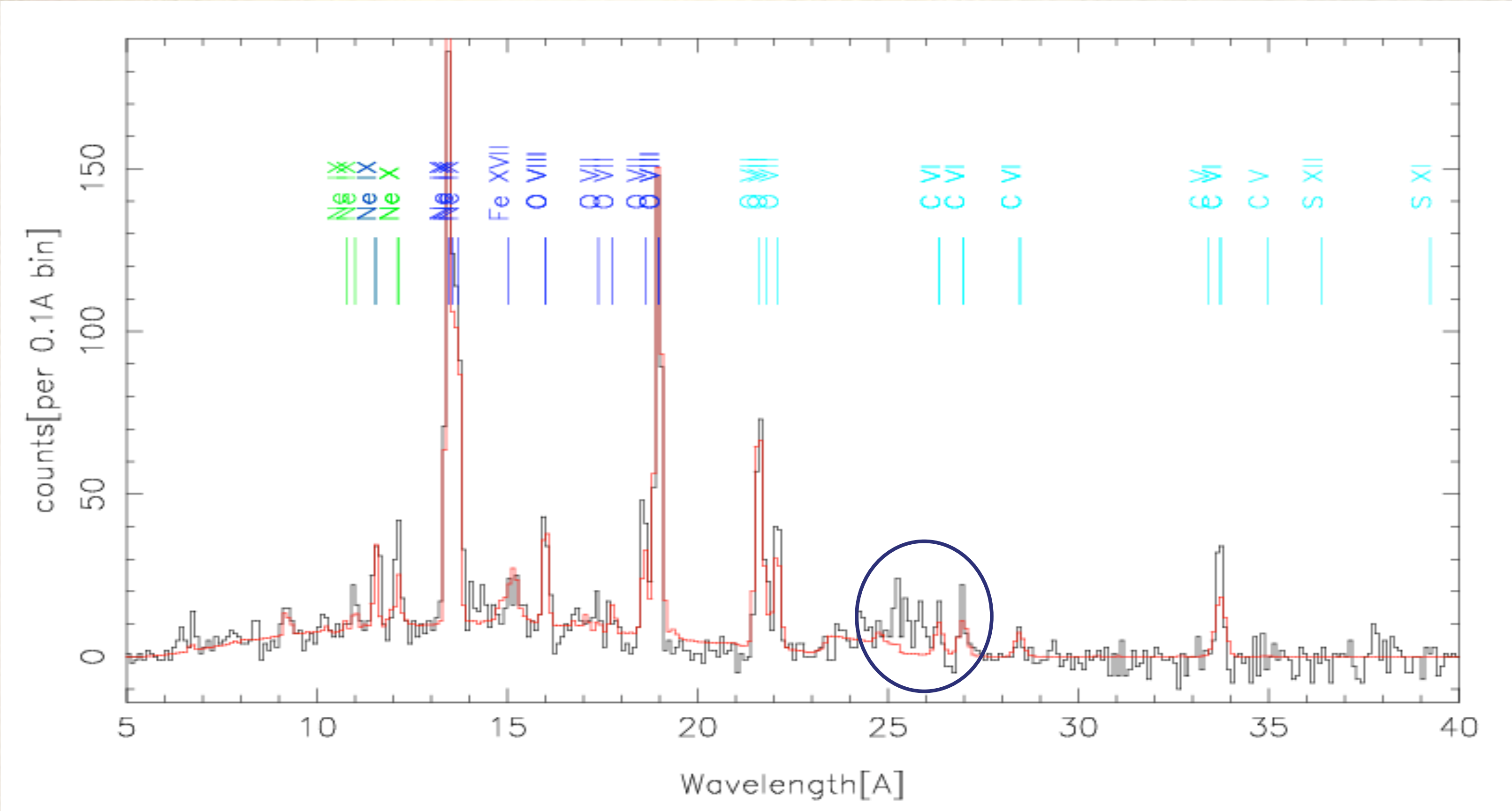
How Well Do We Really Understand Collisionless Shocks?

- How realistic are the assumed sharp jump conditions?
- Collisionless: Mean free path for Coulomb collisions of wind carbon atoms blowing at 1000 km/s through the nebula is large - of the order of the nebular size

$$\lambda_{mfp} = v_w t_s \cong 2 \times 10^{16} \left(\frac{1}{Z_w}\right)\left(\frac{1}{Z_n}\right)\left(\frac{10^4}{n_n}\right)\left(\frac{M_w}{M_C}\right) \text{cm}$$

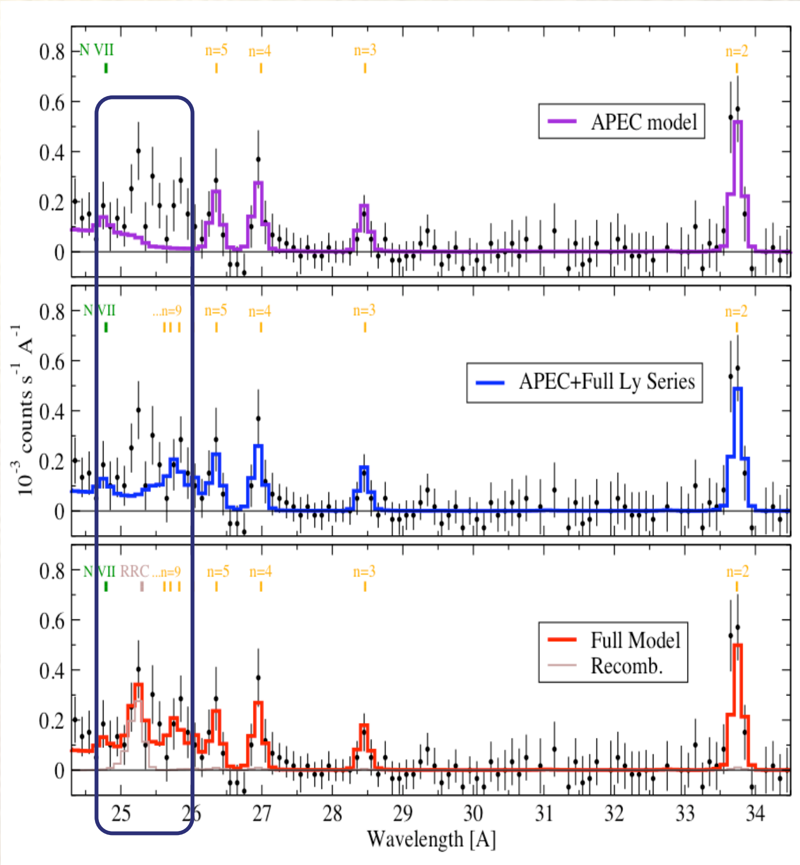
- Magnetic fields could sustain jump conditions of shock and contact discontinuity, but no direct evidence in PNs
- Magnetic fields would inhibit conduction/evaporation
- All these are very hard to study directly and therefore mostly left in the realm of theory
- Can we obtain further insights from the X-ray spectrum?

Interesting Discrepancies

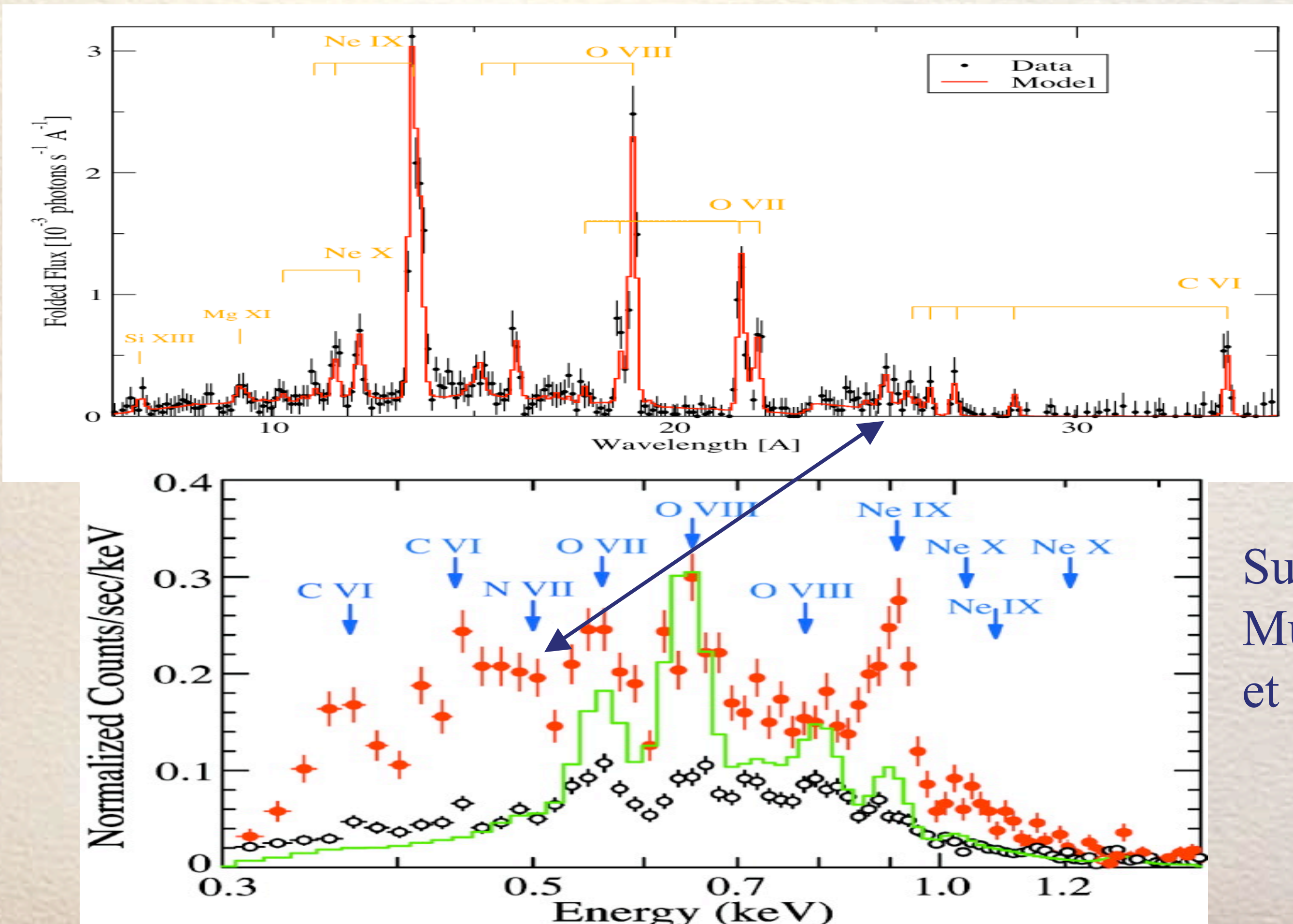


Narrow C VII RRC
Radiative Recombination Continuum

- Recombination of *hot* ions (~100 eV) with *cold* electrons (~ 1 eV)
- RRC width => $kT_e = 1.7 \pm 1.3$ eV
- Intermediate temperatures $1 \text{ eV} < kT < 100 \text{ eV}$ can not be significant
- Origin?



Importance of High Spectral Resolution



Suzaku, Murashima et al. 2006

Physical Origin of C VII RRC: A List to Cross Out

- Photo-ionized plasma (AGN, XRB)
  - But, no hard X-ray source
- Temperature disparity $T_{ion} \gg T_e$
  - But, need hot electrons to ionize
  - and in any case $t_{recombination} \gg t_{e\text{-heating}}$ ($\gg$ iso-species $t_{thermalization}$)
- Plasma instability and rapid radiative cooling
  - But, recombination rates > other radiative cooling processes
- Rapid (adiabatic) expansion and "ionization-freezing"
  - But, during expansion $\alpha^{RR} \propto nT^{-1/2} \propto T$
  - and prohibitive volume $V/V_0 \propto n_0/n \propto (T_0/T)^{3/2} \approx 1000$
- Charge-exchange capture into very high-n levels, or with dust grains
  - But, nebula is ionized

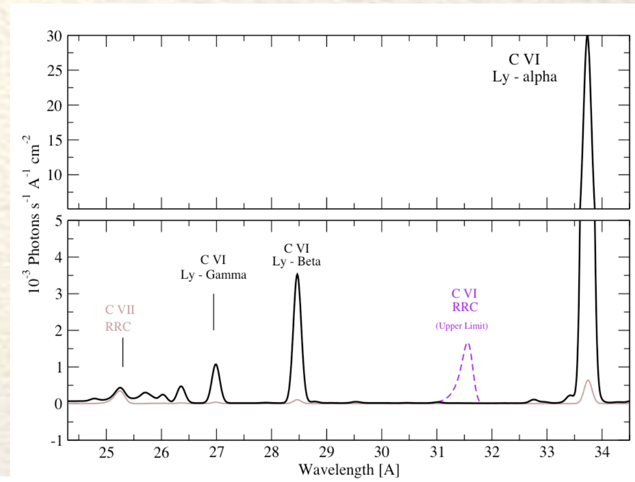
So What *Can* Explain The RRC?

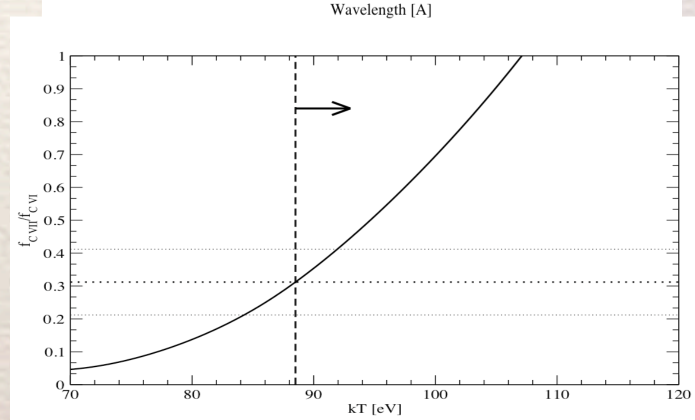
- 100 eV (shocked?) ions interact directly with 1 eV (un-shocked?) electrons, but where?
- Natural Location: Contact Discontinuity, the RRC could support the jump-condition picture, but can ions cross?
- Microphysics around CD is complicated. assuming a magnetic field and mere thermal motion:
  - $\tau_{Larmor} \approx 650\ (M/M_C)(B/1\mu G)^{-1}$ s
  - $\tau_s \approx 1000\ (kT^{cool}/1eV)^{3/2}(n^{cool}/10^4 cm^{-3})^{-1}$ s (by e^-, p)
  - $\tau_{rec} \approx 2\text{x}10^7\ (kT^{cool}/1eV)^{1/2}(n_e/10^4 cm^{-3})^{-1}$ s

  => Ions cross, slow down, & only much later recombine
- Intermediate-temperature region (say 10 eV) can not be large, or ions would stop and recombine before reaching 1 eV region ; $\Delta r_{inter} < v_{ion}\tau_s$ (10 eV) $\approx 10^9$ cm. In contrast with smooth gradient expected from heat conduction.

More Diagnostics

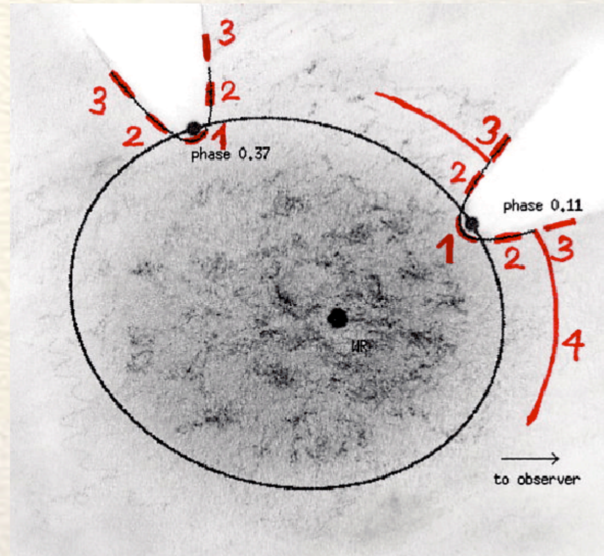
- RRC intensity (10^{40} ph/s): Mass crossing rate of $4\times10^{-8}\ M_{\odot}$/yr ~ 10% wind
- RRC contribution to flux is miniscule:
  - 33 RRC photons (~1/10ks),
  - 300 words/photon in paper
- From upper limit on C VI to C VII RRC flux ratio, very conservative hot-side temp. estimate kT^{hot} > 84 eV, i.e., ΔkT across CD > 80 eV

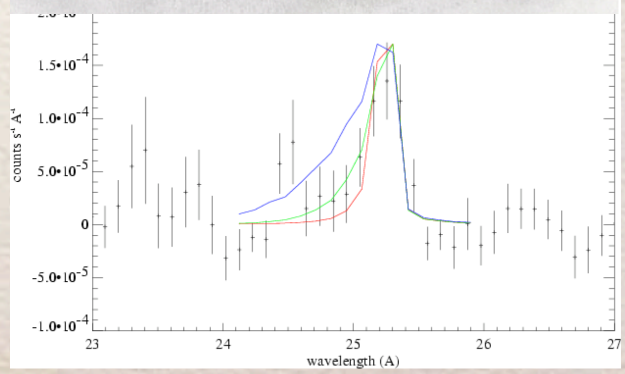




RRCs in Other Stellar Sources

- γ^2 Velorum WC8+O7.5 (Schild et al. 2004)
- θ Muscae WC6+O9.5 (Sugawara et al. 2008)
- Persistence of RRC in γ Vel in two different phases suggests extended origin
- Different scale (~AU) and geometry than in PN, but maybe similar shock physics?





Conclusions

- X-ray gas originates from shocked fast WC wind
- RRC comes from direct interaction between 100 eV ions and 1 eV electrons
- Possible origin is in ions crossing CD into nebula
- For the first time:
  Observed temperature jump ΔkT > 80 eV across CD
- Argues for magnetic fields and against heat conduction (Alternative explanation for low temperatures is required)
- Observed in two WC binaries, same shock physics?
- WC obviously facilitates C RRC detection, but ions crossing the CD may be a general phenomena in stellar shocks

THANK YOU
FOR YOUR ATTENTION