Mixing of hot and cold gas in shocked plasma

LETG observation of BD+30°3639 (Campbell's star)

Raanan Nordon, Ehud Behar, Noam Soker
Technion, Haifa, Israel

Young Sam Yu, Joel Kastner
RIT, Rochester, NY

John Houck
MIT, Cambridge, Massachusetts
Planetary Nebula BD+30°3639

- Intermediate mass (1-8 M☉), post-AGB star.

- Composed of:
  - Slowly expanding (~30 km/s) AGB-gas envelope
  - Fast post-AGB wind ~700 km/s (Leuenhagen et al. 1996)
  - Central to-be white dwarf

- Assumed distance: 1.2 kpc (Li et al. 2002)
X-rays from PN

- Fast wind from the central star is shocked when hitting the slow expanding envelope.
- X-ray emitting bubble is formed between the reverse shock and the contact discontinuity (CD).

HST+Chandra

Akashi et al. 2007
BD+30°3639 Abundances and T

- Imaging spectroscopy (ASCA, Suzaku, Chandra-ACIS) find:
  - C, N, Ne to be significantly over abundant
  - Fe significantly depleted
    (Kastner et al. 2000, Maness et al. 2003, Murashima et al. 2006)

- However, optical/IR measurements of the envelope find Ne to be depleted.

- Predicted temperatures for the shocked gas (spherical model) are ~4 times higher than measured.
Chandra observations

- 5 ACIS+LETG observations during 2006 totaling ~300 ks
- The X-ray bubble is slightly resolved and shows variations from image obtained in 2000 (Yu et al. in writing)
LETG spectrum

- 2 temperatures APEC model with absorption ($N_H = 0.24 \times 10^{22} \text{ cm}^2$)
- Energy dependent Gaussian smoothening to account for spatial broadening
Absorbed thermal model

- $kT_1 = 160 \text{ eV}$, $kT_2 = 260 \text{ eV}$, $N_H = 0.24 \times 10^{22} \text{ cm}^2$
- No significant EM at higher T
- Abundances relative to H poorly constrained. $C/H \geq 40$ solar
- At least half of the continuum is due to scattering from C
- Ne/O enhanced, N/O, Mg/O, Fe/O depleted
- Can be explained by s-process within the pulse driven convective zone (Herwig 2005)

Coming paper by Yu et al.
Source Spectrum

- Fluxed and corrected for absorption
The Carbon lines

- 2-T APEC model, $N_H = 0.24 \times 10^{22}$
The Carbon lines

- 2-T APEC + $N_H$ model with extended Ly series
The Carbon lines

- 2-T APEC + extended Ly series + RRC
RRC model

- Ruled out L-shell Si, S, Ar, Ca, Sc
- $kT_e = 2 \text{ eV} (<10 \text{ eV } 90\%)$, \( I_{\text{rec}} = 1.5 \pm 0.5 \times 10^{40} \text{ s}^{-1} \)
- Requires mixing of hot+cold gas out of ionization balance
- The CD region offers such interface
- Magnetic fields of order $\mu \text{G}$ are likely to exist and suppress heat conduction on scale of a few electron $R_L$ – required for maintaining steep T gradient
- C VII $R_L (\sim \sqrt{mT/q})$ is 26 times larger than electron's – crossing the CD into the cold side.
RRC model - cont.

- Time scales:
  \[ \tau_{\text{slow}} \sim 300 \text{ s} < \tau_L \sim 650 \text{ s} < \tau_{\text{rec}} \sim 10^6 \text{ s} \]

- Crossing C VII ions will tend to thermalize on the cool side and eventually recombine with cool e.

- A “naive” steady-state model:
  \[ I_{\text{rec}} = 0.5V_p S_{CD} n_{CVII} \]

  \[ n_{CVII}^{\text{hot}} = 0.53 \left( \frac{I_{\text{rec}}}{1.5 \times 10^{40} \text{ s}^{-1}} \right) \left( \frac{R_{CD}}{4 \times 10^{16} \text{ cm}} \right)^{-2} \left( \frac{kT}{100 \text{ eV}} \right)^{-1/2} \text{ cm}^{-3} \]

- Taking C/H = 40 solar -> \( n = 400 \text{ cm}^{-3} \) in the ball park
Not the whole picture

- The “naive” model leads to $E > 10^4$ G
- Must account for other plasma effects:
  - Magnetization currents
  - Drifts
  - e penetrating the CD
  - Instabilities

Other Objects

- $\gamma^2$ Velorum (Schild et al. 2004)
- $\theta$ Muscae (Sugawara, yesterday)
  (Colliding wind binaries)
Conclusions

- BD+30 3639 shows extremely high C abundance
- Significant contribution of high C order Ly series due to the high abundance – not included in APEC.
- Detection of RRC from C VII indicating mixing between 100 and 2 eV gas.
- Previous measurements over estimate N abundance due to not considering the above.
- Suggested location for the mixing is at the CD due to magnetic fields and the larger Larmor radius of ions relative to electrons.