High-resolution X-ray Spectroscopy of the Planetary Nebula BD+30 3639

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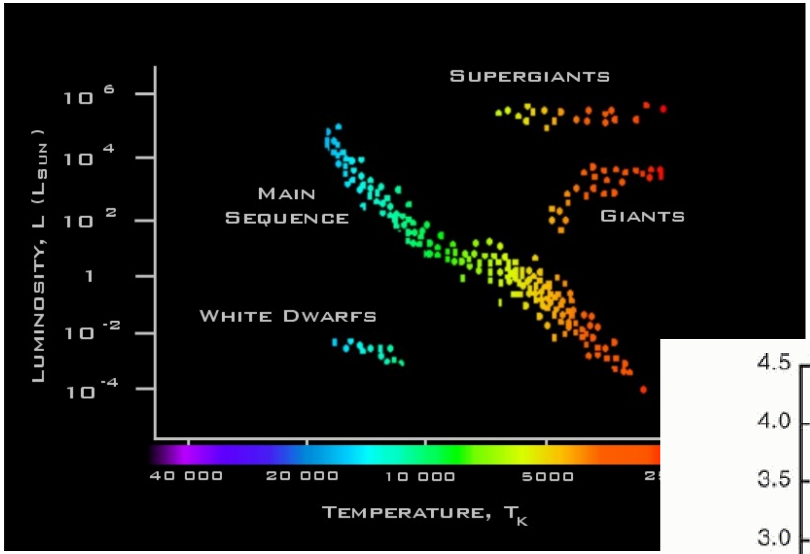
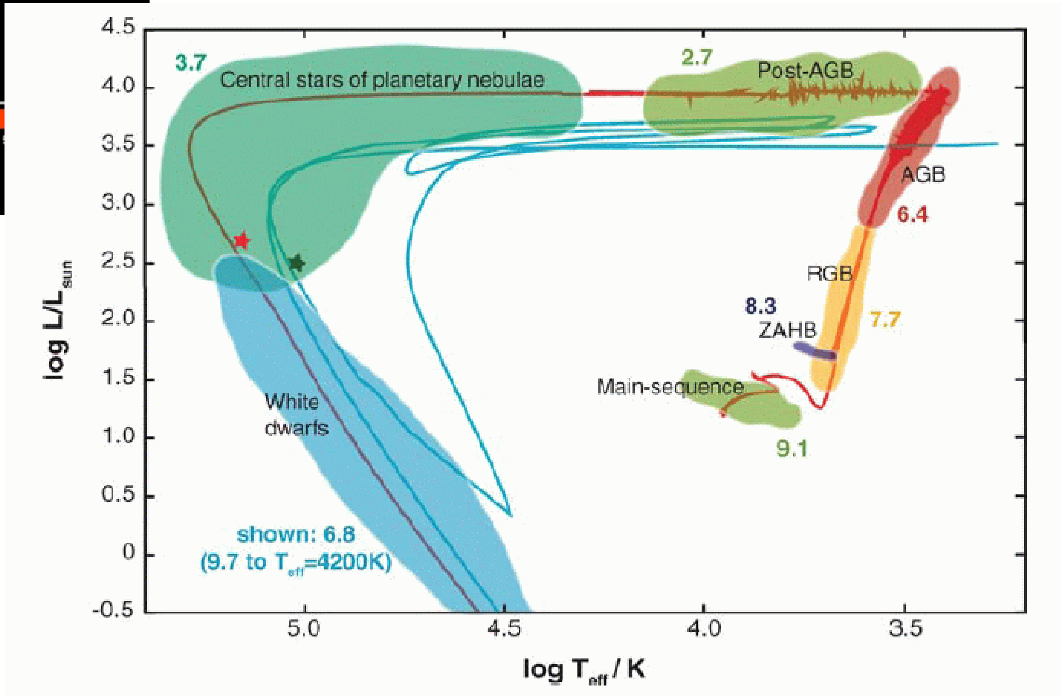
Outline

- Stellar evolution of Intermediate massive star
- What are the Planetary Nebulae (PNe) ?
- X-ray emission scenarios in PNe
- History of X-ray observation of BD+30°3639
- Chandra Observation of BD+30°3639 with LETG/ACIS-S
- Model fitting and Interpretation
- Conclusions

Evolution of star along the H-R diagram

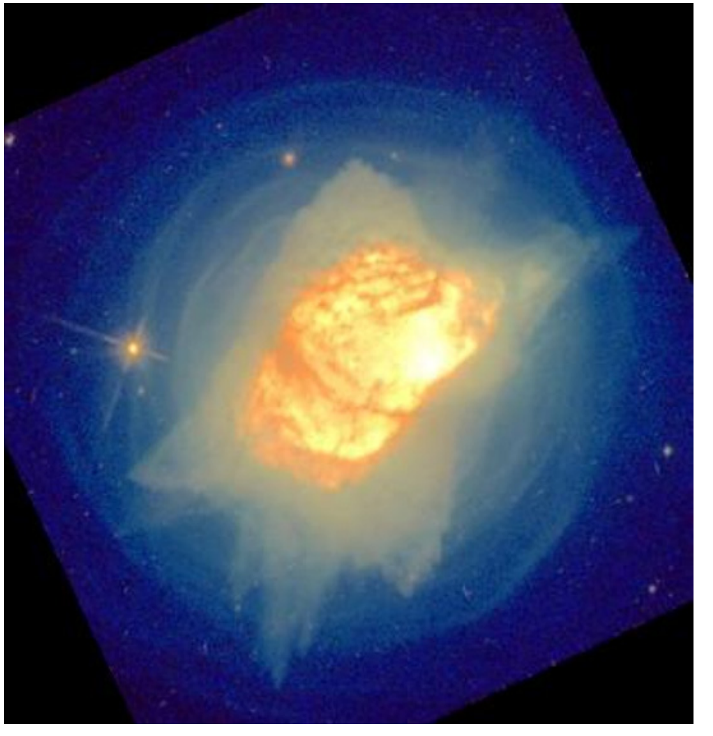




From Herwig (2004, Ann. Rev. Astron. Astrophys.)

What are planetary nebulae?

- Last stages of evolution for stars of initial mass(1-8$M_\odot$)
- PN: ejected red giant envelope ionized by newly unveiled stellar core (emerging white dwarf)
- PN shapes likely generated by interacting (red giant and white dwarf) stellar winds



NGC 7027: planetary nebula poster child

X-ray emission from PNe

- Photoionized gas in PNe is far too cool to emit X-rays
- The central stars are at best source of very soft X-rays

- Theory predicts two types of structures may be caused by wind-wind shocks in planetary nebulae:
  – *Hot bubble* predicted by classical (quasi-spherical) interacting winds theory
  – *Collimated outflows and "jets"*

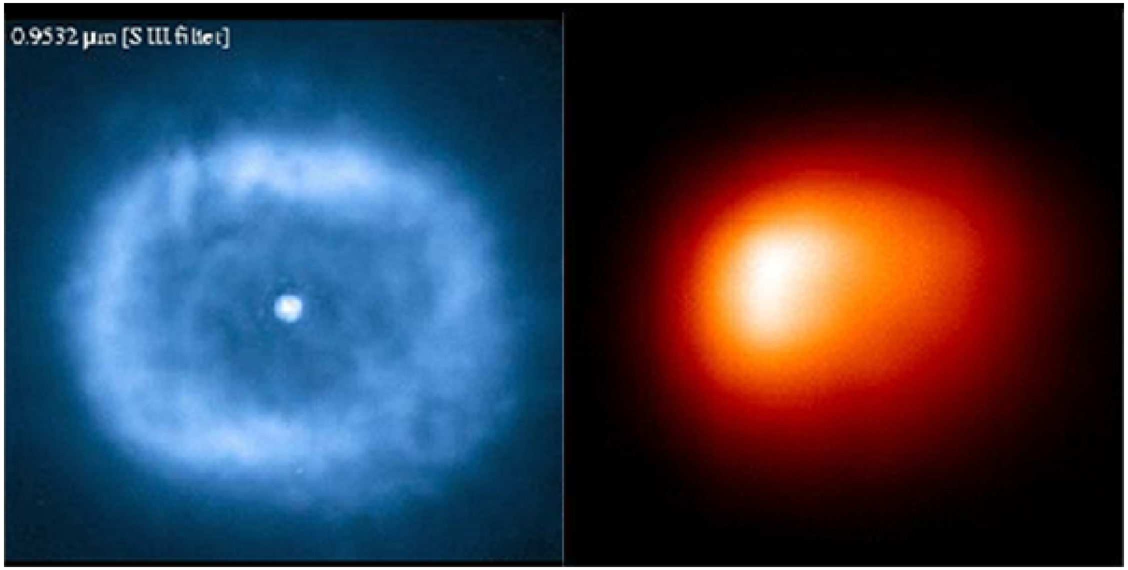
=> X-ray observations are essential to verify & distinguish scenarios

The planetary nebula BD+30˚3639

Basic data:

Distance from Earth : 1.2 kpc
Dimensions: 4 X 5'' (~0.02 pc)
Dynamical age : less than 1000yr

Central Star:
Carbon-rich Wolf-Rayet type
Temp : 30,000K
Mass loss rate : ~10^{-6} M_{solar}/ yr
Wind speed: ~700 km/s



First X-ray image of a hot bubble within a planetary nebula
Left: HST [SIII] image; right: Chandra X-ray image (0.3-2.0 keV)
(Kastner et al. 2000)

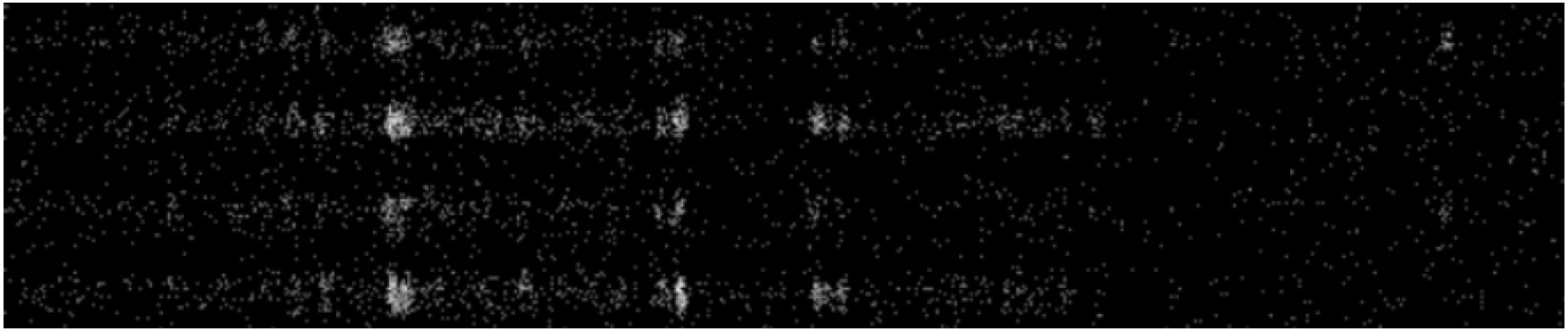
Previous results from X-ray CCD spectroscopy: Fitting models to BD+30°3639 spectra

telescope (instrument)	N_H (10^{21} cm^{-2})	T_X (10^6 K)	abundances	reference
ROSAT (PSPC)	1.4*	2.5	…	Kreysing et al (1992)
ASCA (SIS)	1.2*	3.0	C greatly enhanced; N, Ne enhanced; Fe depleted	Arnaud et al. (1996)
Chandra (ACIS)	1.0	2.7	C, Ne enhanced; Fe depleted	Kastner et al. (2000)
Chandra (ACIS)	2.5	2.1	C, Ne greatly enhanced; N, O enhanced; Fe depleted	Maness et al. (2003)
Chandra (ACIS)	2.0	2.4	*No useful constraints!*	Georgiev et al. (2006)
SUZAKU	2.1	2.2	C, N, Ne greatly enhanced; Fe depleted	Murashima et al. (2006)

* N_H constrained by A_V for PSPC and SIS model fits

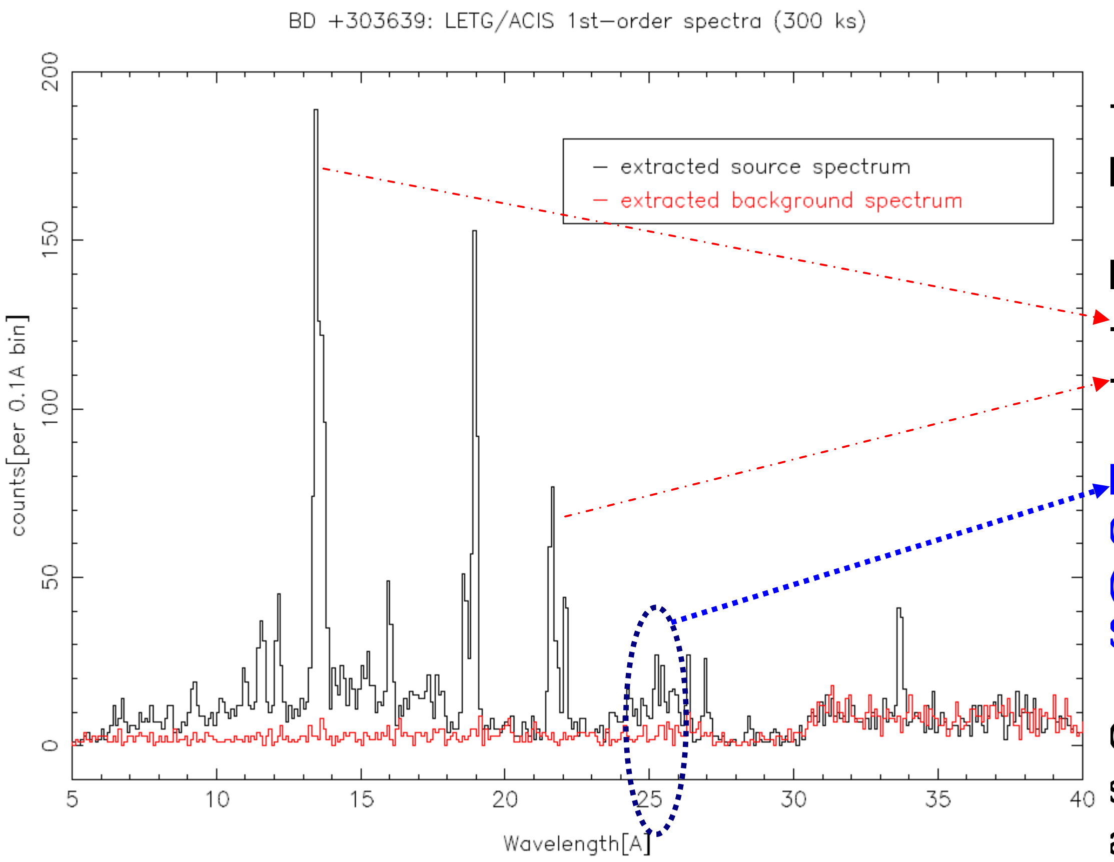
Dispersed spectral images of BD+30°3639

We obtained observations of BD+30°3639 totaling 300 ks exposure time with LETG/ACIS-S during the CXO Cycle 6



5 to 40 Å for $\pm$ 1 order from first-epoch (Feb+Mar, 2006; Lower Two) and second-epoch (Dec, 2006; Upper Two) observatin.

Combined positive and negative first order LETG/ACIS-S Spectrum



The brightest resonance lines:
H-like lines : OVIII (18.97), C VI (33.6)

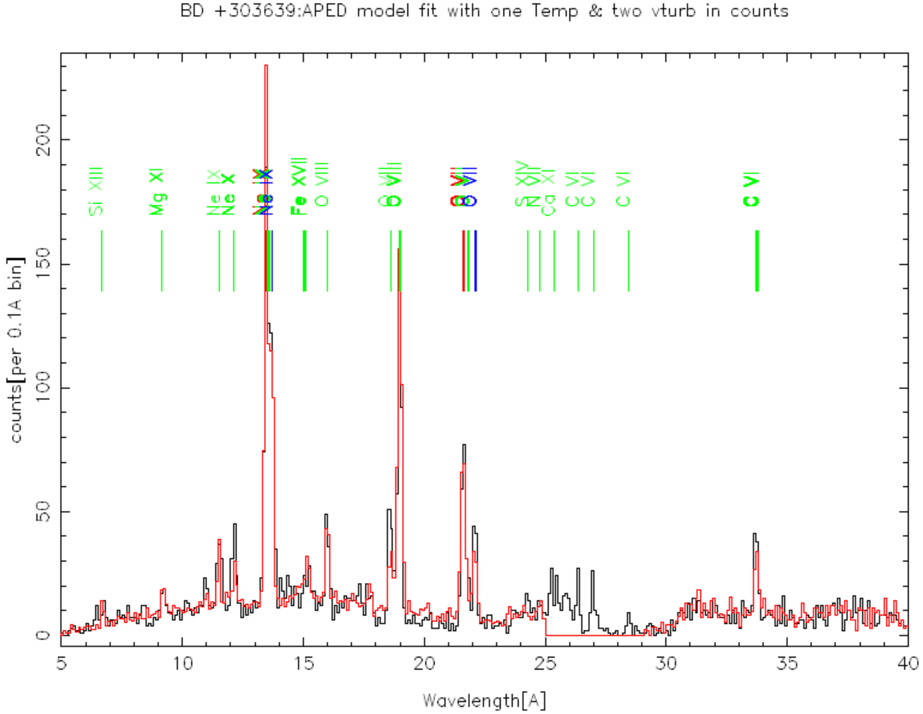
He-like triplet line complexes
-Ne IX (13.45, 13.55, 13.7)
-O VII (21.60, 21.80, 22.10).

Narrow Radiative Recombination Continuum (RRC) emission feature (C VII, 25.30) is identified
See talk by **Ehud Behar**

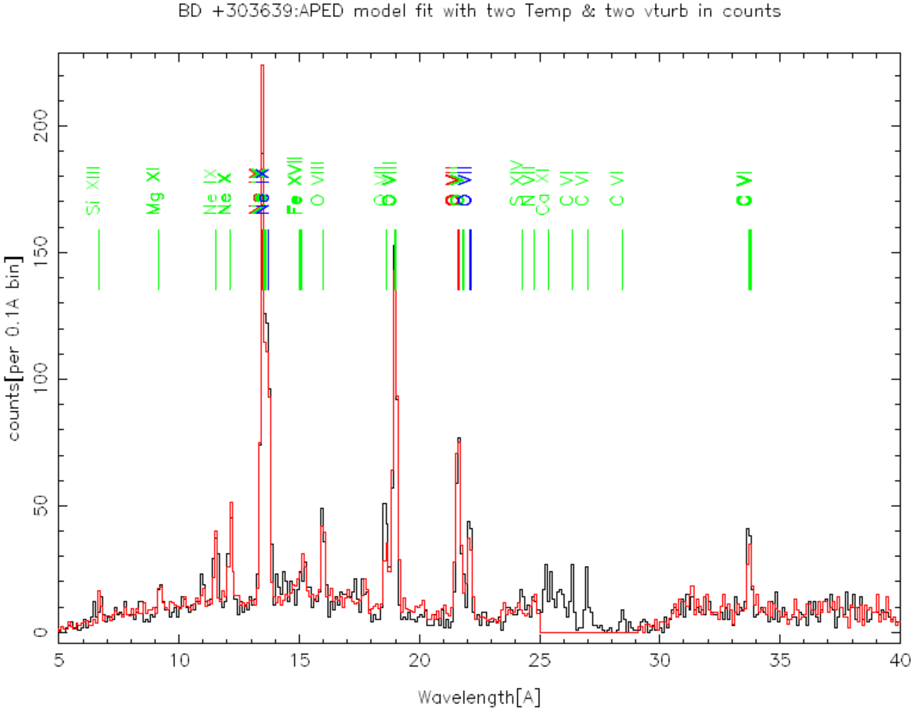
Other H-like resonance lines, such as N VII (24.78), and lines of highly ionized Fe, are weak or absent.

Model Fitting

One Temperature model



Two Temperature model



Yu et al. 2009, ApJ, 690, 440Y

Results

- Temperature of shocked plasma: T ~ $(1.7 – 2.9)\times10^6$ K
- Hydrogen column density : $\log N_H$ (cm^{-2}) = 21.4
- Plasma abundances, relative to solar:
  - C/O ~ 32.5 (yes, C is *very* overabundant!)
  - Ne/O ~ 3.8 (yes, Ne is overabundant)
  - Fe/O ~ 0.2 (yes, Fe is quite depleted!)
  - N/O ~ 0.4(yes, N is quite depleted)
  - Mg/O ~ 0.7 (yes, Mg is depleted)

Comparison to previous study

Parameter	A96 *ASCA*/*SIS*	K00	M03 *Chandra*/ACIS-S3	G06	M06 Suzaku/XIS	This Paper *Chandra*/LETG/ACIS
N_H (10^{22} cm^{-2})	0.12	0.1 [0.09–0.11]	0.24 [0.23–0.25]	0.2 [1.7–2.3]	0.21[1.4–2.5]	0.24 [0.20–0.28]
L_X (10^{32} ergs s^{-1})	1.3–1.7	2.3	...	...	12	8.6
T_1 (10^6 K)	3.0 [2.7–3.3]	2.7 [2.6–2.8]	2.1 [2.08–2.12]	2.4 [2.1–2.6]	2.2 [2.1–2.3]	2.9 [2.6–3.3]
T_2 (10^6 K)	...	...	...	...	...	1.7 [1.3–2.1]
Fe/O	0	...	0	0.3 [0.1–0.8]	<0.1	0.2 [0.1–0.4]
Ne/O	8.3	...	4.6 [3.9–5.3]	5.4 [0.1–57.7]	5.8 [4.7–7.5]	3.8 [3.3–5.0]
C/O	281	...	84 [79–90]	97 [8.1–813]	85 [71–101]	32.5 [15–45]
N/O	7.2	...	2.2 [2.0–2.3]	5.8 [1.3–80.1]	3.2 [0.9–5.5]	0.4 [0.0–1.0]
Mg/O	...	...	0.24 [0.22–0.26]	0.3 [0.1–0.8]	...	0.7 [0.4–1.5]

References. A96 = Arnaud et al. 1996; K00 = Kastner et al. 2000; M03 = Maness et al. 2003; G06 = Georgiev et al. 2006; M06 = Murashima et al.2006; This paper= Yu et al. 2009

Interpretation

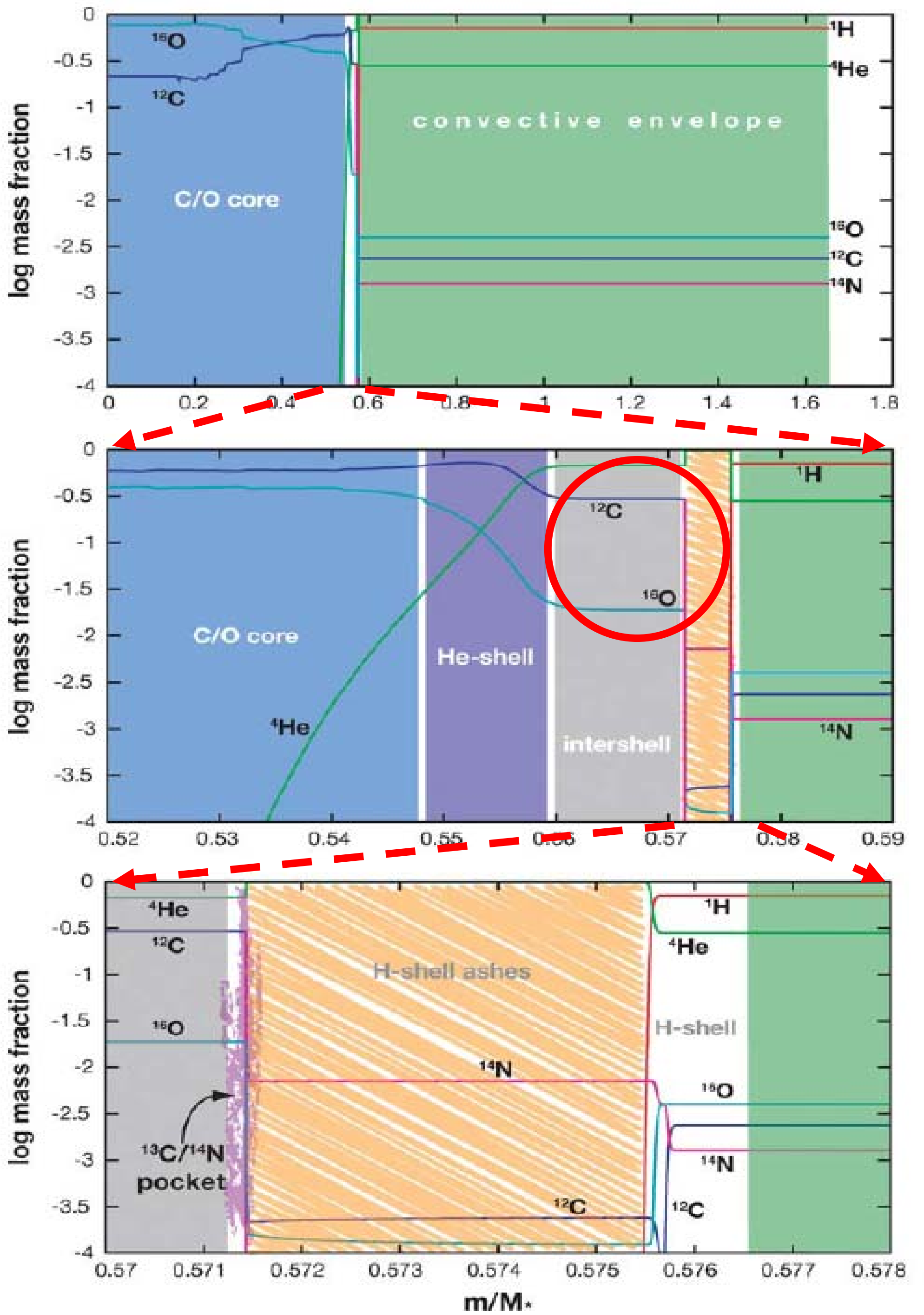
- **X-ray temperature (T_x)**
  - Two temperature represents the temperature gradient within the hot bubble.
  - lower than expected from a simple adiabatic shock model (700 km/s wind should produce a few x 10 million degree plasma)
  - **Possible scenarios**
    - Shocked wind presently seen in X-rays was ejected at earlier epoch, when the "fast wind" was slower (~400km/s)
- **C/O overabundance**
  - Triple alpha process produces ^{12}C and ^{16}O in the intershell.
  - He shell burning and subsequent dredge-up (AGB "third dredge-up") brings intershell products (C, s-process elements) to the surface
- **Ne/O over abundance, Fe/O, N/O depletion**
  - S-process within pulse-driven convection zone (PDCZ)), associated He shell burning
  - $^{14}N + \alpha \to {}^{18}O$(Burnt in He shell burning) -> ^{22}Ne
    ^{18}F
  - ^{22}Ne (and ^{16}O) is neutron source in s-process and Fe become the "starting material" (or seed) for this neutron capture

$\Rightarrow$ Therefore, Ne is enhanced but N and Fe is depleted.

The inner layers of a highly evolved star

AGB stars are carbon factories!

From Herwig (2005, Ann. Rev. Astron. Astrophys.)



Conclusions

- X-ray emitting gas originates essentially from the “WC star” (From comparison of UV/optical observation for central star; Marcolino et al. 2007)
- Sharply non-solar composition of shocked gas originated from intershell region of AGB star
- Two temperatures indicate the temperature gradient within the wind-collision-generated "hot bubble" of a planetary nebula
- The results will provide constraints on wind collision models

Thank you!!!