Exposing the Nuclear Burning Ashes of Radius Expansion Type I X-ray Bursts

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Punch-line

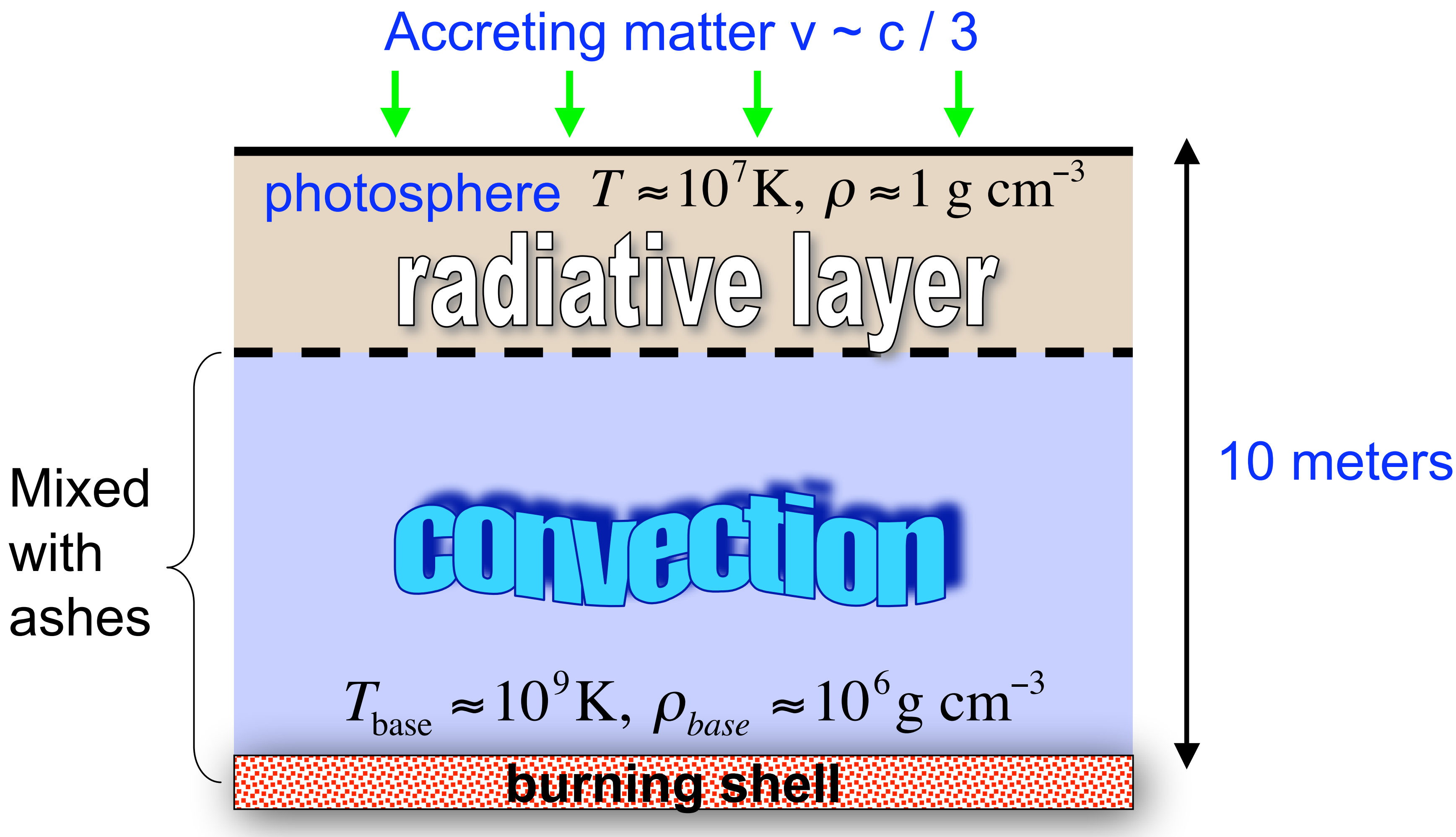
During radius expansion X-ray bursts ($L > L_{eddington}$) ashes of nuclear burning can be ejected by the radiative wind.

Heavy element ashes not fully ionized → Detect spectral lines of ashes

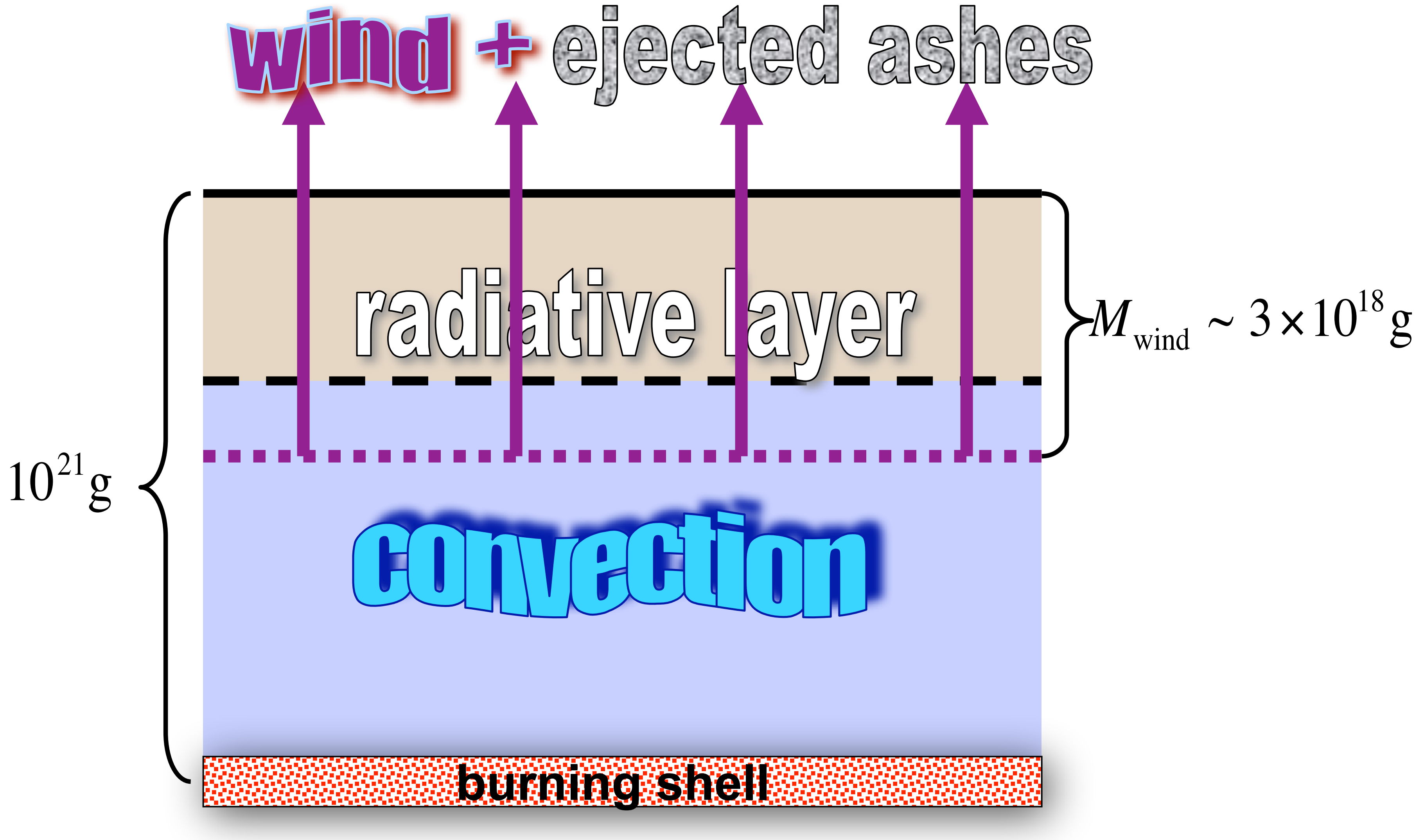
We find that the spectral features of ashes should be detectable with current high resolution X-ray telescopes (e.g., XMM, Chandra, ~~Astro E2~~):

1. In the wind during the radius expansion phase and
2. At the neutron star surface during the burst decay/cooling.

Neutron star atmosphere during a burst



Atmosphere during a radius expansion burst



Vertical extent of convective zone

During burst rise, convective zone reaches out to pressures where the entropy matches that at the base of the burning layer.

In convective zone: $T \sim T_{base}(P/P_{base})^{2/5}$

In radiative zone: $T \propto P^{1/4}$

} Convection stops near intersection of the two profiles

How far out convection reaches depends on:

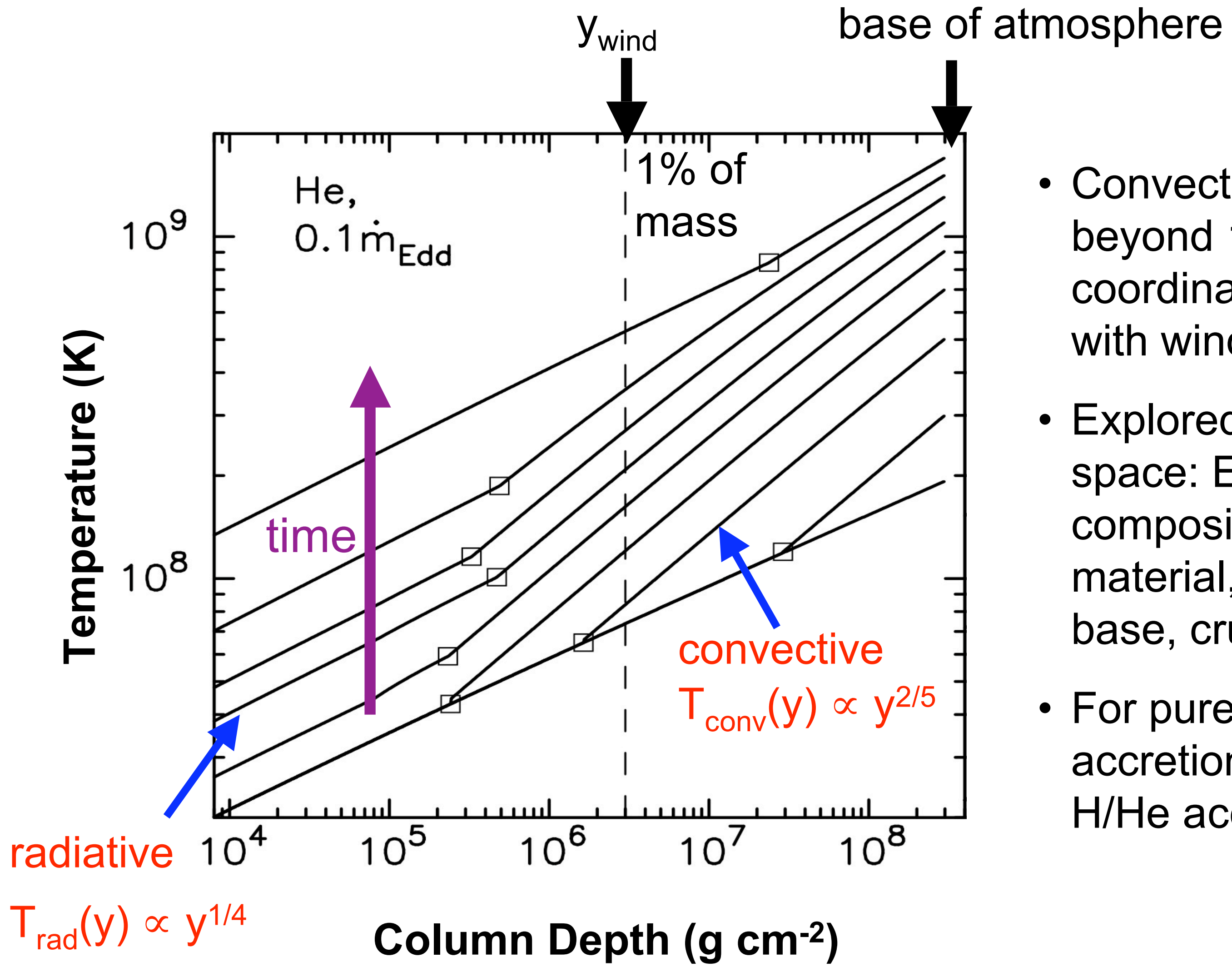
1. The thermal state of the outer envelope prior to burst ---the colder it is, the farther out convection reaches.
2. The rate at which the radiative region heats up due to radiation escaping out the top of the convective zone:

$$F_{loss} = \frac{4acT^4}{3\kappa y}\left(\frac{d\ln T}{d\ln P}\right)_{ad}, \text{ and a heating time } t_{\rm th} = \frac{c_p y T}{F_{\rm loss}}$$

3. The rate at which the temperature at the base of the convective zone grows due to nuclear burning: $t_{\rm gr} \approx \frac{c_p T_b}{\epsilon}$

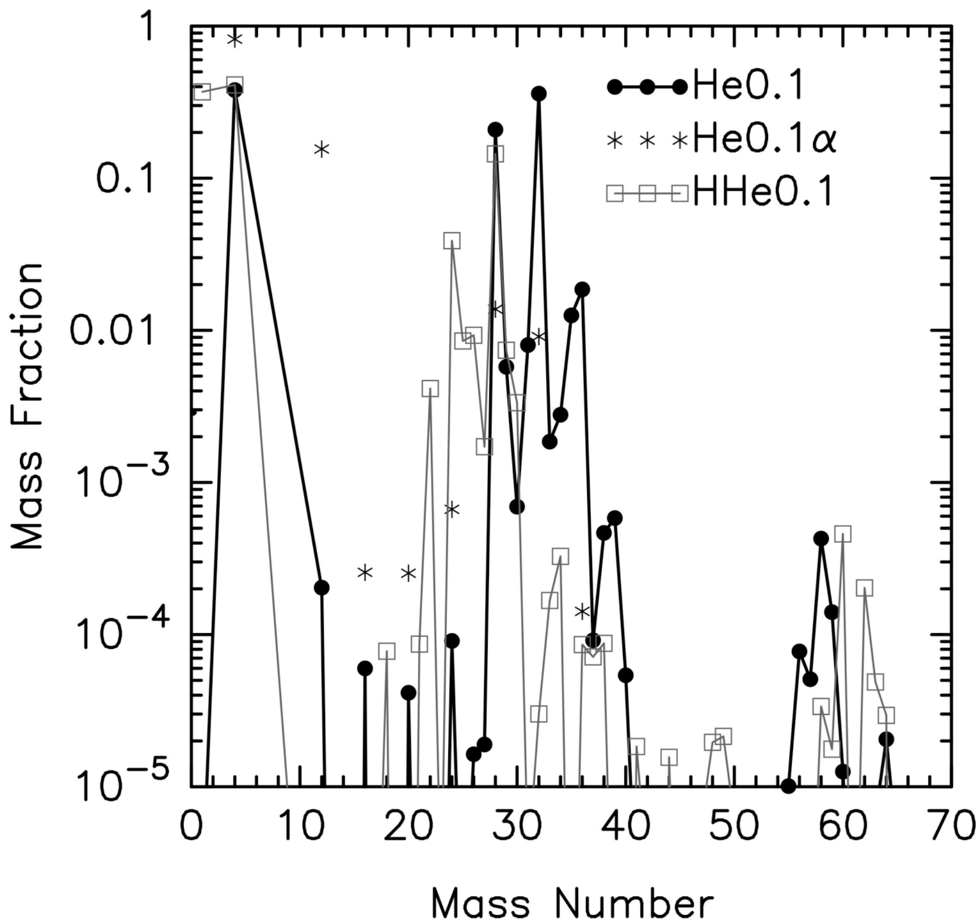
We calculate energy generation rate ε and nucleosynthesis using a full nuclear reaction network.

Evolution of temperature profile



- Convective zone extends beyond 1% pressure coordinate => ashes mixed in with wind ejecta
- Explored burst parameter space: E.g., accretion rate, composition of accreted material, column depth of base, crustal heat flux.
- For pure He accretors or low accretion rate (~0.01 Edd) H/He accretors, $y_{conv,min} < y_{wind}$.

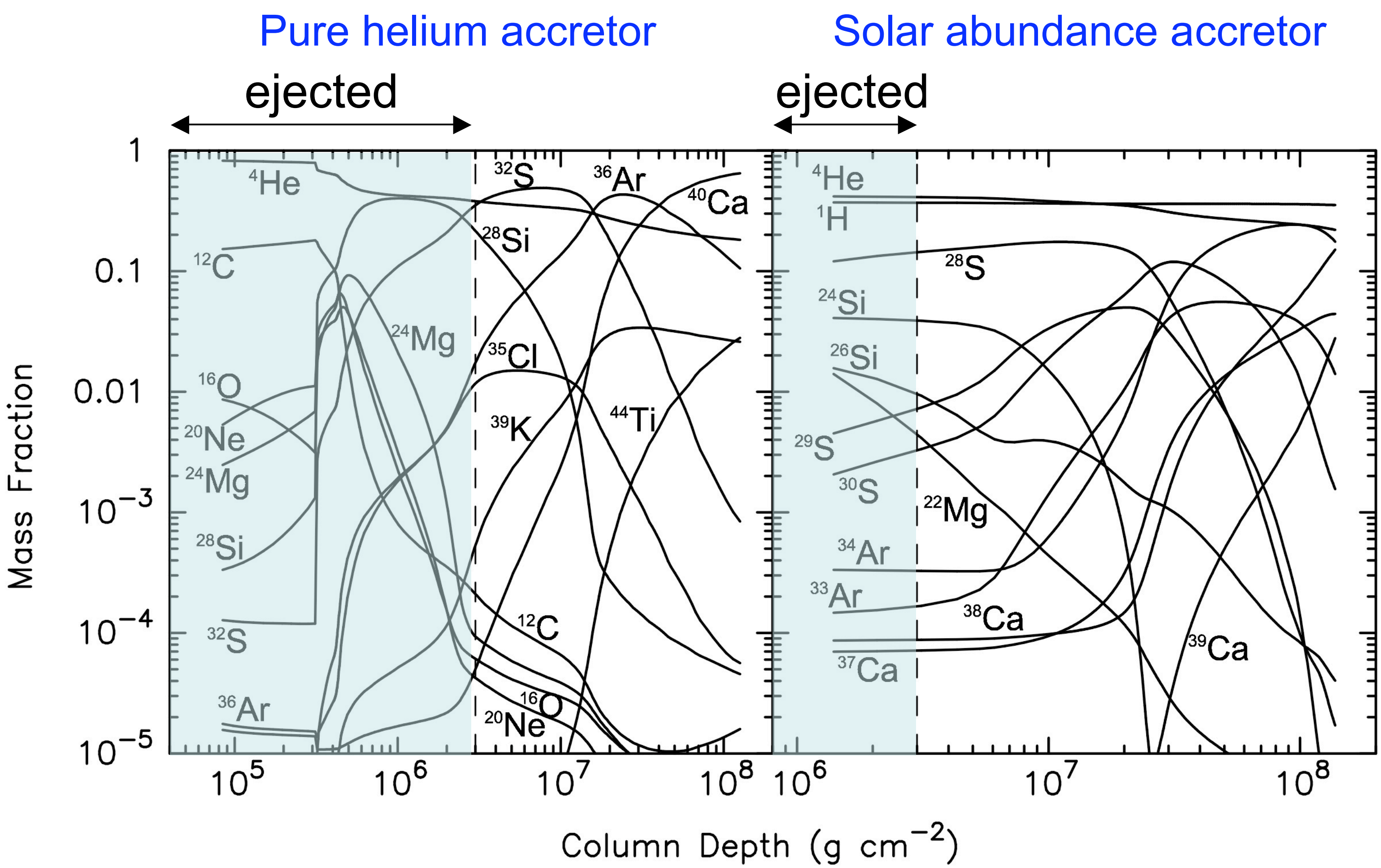
Composition of ejected ashes



- Si and S are the most abundant ejected ashes.
- In burning layers that are initially pure He, protons from (α, p) reactions enable the rapid onset of the $^{12}C(p, \gamma)^{13}N(\alpha, p)^{16}O$ reaction sequence.
- This sequence bypasses the relatively slow $^{12}C(\alpha, \gamma)^{16}O$ reaction and leads to a spike in energy generation and broadening of abundance pattern beyond α-nuclei.

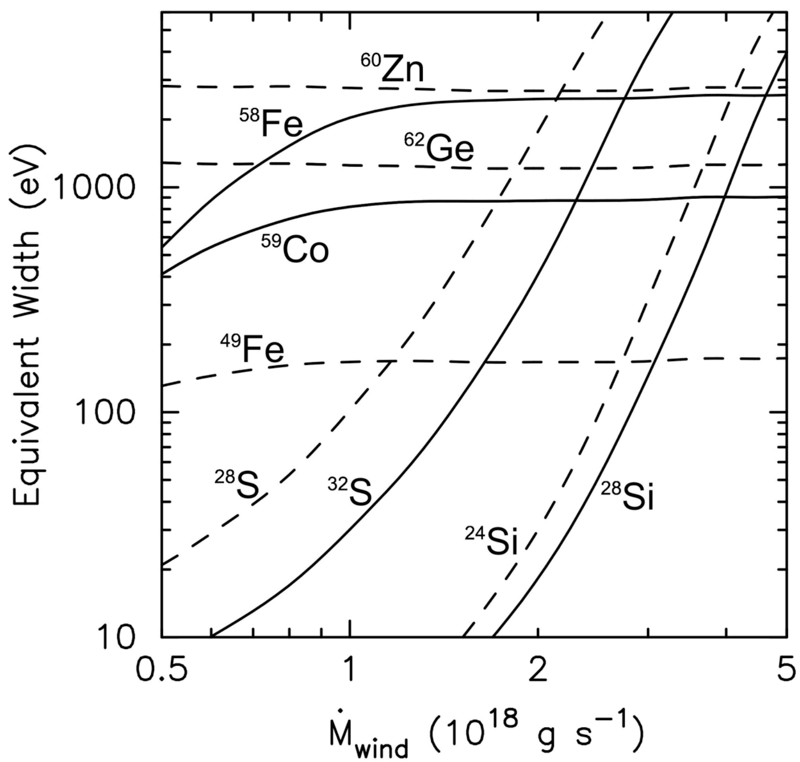
Aside: Spike should also be directly observable as a sharp rise in flux during burst rise.

Composition profile of ashes



Detecting the ashes

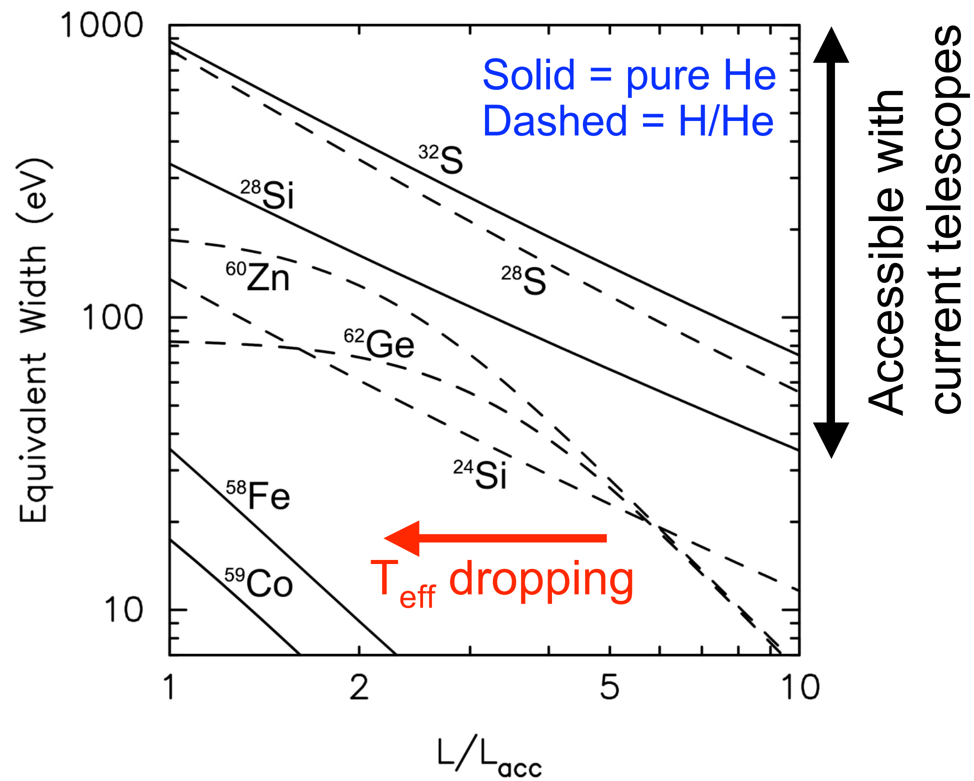
Photoionization edges in winds



wind mass loss rate

- These ejected nuclei imprint photo-ionization edges in wind out at radii of 100 - 1000 km.

…and in the cooling photosphere



cooling luminosity relative to accretion luminosity

- Once the photosphere recedes back to R_{NS}, exposed ashes may yield lines useful for redshift measurement.

Summary

- Calculations of the convective zone evolution suggest that ashes of nuclear burning are ejected by the radiative wind during radius expansion bursts in systems accreting pure He or mixed H/He at low accretion rates.
- Large abundance of ashes with mass number A = 30 – 60.
- The column density of ashes in hydrogen-like states is high enough that current high resolution X-ray telescopes should be able to detect spectral features of ashes:
    1. in the wind and,
    2. in the photosphere at R_{NS} during burst cooling.
- Detecting spectral features would probe nuclear burning processes during bursts and may enable a measurement of the neutron star gravitational redshift.