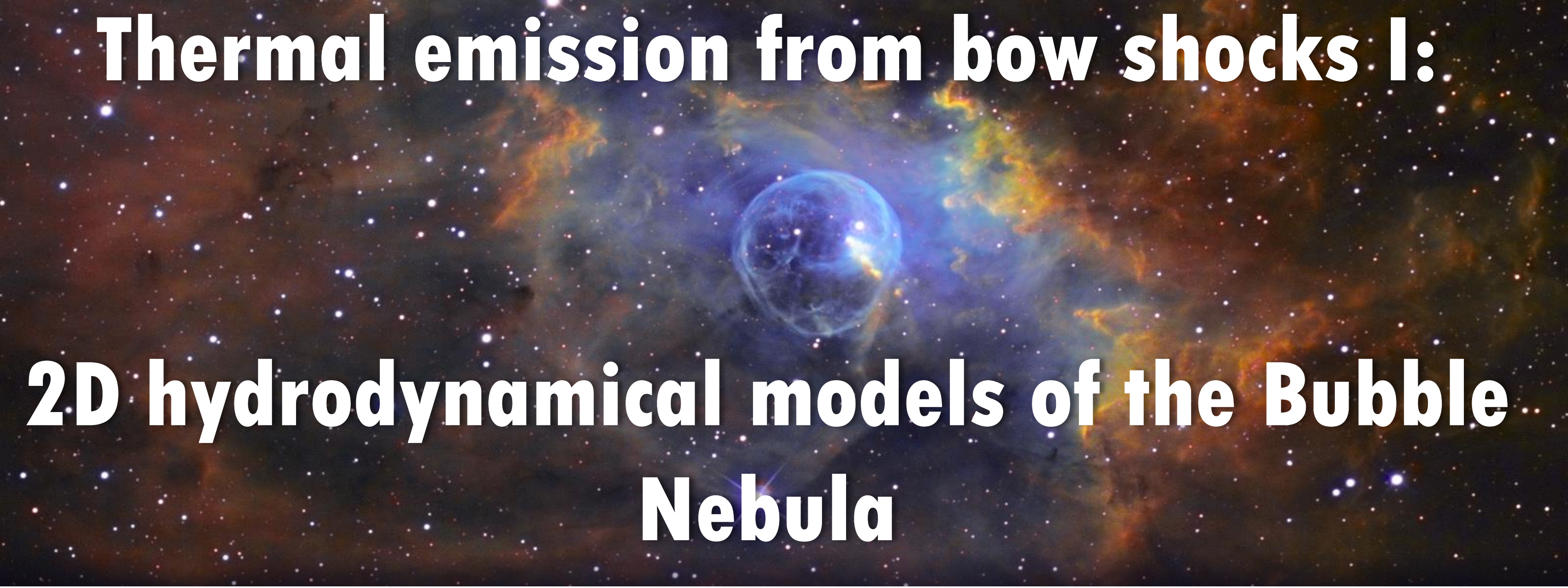
Thermal emission from bow shocks I:

2D hydrodynamical models of the Bubble Nebula



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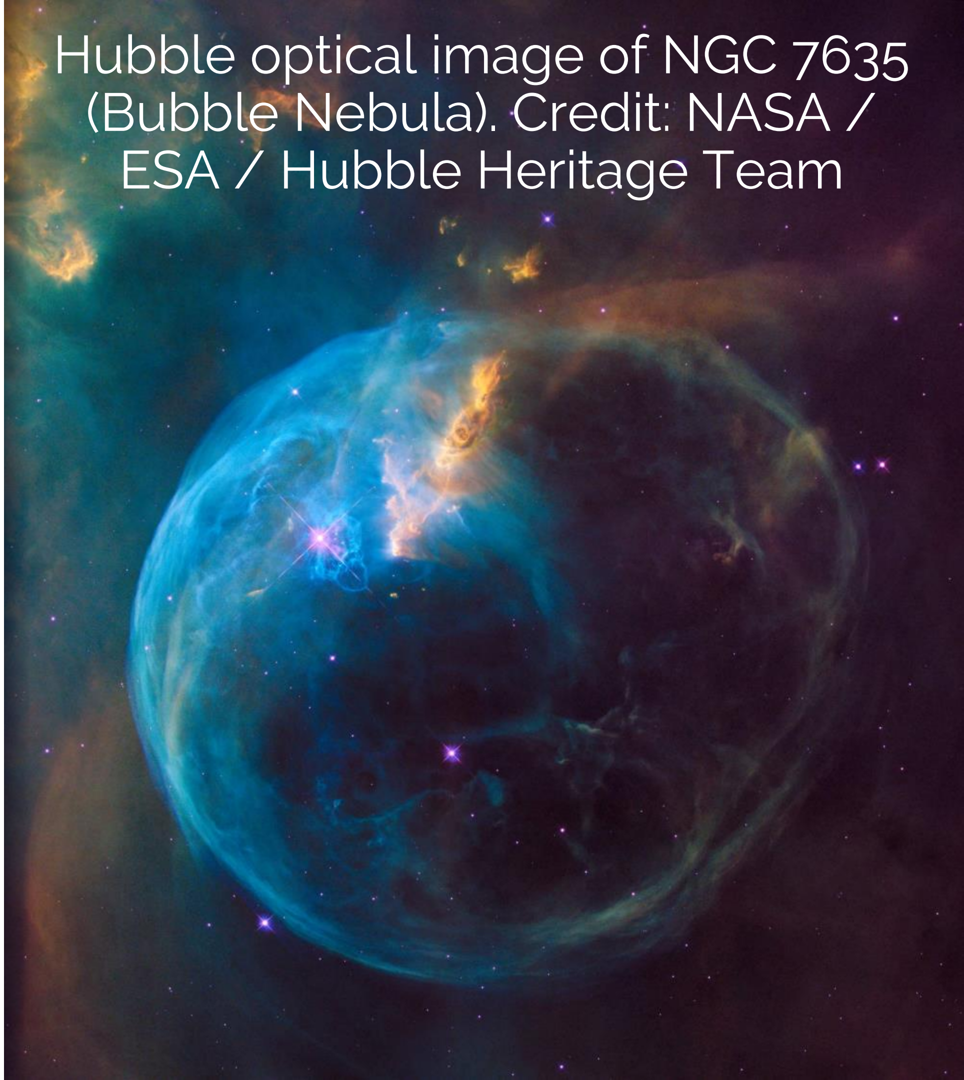
- Massive stars have strong winds.

- The hydrodynamic interaction of such a wind with the surroundings heats the ambient ISM.

- For young hot stars with fast winds, a low-density bubble is created from this interaction, expanding with time and displacing the ISM.


Hubble optical image of NGC 7635 (Bubble Nebula). Credit: NASA / ESA / Hubble Heritage Team

Star/Nebula Parameters

Parameters of BD $60^{\circ}+2522$

- Temperature: 37,500 K
- Wind Velocity: 2,500 km s^{-1}
- Mass-loss rate: $10^{-5.76}$ $M_{\odot} yr^{-1}$
- Distance: 2.7 ± 0.2 kpc
- Transverse peculiar velocity: 28 ± 3 km s^{-1}

Parameters of NGC 7635

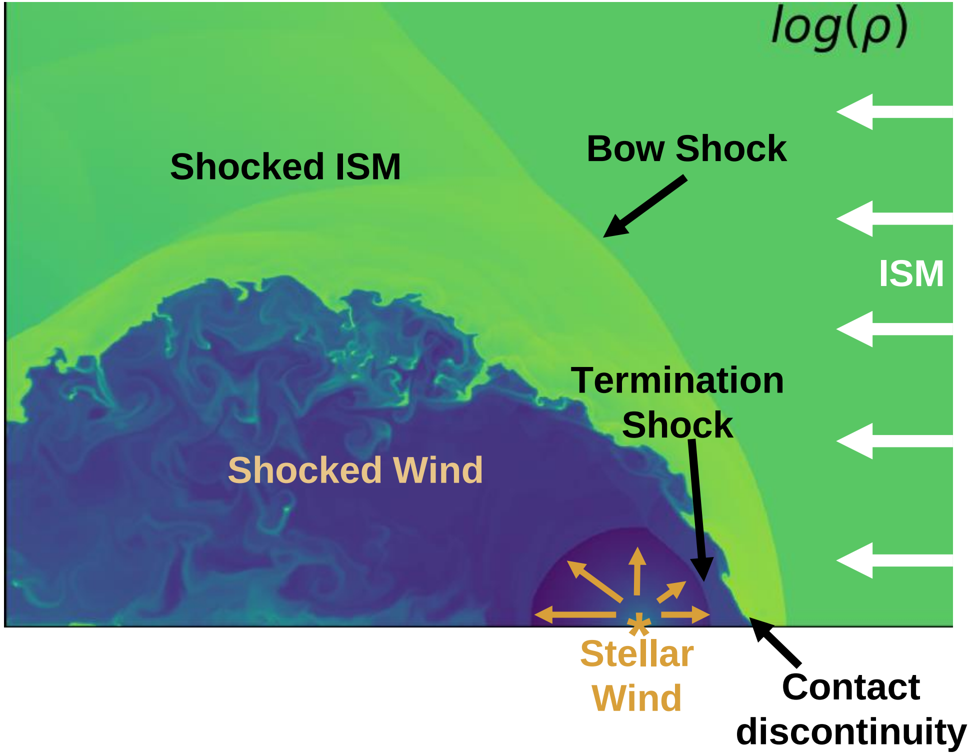
- Linear diameter: 2.3 ± 0.2 pc
- Bow shock density: ~100 cm^{-3}

Bow Shock Schematic

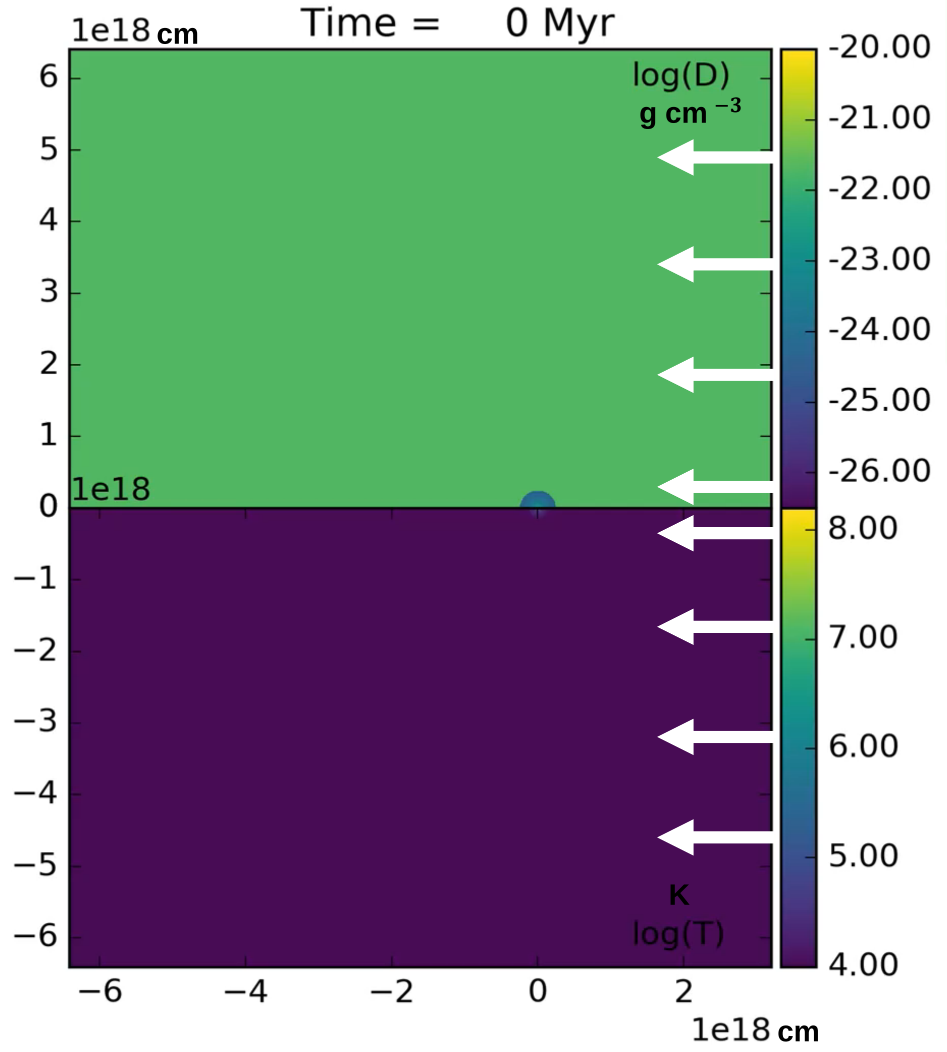
- Post-shock temperature of the gas for a strong shock can be calculated using:

$$T_s = \frac{1}{2}\frac{\mu m_H v^2}{k_B}$$

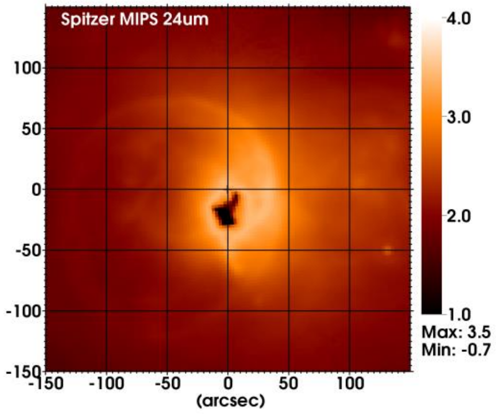
- For example: stellar winds of 2500 km/s produce 2x10^8 K gas.

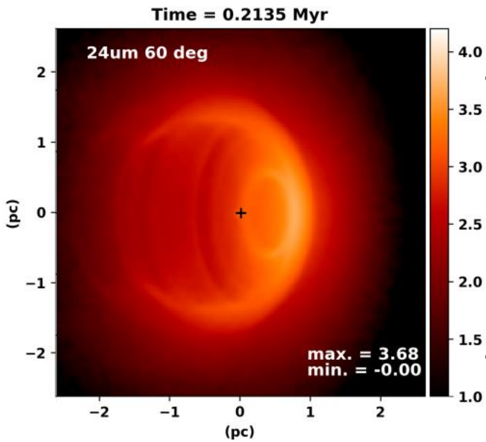


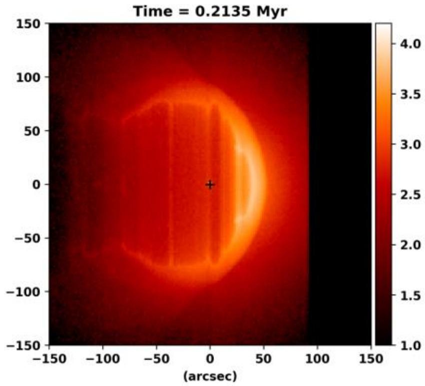
- 2D hydrodynamical simulation
- Used PION (PhotoIonization Of Nebulae) hydrodynamical code, Mackey (2012)
- Point source of stellar wind with uniform ISM flowing right to left
- Rotational symmetry about the x-axis
- High T cooling assumes CIE
- Low T cooling appropriate for photoionized HII region



Infrared Emission



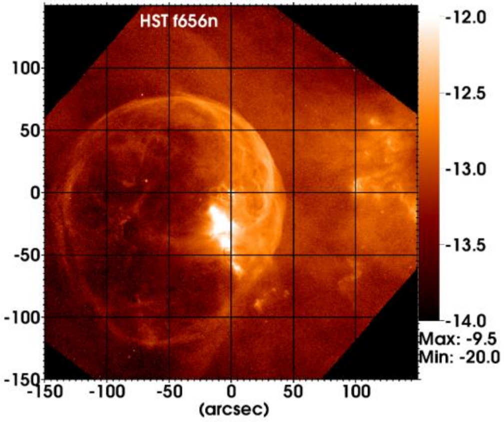


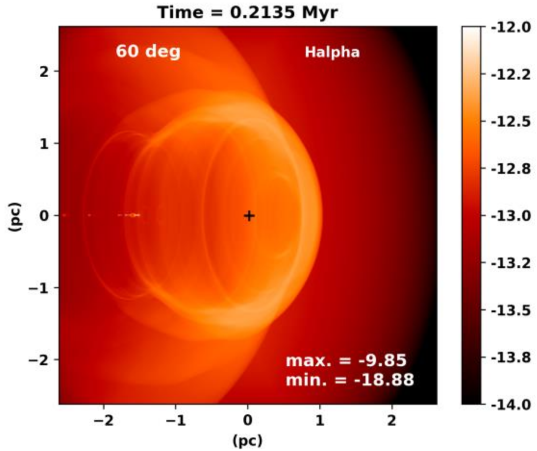


Synthetic infrared emission maps of bow shock, colour scale in $log_{10}(MJy\ ster^{-1})$.

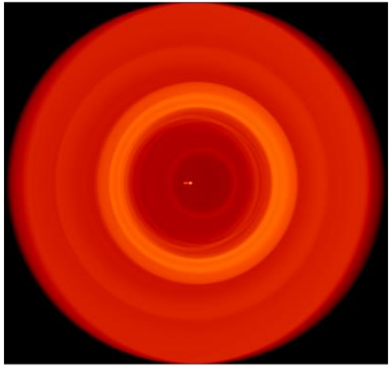
- The dust emission from Monte Carlo radiation transport code TORUS (Harries, Haworth et al. 2019).
- Produced dust images (24μm) at angles to the symmetry axis, from 0^o - 90^o for each snapshot.
- The scale on the right of each plot shows the total brightness of the bow shock in the infrared.

H_α Emission





Emission map of bow shock H_α 6563Å captured with the HST, colour scale in log_{10}(erg cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$).



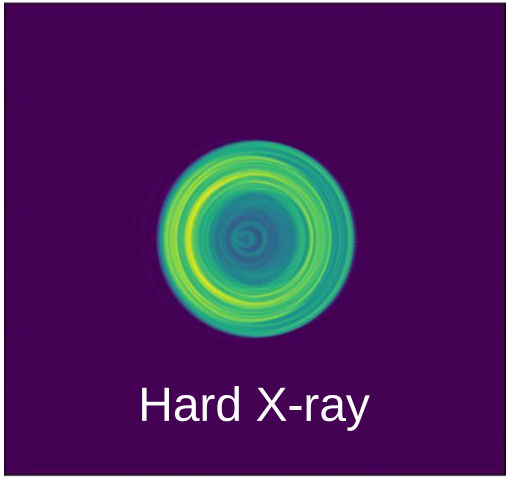
- Most of the H_α emission occurs inside the bubble region in a thin layer near the bubble boundary.

- H_α gives an indication of the presence of a H II region around the star.

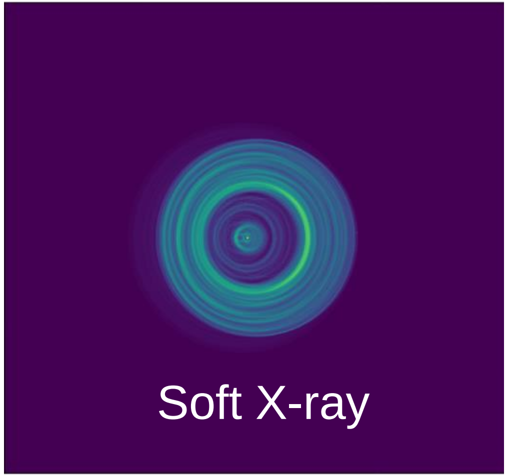
X-ray Emission

- Calculate the x-ray emissivity map from simulation.
- Most of the x-ray emission occurs in the wake behind the star.
- From this we can predict what values new satellites can see observationally.
- Units: erg cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$

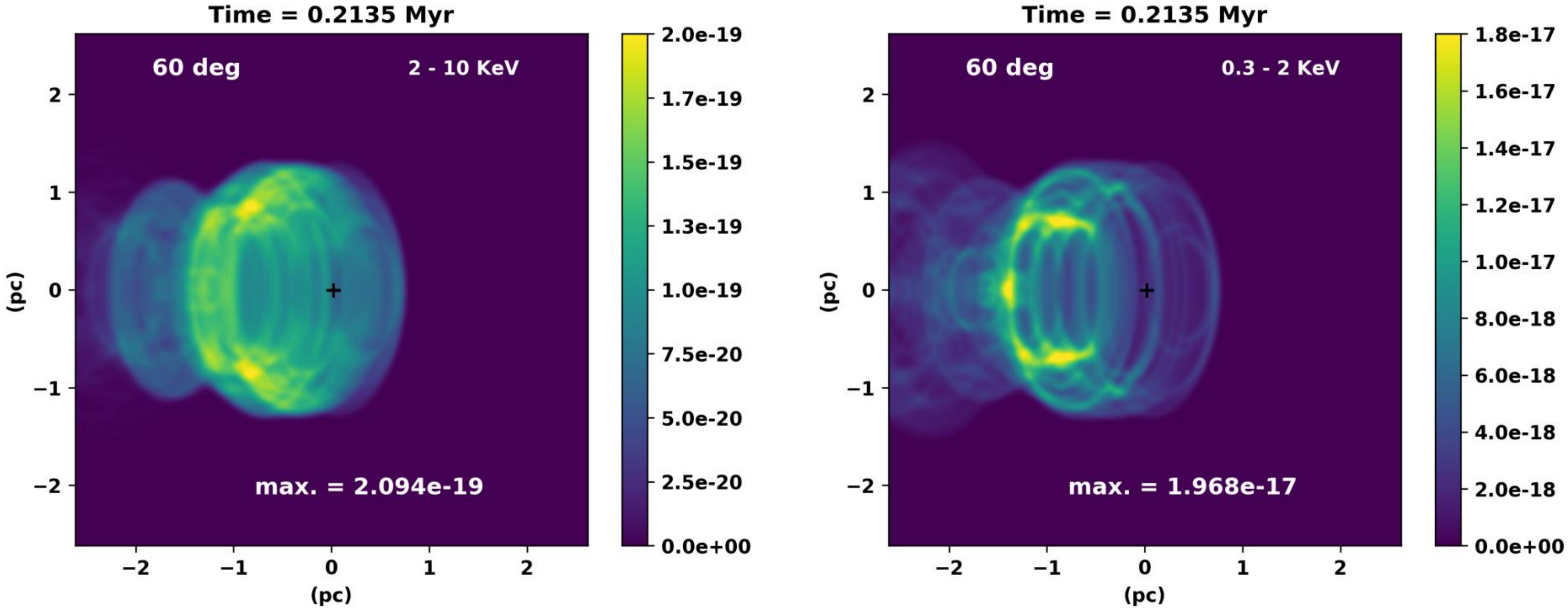
2 – 10 keV



0.3 - 2 keV

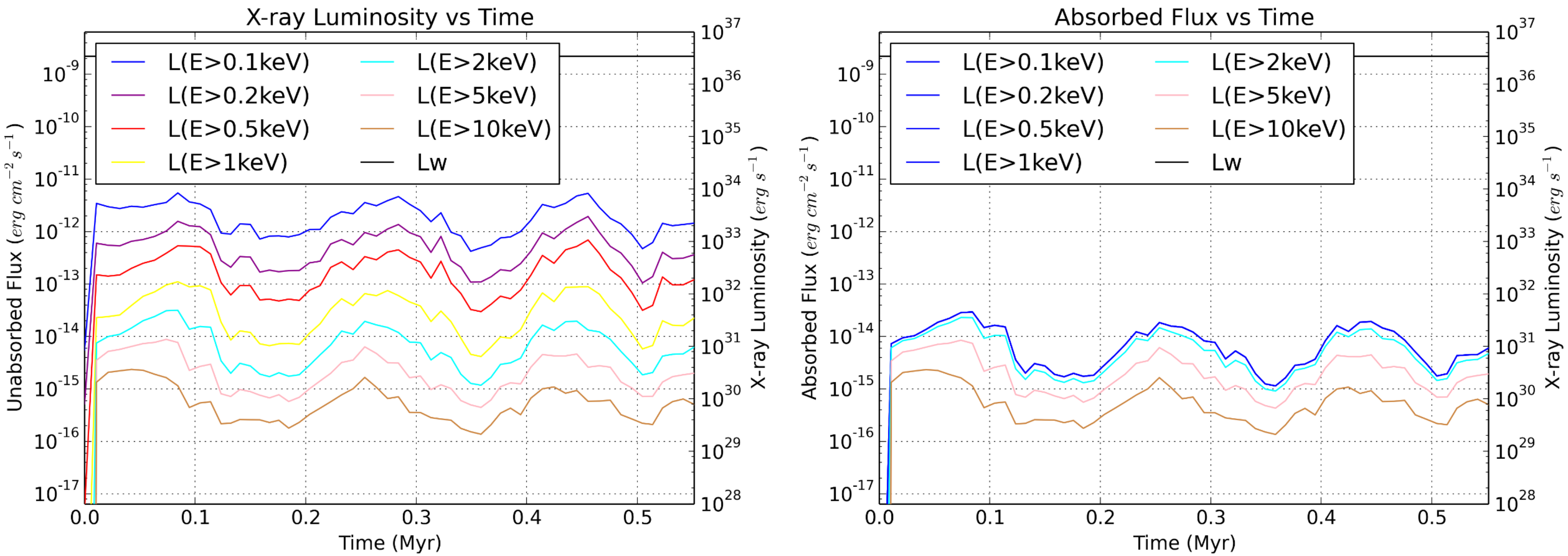


Both images are on different scales.



- Smoothed to angular resolution of XMM-Newton EPIC cameras (6 arcsec)
- Units: erg cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$

X-ray Luminosity/Flux



- Luminosity/Flux integrated over the whole nebula
- A_{ν} = 2 magnitude

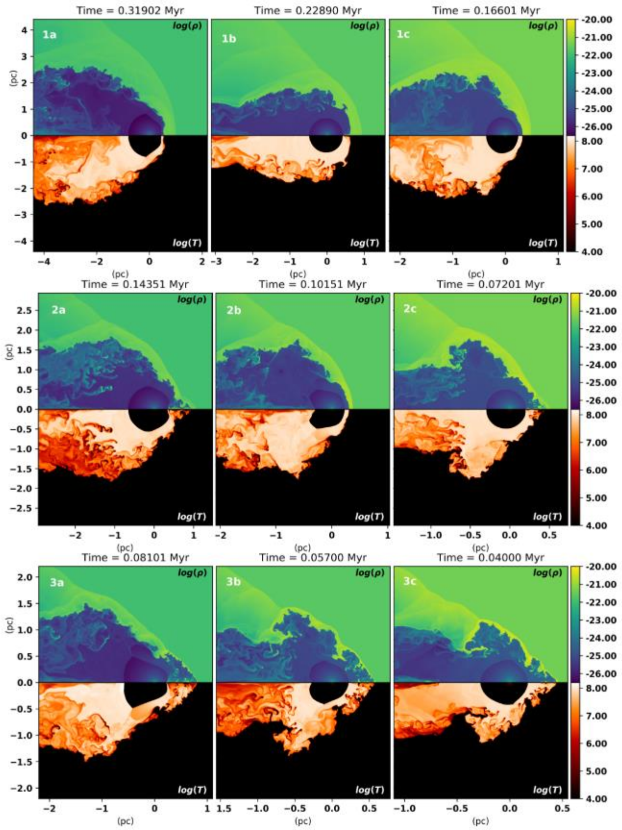
Issues with our Model

- Our 1b simulation produces a nebula of 3pc in diameter.

- This implies that some of the input parameters are incorrect. Either $\dot{M}$ or v_∞ is too big, or that ρ_{ISM} or v_* is too small.

- Our chosen simulation has v_* = 20 km s $^{-1}$.

- A larger v_* would prevent the nebula from expanding as much as our simulation.



Future Work

- The inclusion of a magnetic field can weaken Kelvin-Helmholtz instabilities.
- There is a density gradient present in the HII region around the Bubble Nebula.
- A well-known problem with 2D hydro simulations is gas piling up at the apex of the bow shock and becoming unstable.

Conclusions

- This work presents the beginning of a project to investigate thermal emission from stellar wind bubbles.

- Results conclude that the O star creates a bow shock as it moves through the ISM and in turn creates an asymmetric bubble visible in optical, infrared, and X-rays (predicted).

- Extinction means UV and soft X-rays will be hard to detect and therefore it is difficult to constrain the mixing between the hot and cold plasma.

- Further investigation is underway to add further complexity to the Bubble Nebula model.

Velocity Profile

- $PION$ also solves for the gas velocity in the x- and y-direction.
- Vector arrows show the direction of each part of the bow-shock and bubble.
- Anything more than 30km/s is plotted as yellow.