Synthetic Spectra with ExTraSS — 3D NLTE Nebular Phase Supernovae

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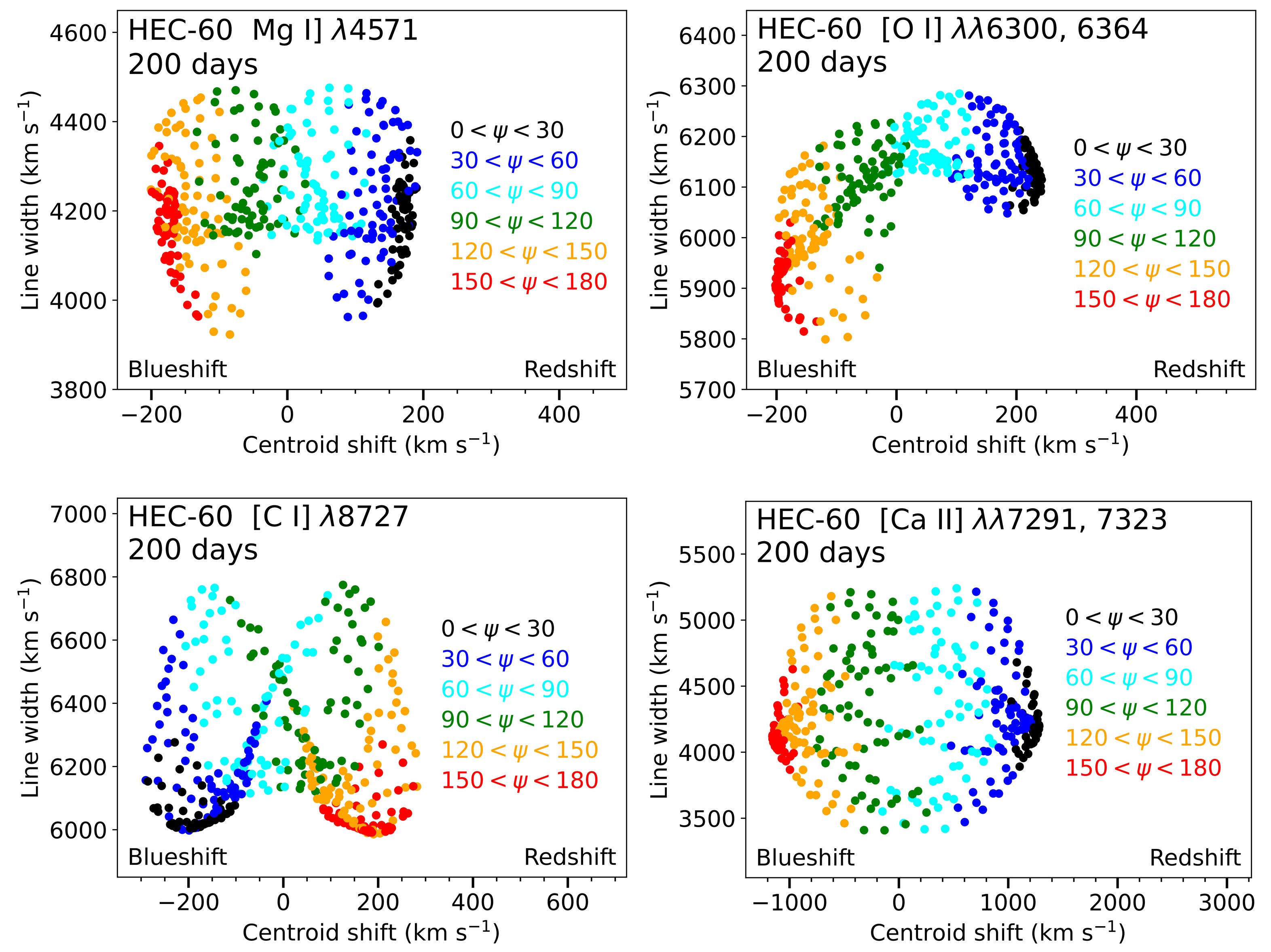
Nebular Phase Supernovae & 3D Spectral Synthesis

A few months after the explosion, the expanding supernova will become (mostly) optically thin and its inner structure becomes visible, entering the "nebular phase". The remnant is relatively hard to observe in this phase due to its relative faintness, and observations more than a year after explosion are rare. In the nebular phase, the nebula shines through the radioactive decay of isotopes such as ^{56}Ni, which are created in the explosion (Jerkstrand, 2017).

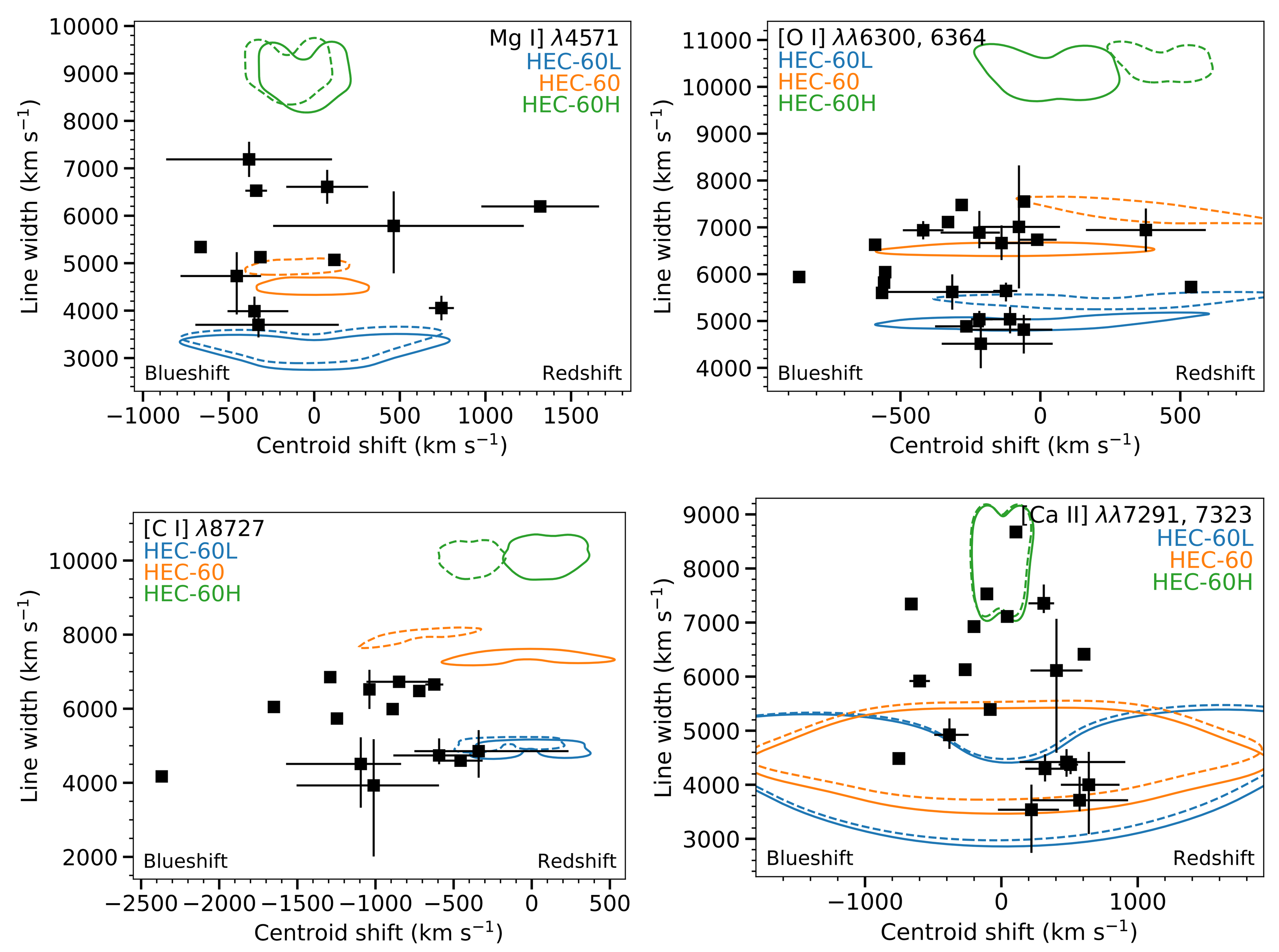
ExTraSS (EXplosive TRAnsient Spectral Simulator) is a 3D NLTE spectral synthesis code (van Baal et al., 2023, 2024) which can use 3D explosion models as inputs. Previous studies used spherically symmetric, 1D models to determine the structure of the nebula and the spectrum created from such a model. However, such models can only approximately account for the complex 3D morphology.

The work focuses on the line centroid shift and line width and how these vary across viewing angles. We concentrate on the four optical lines of Mg I] $\lambda 4571$, [O I] $\lambda\lambda 6300, 6364$, [Ca II] $\lambda\lambda 7291, 7323$ and [C I] $\lambda 8727$, although we also look at the $1.08\,\mu$ and $2.06\,\mu$He lines appearances in the NIR.

Results — Line Widths and Centroid Shifts



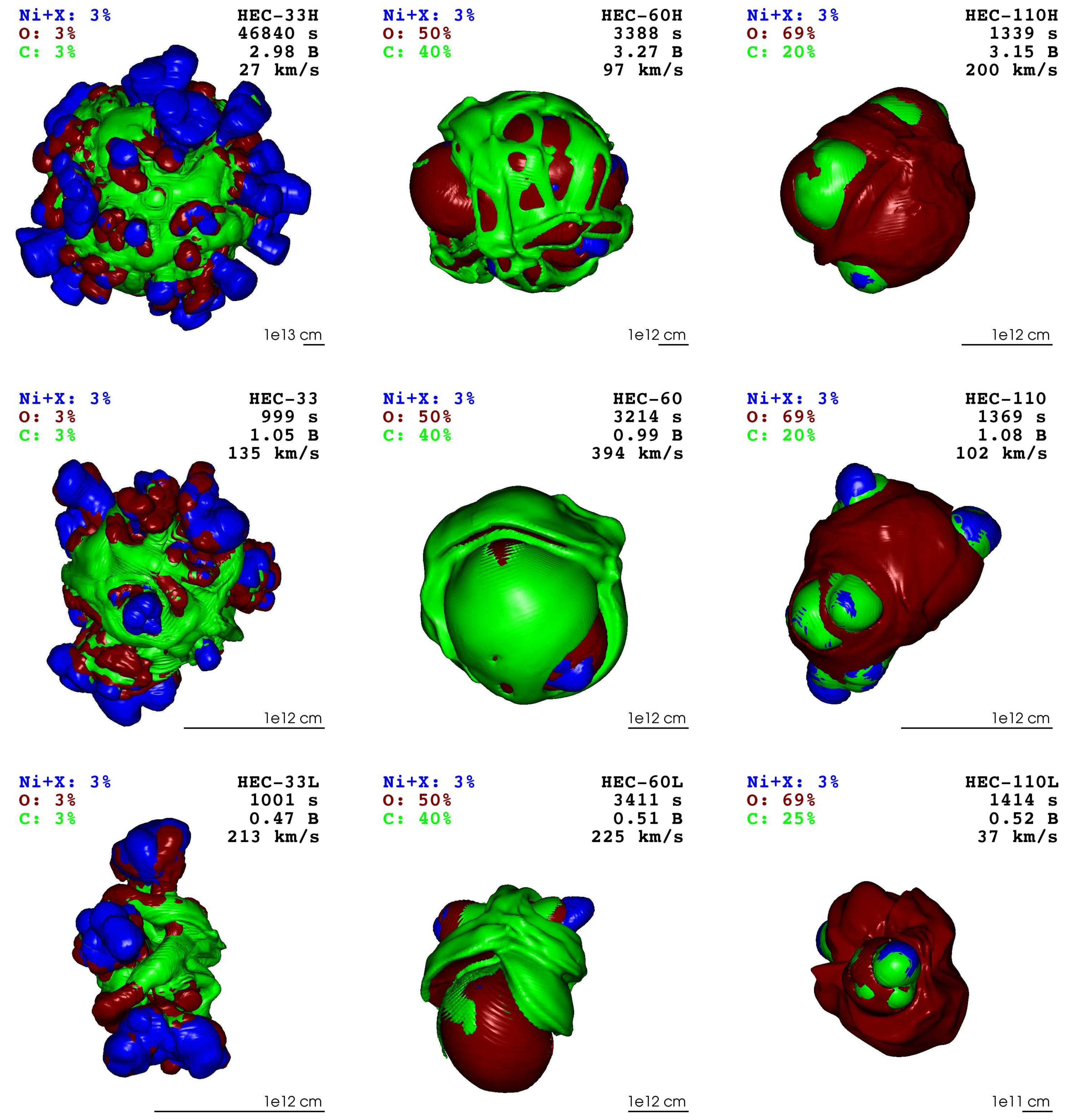
The line properties of HEC-60 for the four spectral features, for all of our viewing angles. The angles Ψ are color coded by the angle between the direction vector to the viewer and the neutron star motion vector; the black points (small Ψ) correspond to viewing angles where the neutron star is moving almost directly towards the observer.



The contours of the line centroid shifts and line widths for all $6.0\,M_\odot$ models, compared to the observational SNe in black. The error bars indicate variation between different observations from the same SN. The solid contours show the line properties calculated from just that element, while the dashed contours are calculated using all emission.

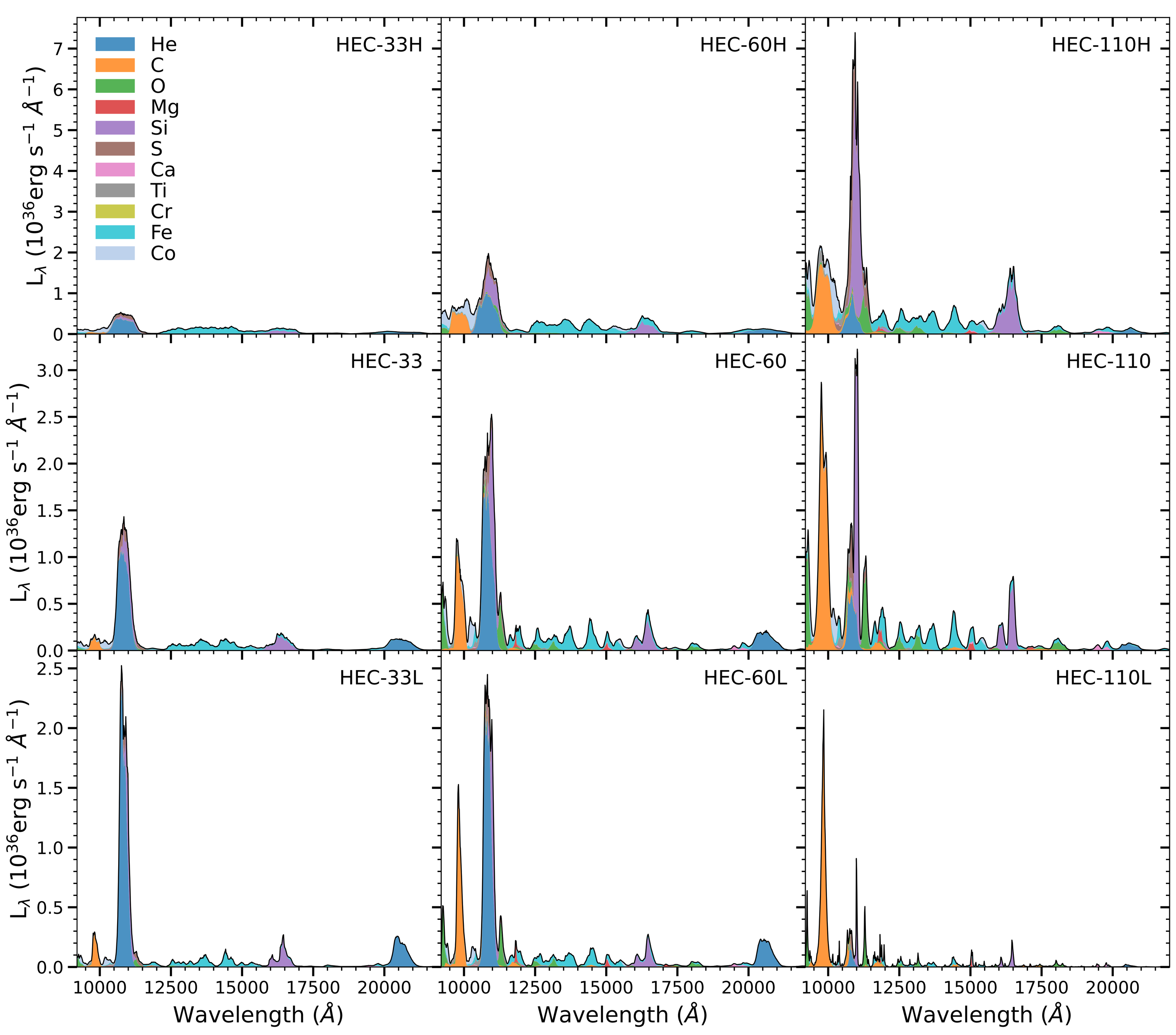
The Models — 9 He-core explosions

Nine different explosion simulations are investigated, with three different progenitor stars exploded with three different explosion energies. The progenitor stars are Ertl et al. (2020)'s 3.3, 6.0 and $11.0\,M_\odot$ He-core stars, each exploded with ~ 0.5, 1 and 3 B. The explosions were carried out with the Prometheus-HotB code.



The 3D renderings of all explosion models, showing iso-surfaces of C (green), oxygen (red) and Ni+X (blue), at the end of the 3D SN simulations with P-HotB. Each row has similar explosion energies (from top to bottom, 3, 1 and 0.5 B), while each column has the same progenitor star (from left to right, 3.3, 6.0 and 11 $M_\odot$ He-cores). Each panel is orientated such that the neutron star motion is vertically upwards; the neutron star kick velocities are noted in the top-right of each panel.

Results — He Lines in NIR



The NIR spectra ($9200 - 22500$ Å) for each of our models at 200 days post-explosion. Note that every row has its own y-axis scale. The relevant He lines are the He I $1.08\,\mu$ and $2.06\,\mu$ lines; only in some models are these uncontaminated and clearly visible.

References

Ertl T., Woosley S. E., Sukhbold T., Janka H. T., 2020, ApJ, 890, 51
Jerkstrand A., 2017, Handbook of Supernovae, p. 795
van Baal B. F. A., Jerkstrand A., Wongwathanarat A., Janka H.-T., 2023, MNRAS, 523, 954
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