ered ($\omega = 10^4$ rad s^{-1}), a full r-process pattern extending through the third peak is produced. Here, the wave heating due to weak shocks begins before the start of seed formation. Therefore, the substantial increase in the entropy inhibits seed formation, and leaves a large neutron-to-seed ratio when alpha capture ends. This is mainly driven by the impact of ω on the shock heating activation radius, and less so by the variation in l_d with ω. This is illustrated by the model shown in figure 9 that assumes $\omega = 2 \times 10^3$ rad s^{-1} but an instantaneous activation of shock heating. This results in nucleosynthesis that is very similar to the $\omega = 10^4$ rad s^{-1} model.

Therefore, as a limiting case given the uncertainty in the shock activation radius and to compare to previous work (Suzuki & Nagataki 2005; Metzger et al. 2007), we show in figure 10 final abundances for varied L_w/L_ν for $\omega = 2 \times 10^3$ rad s^{-1}, $M_{\rm NS} = 1.5 M_\odot$, $L_\nu = 3 \times 10^{52}$ erg s^{-1}, but with instantaneous activation of the shock heating. The results are noticeably different than those shown in figure 6, which shows models with the same parameters but without instantaneous shock heating. For instantaneous activation, the average mass of the abundance distribution increases monotonically with L_w/L_ν and for even moderate wave luminosities is able to produce a full r-process. This illustrates that uncertainty in the shock formation radius translates into significant uncertainty in the predicted nucleosynthesis for gravito-acoustic NDWs.

To illustrate the important impact of the reduced electron fraction from the wave contributions, we show in figure 11 abundance distributions from a wind with $M_{NS} = 1.9 M_\odot$, $L_\nu = 6 \times 10^{52}$, and $Y_{e,\rm eq} = 0.52$. In the absence of wave effects, the neutrino spectrum used here should preclude any r-processing whatsoever. The wind would undergo an alpha-rich freezeout, leaving only free protons to capture onto seed nuclei. However, with wave effects included, we find similar r-processing regimes to those obtained with neutrino energies tuned to $Y_e = 0.48$. In the wave stress regime, with $5 \times 10^{-4} \lesssim L_w/L_\nu \lesssim 5 \times 10^{-3}$, the change in Y_e is not large enough to make the wind neutron rich, but the faster outflow caused by the wave stress prevents an α-rich freezeout from occurring. R-process elements are then synthesized from the free neutrons in the wind, despite the wind being overall proton-rich. This gives rise to the suppressed, actinide-free r-process patterns in figure 11. In between the r-processing regimes, we again find a region where the combined entropy and dynamical timescale in the wind favor strong seed formation and thus no r-processing, regardless of Y_e or the presence of an α-rich freezeout. At high L_w, the wind becomes neutron-rich again, and early wave heating suppresses seed formation and drives the same strong r-processing as in figure 7.

5.2.3 *Nucleosynthesis in the L_w - L_ν - M_{NS} parameter space*

In figure 12, we show the total final abundance of nuclei with mass number $A \geq 150$ as a function of L_ν and L_w/L_ν for a variety of PNS masses. Here, we have used $Y_{e,\rm eq} = 0.48$, $\omega = 2 \times 10^3$ rad s^{-1}, and assumed the shock formation radius is given by equation 13. We find the abundance of nuclei with $A \geq 150$ to be an effective proxy for the strength of the r-process in the wind (see e.g. figure 7). Two r-processing regimes appear. For the highest neutrino and wave luminosities, shock heating begins early enough in the wind to drive a strong r-process. This shock heating regime is fairly insensitive to PNS mass but very dependent on wave frequency, which sets how early shock heating can begin in the wind. The second r-processing regime, driven by acceleration due to the wave stress, is strongly dependent on mass but insensitive to wave frequency. We see this regime emerge at a PNS mass of around $1.8 M_\odot$, and grow to dominate the parameter space for the most massive neutron stars. The non-monotonic dependence of the average mass number of the final abundances is also visible here. At higher masses, the wave stress contribution is able to drive strong r-processes even for very low neutrino and wave luminosities, where shock heating begins too late to strongly affect the nucleosynthesis. We have also run similar calculations with $Y_{e,\rm eq} = 0.45$. These show qualitatively similar behavior to the results shown in figure 12, except that the onset of wave stress-driven r-process nucleosynthesis is shifted to lower PNS mass.

In order to quantify the impact of the reduced electron fraction due to the wave stress contribution, we show in figure 13 the same parameter set as in figure 12, but with Y_e fixed to a constant value of 0.48. We find that including a self-consistent Y_e evolution results in a noticeable broadening of the region in L_ν-L_ν/L_w space where the r-process occurs, especially the wave stress-dominated regime at lower L_w and L_ν. This is perhaps to be expected, as the change in Y_e is driven primarily by the wave stress reducing the amount of neutrino heating needed to unbind the wind material. We also observe generally higher yields of r-process material when Y_e evolution is included, due to the higher number of free neutrons available.

Finally, in figure 14, we show the impact of instantaneous shock formation on nucleosynthesis across the entire parameter space (once again with $Y_{e,\rm eq} = 0.48$ and $\omega = 2 \times 10^3$ rad s^{-1}, and self-consistently evolving Y_e). In this case, we find third peak r-process production for nearly all considered neutrino luminosities and PNS masses when $L_w/L_\nu \gtrsim 2 \times 10^{-4}$. Although the acceleration of the wind due to the wave stress plays a role in determining the nucleosynthesis in these models, the impact of the waves is mainly driven by the shock heating that they provide.

6 CONCLUSIONS

We have investigated the impact of gravito-acoustic waves launched by PNS convection on the dynamics and nucleosynthesis of the neutrino-driven wind. When these waves propagate through the NDW, they impose additional stresses on the wind and also may shock and provide an extra source of heating. Using steady-state, spherically symmetric models for the wind that include the impact of an acoustic wave energy flux, we surveyed the parameter space of the gravito-acoustic wave luminosity and frequency that is expected to be produced by PNS convection. The presence of shock heating in the wind precludes reliance upon the common predictive metric s^3/τ_d, as entropy is no longer nearly constant during seed formation. Therefore, using the results of our hydrodynamic models, we then performed calculations of nucleosynthesis for the marginally neutron-rich compositions that may be encountered in some NDWs.

For $L_w \gtrsim 10^{-5} L_\nu$, the waves strongly impact the dynamics of the wind via two mechanisms, acceleration due to wave stresses and entropy production via wave shock heating. Acceleration of the NDW by wave stresses reduces the dynamical timescale, but also reduces the entropy and electron fraction of the wind since a faster wind has less opportunity to undergo neutrino heating. Depending on L_w/L_ν, this competition between reduced dynamical timescale and reduced entropy can make conditions more or less favorable for strong r-process nucleosynthesis.

Similarly to previous work (Suzuki & Nagataki 2005; Metzger et al. 2007), we find that if the wave energy is deposited (in our case through shock heating) before r-process seed nucleus formation begins, the entropy of the wind at seed formation is substantially increased. This in turn results in an alpha-rich freeze out and more favorable conditions for producing nuclei in the third r-process peak. Here, we found that the exact position of shock formation has a strong