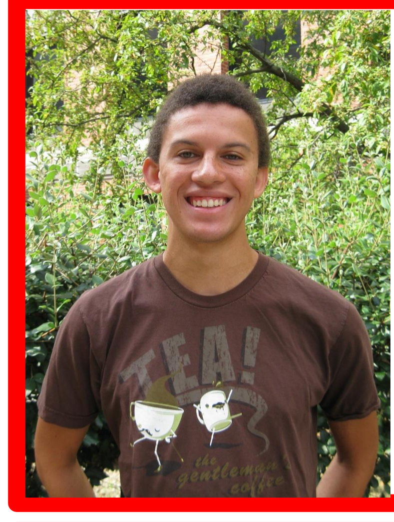

Measuring the Asymmetries of Heavy Elements in the SNR Cassiopeia A

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Introduction

Simulations of CCSNe make predictions about asymmetric explosion mechanism(s)

1. Heavy Elements (e.g, Ca, Ti, Fe) should be more asymmetric than lighter elements (e.g., O, Ne, Mg)
2. Neutron Stars (NSs) should be `kicked' opposite to the heaviest elements

Previous studies (e.g., Holland-Ashford et al., 2017 and Katsuda et al., 2018) have shown that NSs are kicked opposite to the bulk of ejecta, but there has not yet been a systematic study of the relative asymmetries of different elements in SNRs.

Observations, Data Prep, and Element Maps

We utilize 15 archival X-ray observations the CCSNR Cassiopeia A (Cas A) from NASA's *Chandra X-ray Observatory* totaling ~1.3 Ms. These observations allow us to perform a detailed analysis of X-ray spectra extracted from regions down to 5" in size. We fit spectra in 2517 regions and subtract the continuum emission in order to measure only the flux from emission lines (continuum-subtracted maps shown below).

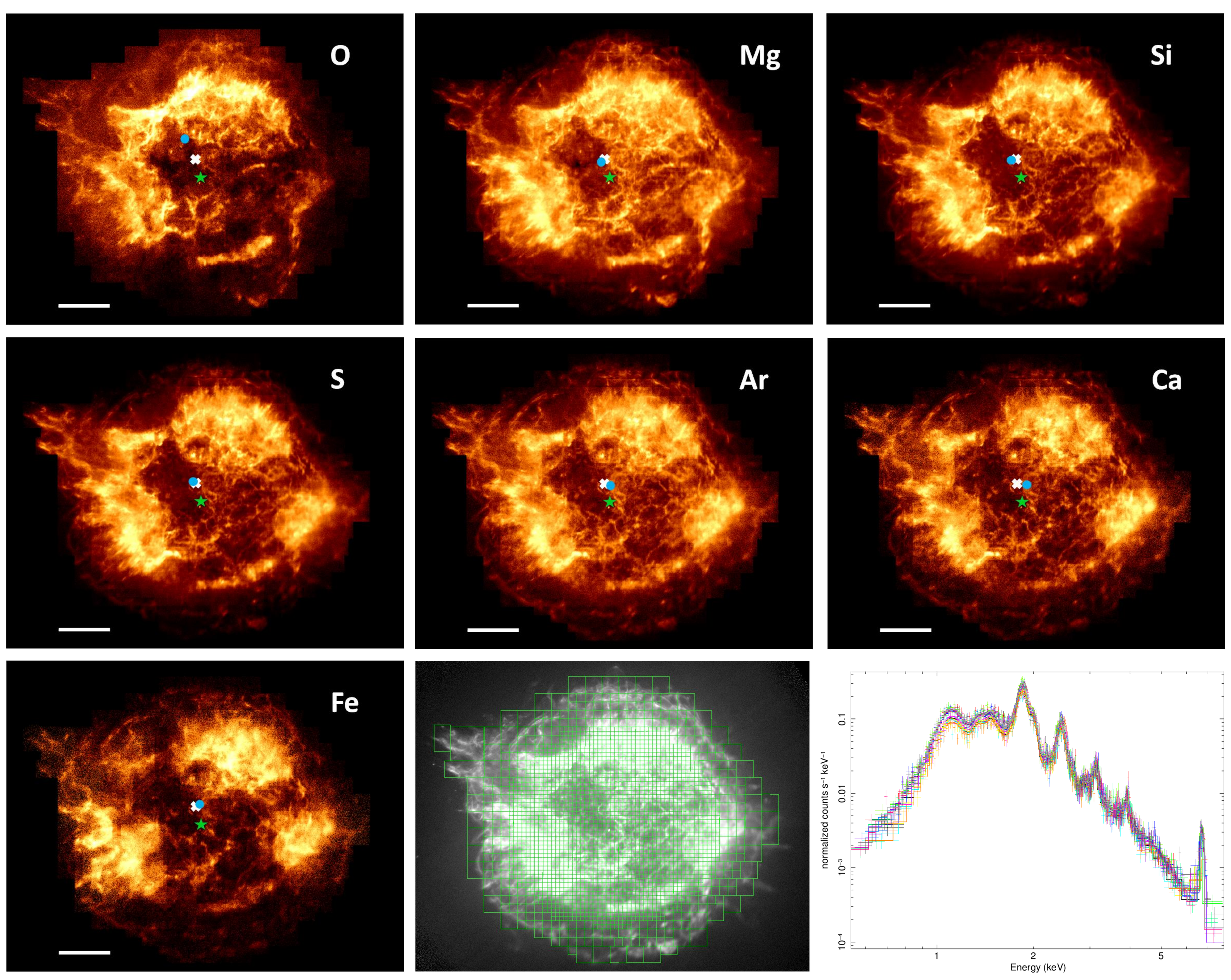

Figure 1. Continuum-subtracted images of Cas A (top two rows; bottom left image), the full 0.5-8.0 keV *Chandra* image of Cas A with an overlay of the regions analyzed (bottom-middle), and a sample fit to the X-ray spectra of a region (bottom-right). Labeled in the element images are the full-band center-of-emission (0.5-8.0 keV; white X), the element center-of-emission (cyan circle), and the explosion site of Cas A (green star).

Note: We also create mass maps by dividing the continuum-subtracted images by the emissivity of each emission line. Our mass-map results are generally consistent with our continuum-subtracted image results.

Future Work

• Systematically analyze the relative element asymmetries in multiple young, Galactic CCSNRs
  - e.g., G11.2, Puppis A, W49B, Kes 73
• Extend this analysis to Type Ia SNRs in the Milky Way
  - e.g., Kepler, Tycho, G1.9
  - Ejecta stratification would provide evidence for detonation over deflagration explosion models (Badenes et al. 2006)

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Results

We analyze our images using the power-ratio method (see Lopez et al. 2009 for more details), which measures normalized multipole moments. We center our analysis at each image's center-of-emission where the dipole moment power-ratio (P1/P0) approaches zero and the quadrupole (P2/P0) and octupole moment power-ratios (P3/P0) reveal details about the successively smaller scales of asymmetry.

We find a consistent correlation in all our analyses: **the distribution of heavier elements is generally more elliptical and more mirror asymmetric than that of lighter elements.** This result holds true for nearly all elements analyzed using the continuum-subtracted images (below, right), whereas Ar and Ca are measured to be less asymmetric than the lighter elements Si and S when using narrowband images (below, left). **In order to distinguish between elements formed by the same burning process, it is necessary to perform continuum-subtraction.**

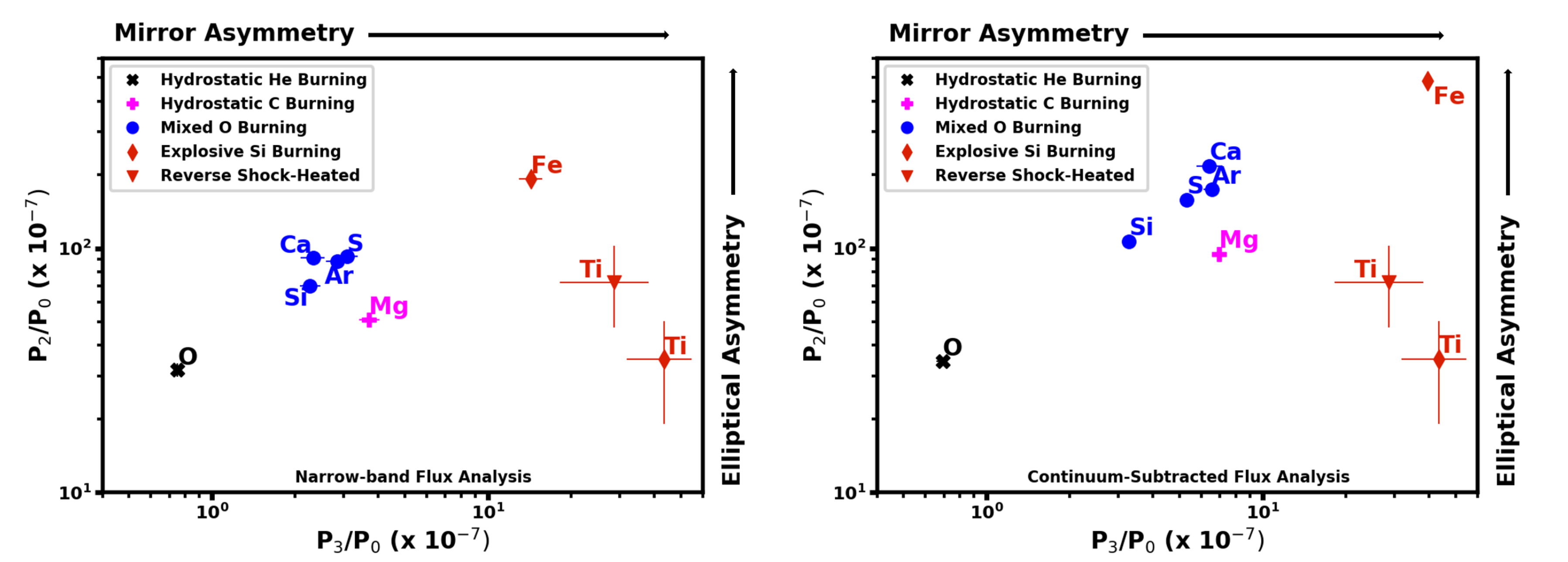

Figure 2. Asymmetry analysis using the narrowband (left) and continuum-subtracted (right) images. The Ti data point is from *NuSTAR* images (Grefenstette et al. 2017) of Ti-44, and we did not perform any additional analysis on these narrowband images. However, we note that the Ti narrowband images should reflect mostly line emission. *The* "Reverse Shock-Heated" Ti data point results from manually zero-ing regions interior to the reverse shock, to more closely match the distribution of the other reverse shock-heated elements which result from shock-heating as opposed to radioactive decay as in the case of Ti.

We also measure the power-ratios of the maps, created from dividing the continuum-subtracted images by the emissivity of each line. **The power-ratios of these mass maps (right) are generally consistent with our above results, although the errors are too large to distinguish between elements created from the same burning process.**

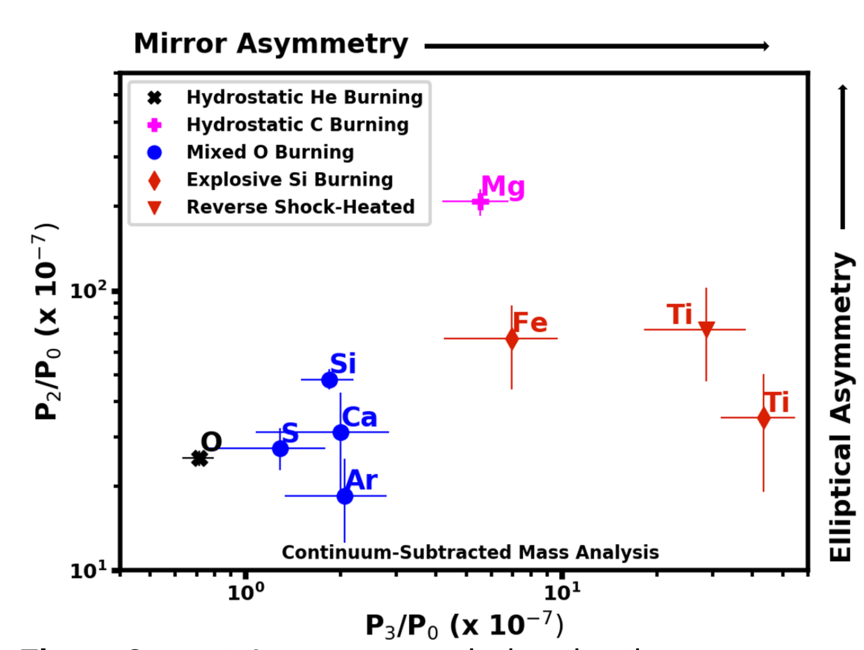

Figure 2, cont. Asymmetry analysis using the mass maps for each element. The error bars result from the uncertainty associated with the spectrally fit parameters: kT, ionization timescale, and abundance.

We find (below) that the NS kick direction is most opposed to the heaviest elements.

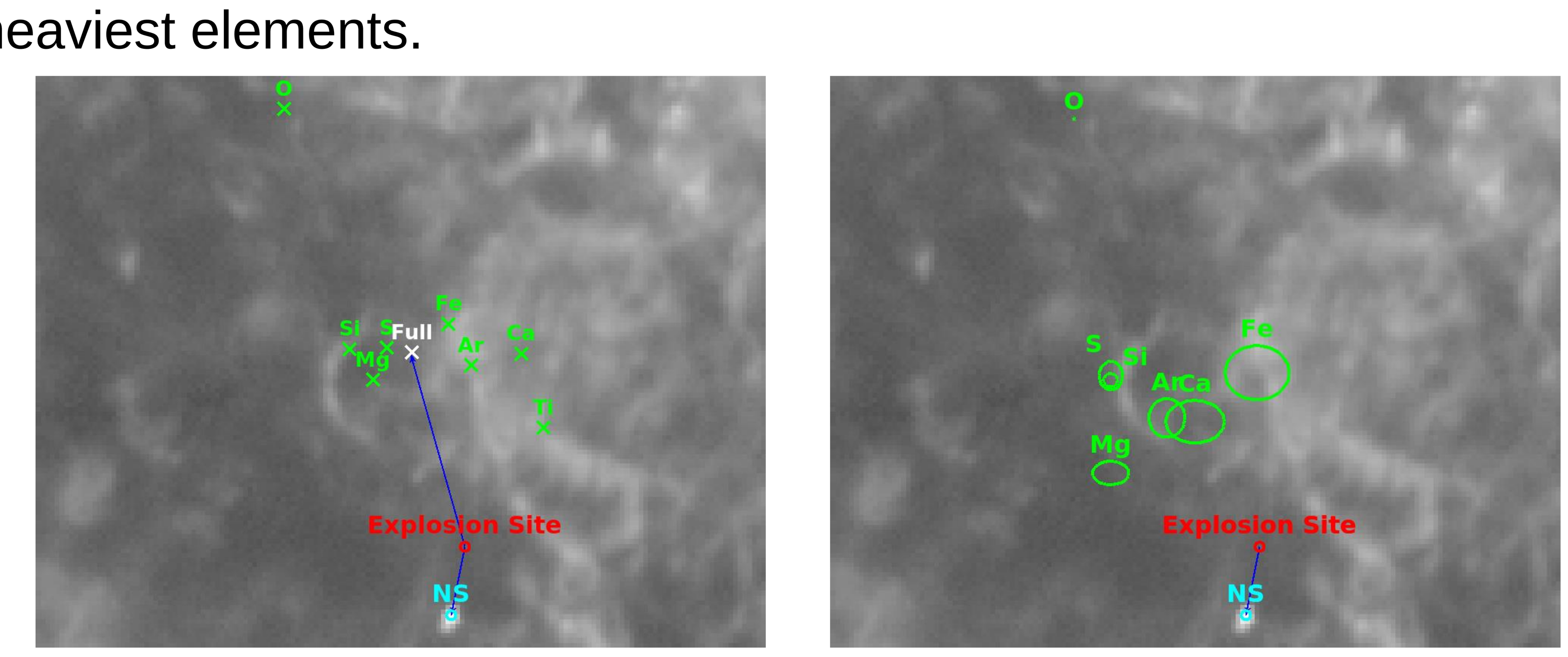

Figure 4. Zoomed in images of Cas A. The left image displays the locations of each element's center-of-emission (green Xs) and the full-band center of emission (0.5-8.0 keV; white X). The right image marks each element's center-of-mass including the 1-sigma error bars (green circles). Both images display the locations of Cas A's explosion site and the current NS location. Note that the heavier elements are more directly opposed to the NS direction of motion.

Our results support the theories of Wongwathanarat et al. (2013), Gessner & Janka (2017), and Muller et al. (2018) that SNR ejecta asymmetries are generated by an asymmetric explosion mechanism(s) and generate NS kicks through the gravitational tugboat mechanism.