SN 2023ixf: Shock-Powered Excess, Dust Formation and the Emerging Asymmetries from Nebular Phase Observations

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Introduction

Core-Collapse Supernovae (CCSNe) exhibiting circumstellar matter (CSM) interactions and dynamic signatures provide critical insights into the mass-loss histories of massive stars. In the era of modern sky surveys, we have observed several infant Type II SNe with "flash-ionized" features. However, limited studies exist to connect the observed early-time signatures with the late-stage evolution, leaving key questions open regarding the origins of the dense CSM and its connection to the characteristics of the progenitor.

We present a comprehensive study of the late nebular phase evolution of SN 2023ixf, focusing on optical and near-infrared (NIR) observations to investigate asymmetries, dust formation, and ejecta dynamics. Persistent redward attenuation of the Hα profile, observed from day 125 to 450, alongside the emergence of axisymmetric high-velocity components (>5000 km/s) in Balmer line profiles, highlights significant asymmetries in the ejecta due to interaction with the circumstellar medium (CSM).

Multi-wavelength Photometric Observations

- UV-Optical-Infrared-band light curves from **SWIFT**, Kanata, Seimei, ZTF and ATLAS, spanning up to 650 d from the estimated explosion date.
- Notably, all the **light curves starts flattening at around 250 d**, possibly due to rise of shock-powered emission contributing, in addition to luminosity from radioactive decay.
- **Shock-powered excess is indicated by the increasing contribution of UV-flux to the Bolometric flux.**

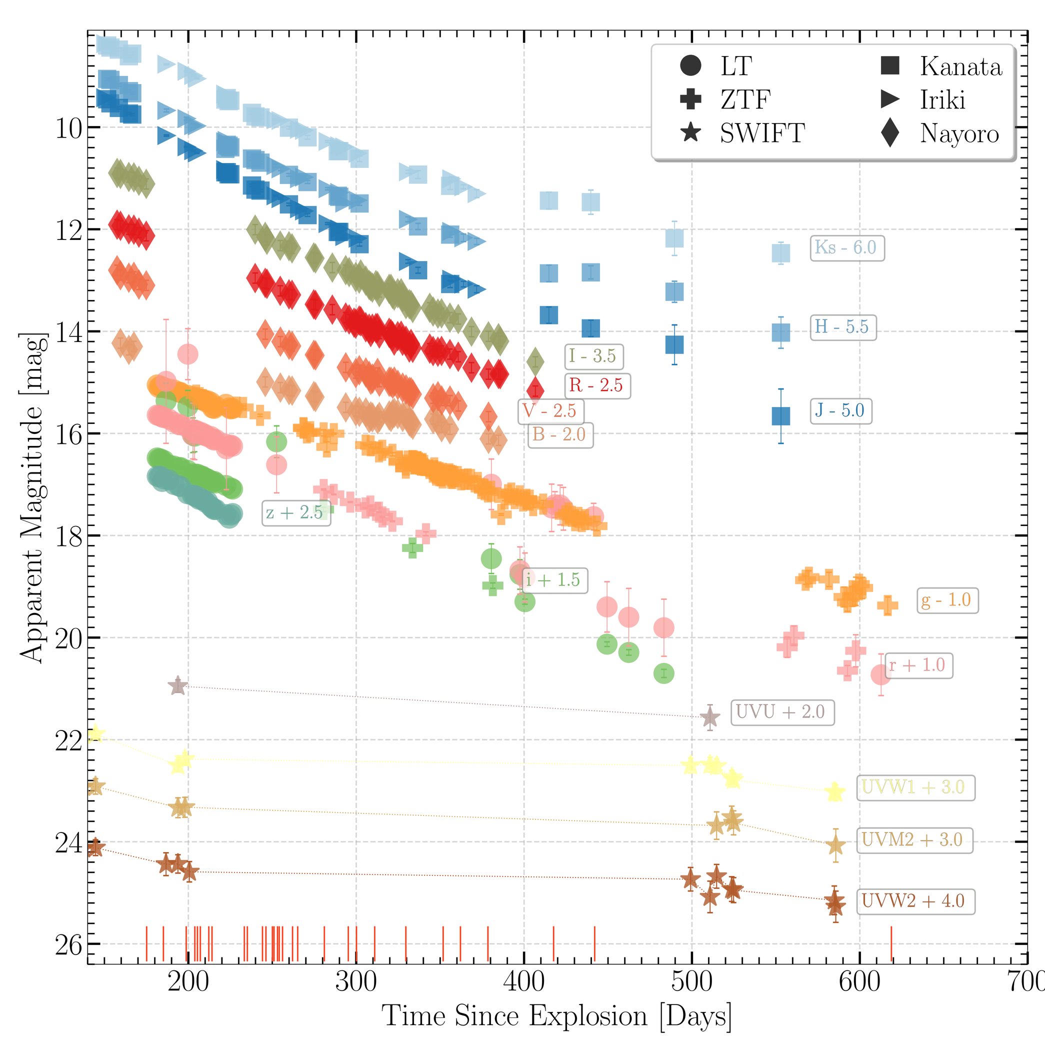

Figure 1. Multi-wavelength light curves of SN 2023ixf from 150 d to 650 d.

Shock-Powered Emission

- **Bolometric flux starts flattening fairly early in the evolution around 250 d.**
- The flattening is not common in Type II SNe, where the LC typically steepens due to γ-ray leakage, leading to reduced thermalization of contribution from ^{56}Ni.
- This is a direct indication of shock-powered emission.

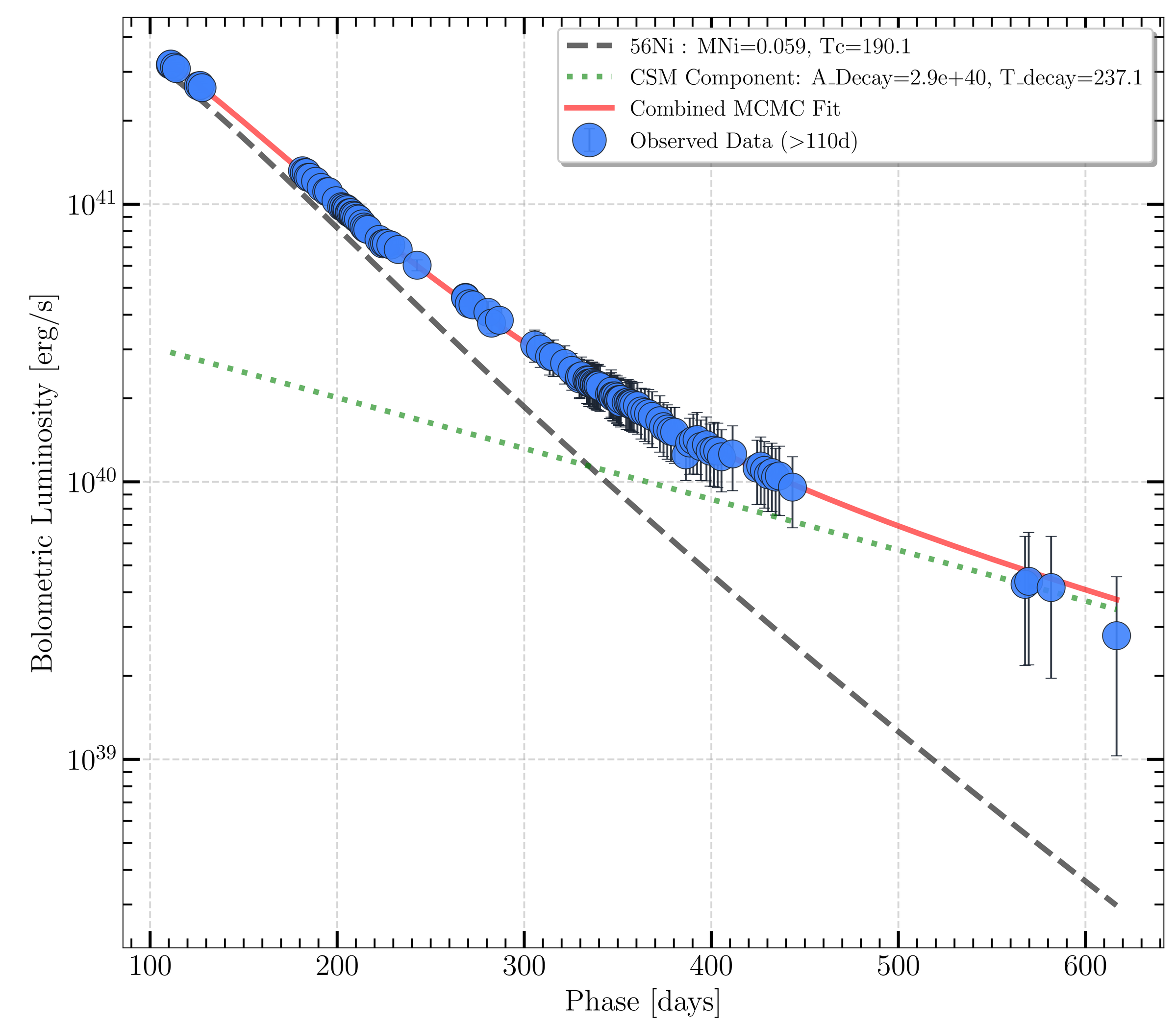

Figure 2. **UV-Optical-Near-Infrared Bolometric** Flux evolution of SN 2023ixf during the late-nebular phase. The deviation from ^{56}Ni tail is evident.

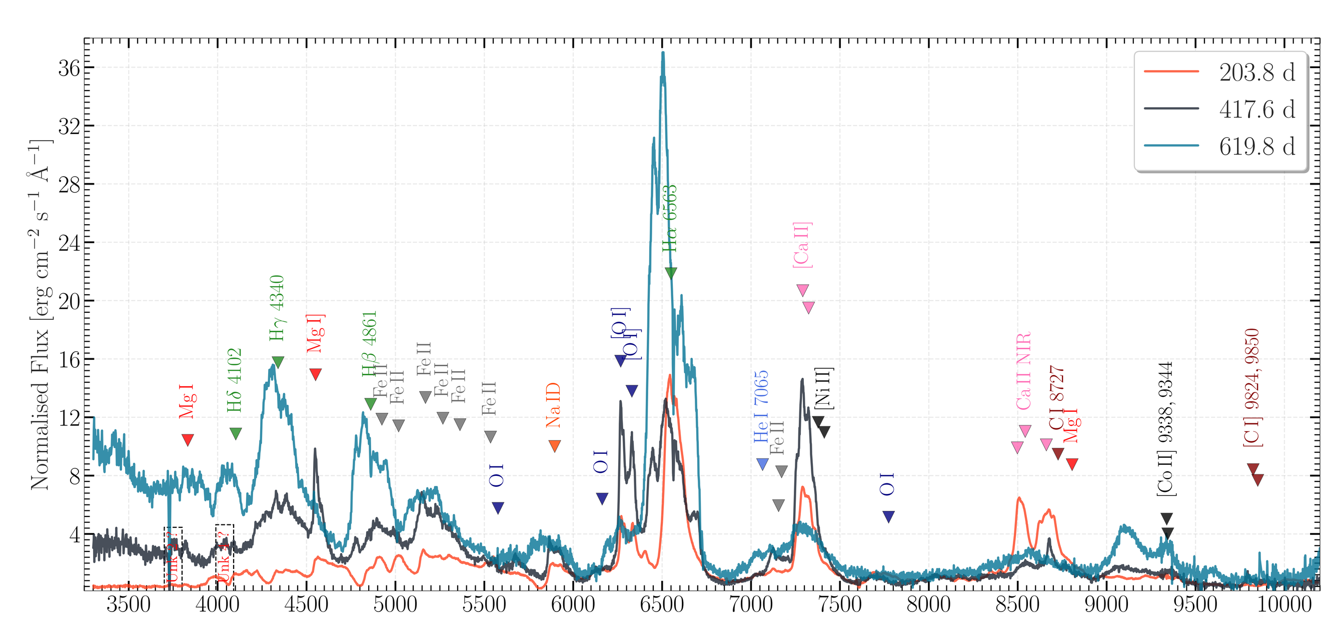

Figure 3. Spectroscopic sequence of SN 2023ixf, showing asymmetric line profiles, Fe-forest excess and rise of shock-powered emission

Near-Infrared Observations

- In the NIR regime, excess emission in $J-H$ and $J-Ks$ bands emerges immediately after the end of the plateau phase ($\sim$80 days), signaling the early presence of a thermal dust continuum in a Type II SN.
- This is further supported by flattening the of the Ks-band light curve and detecting CO overtone bands.
- CO-molecular formation is confirmed to have occurred at least 217 d from explosion. The continuum in the NIR spectra seems to rise towards the Ks-band in the same spectrum, in confirmation with the colors.

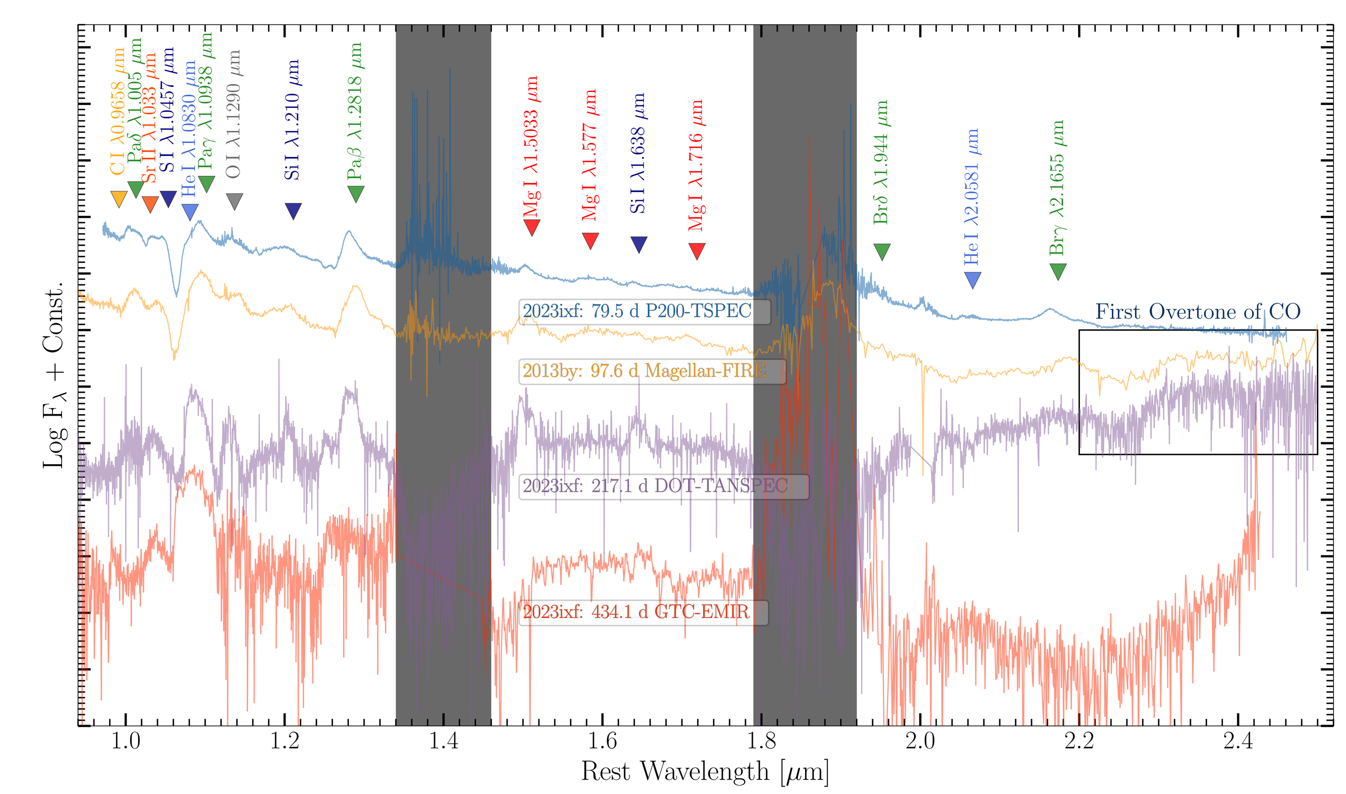

Figure 4. NIR Spectroscopic observations of SN 2023ixf

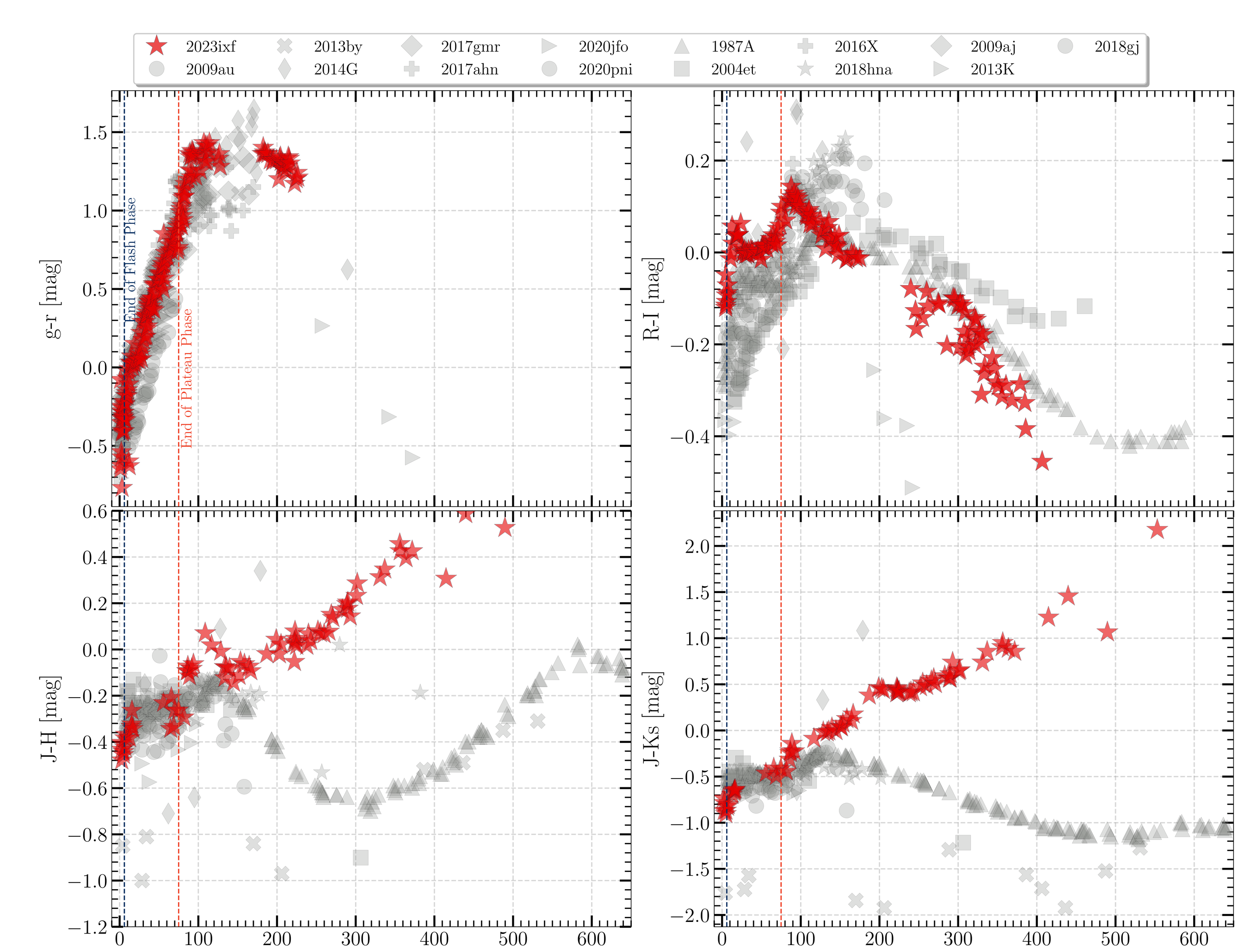

Figure 5. Evolution of optical and near-infrared colors of SN 2023ixf from the explosion until 600 d.

Halpha Oxygen Complex

- **The [OI] Doublet and the Halpha display a complex profile due to several blended components.**
- The [O I] doublet remains blueshifted (1500 km/s) with stable broad and narrow components, which shows no significant shift in velocity over time. Similar line behavior is replicated for [CaII].
- The "horns" in Balmer line profiles become evident in the spectrum at 200 d and more pronounced at 300 d and settle to 5,500 kms^{-1} at around 400 d.

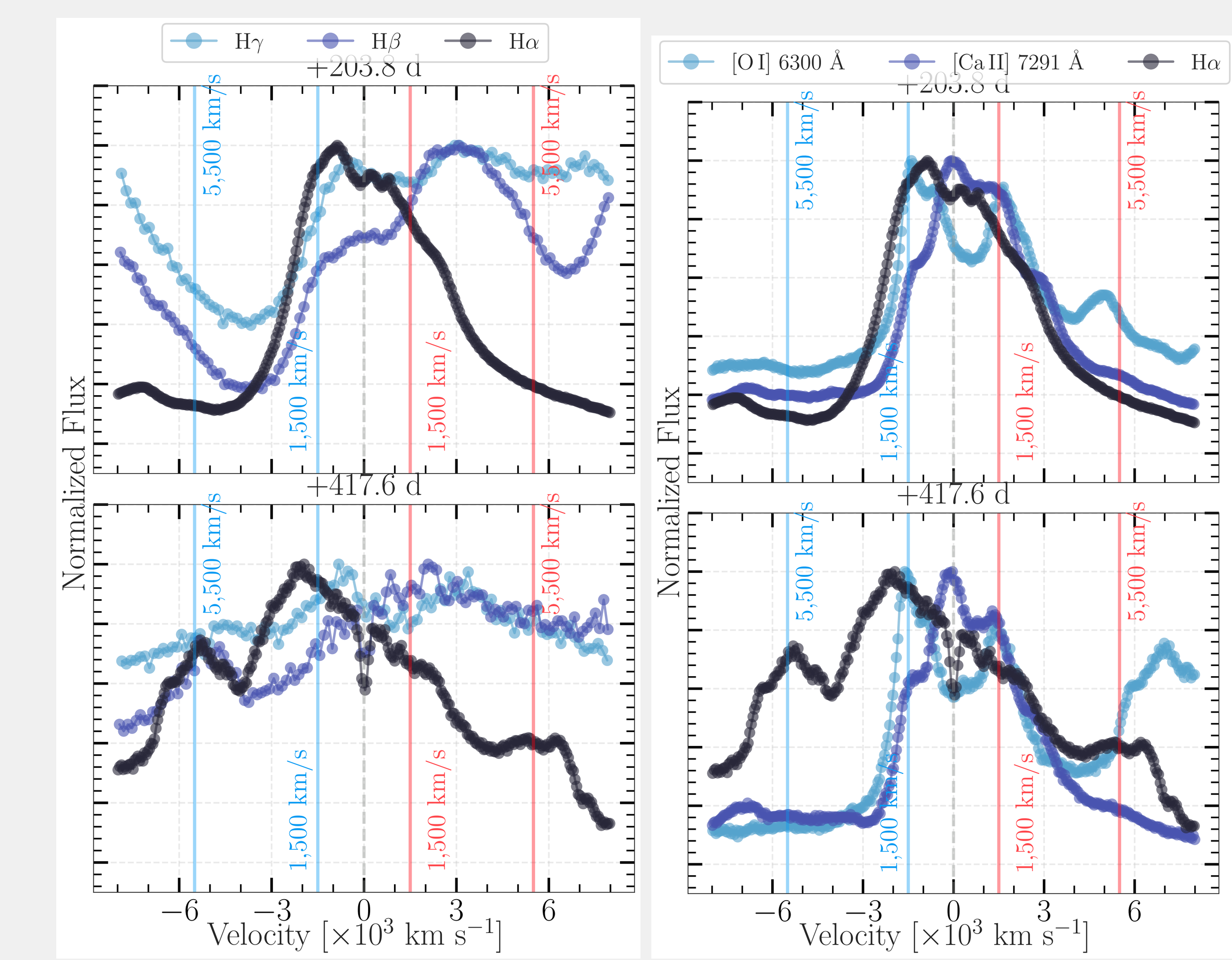

Figure 6. Line Profile evolution of Hα, [CaII], [OI] and Mg,I] in Type II SN 2023ixf. The line asymmetries at 1,500 kms^{-1} in [CaII] and [OI] are evident. The shock-powered interaction "horns" are concurrently seen in all the Balmer features at 5,500 kms^{-1}.

Forthcoming Work

- Model the thermal dust-emission in the NIR light curves.
- Investigate the strength of shock-power from the onset of bolometric flux excess and "horns" in the Balmer line profiles.
- Inferring the kinematic structure of the ejecta based on the spectral decomposition of the late nebular phase line profiles.
- Model the nebular spectra using radiative transfer codes to constraints the He-core and H-envelope mass.
- Is the asphericity in ejecta/shock-powered emission of 2023ixf driven analogous to the asymmetries in the dense CSM?

References

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