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Luminous Red Novae as shock-powered transients I: Electron-scattering wings and deviations from Case B

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ABSTRACT

Luminous red novae (LRNe) are a class of optical transients resulting from the mergers of binary stars or common envelope events. The population displays heterogeneous light curves with extended luminosity plateaus and/or secondary peaks, suggested to be powered by hydrogen recombination or shocks between pre- and post-merger ejecta. However, much of their spectroscopic behaviour remains unexplained. Using a sample of six LRNe, we identify telltale spectral evidence for shock processes across the LRNe luminosity range (10^{38}-10^{41} erg/s): (i) fast ejecta sweeping up slower upstream material; (ii) composite epochs with two distinct components, namely a cool stellar-like continuum underneath a hot nebular recombination region; and (iii) extremely broad line wings extending to 1000-10 000 km/s. Such line profiles reveal photons scattering off hot electrons in an outflow (T_e ~ 5000-10 000 K, v_{es} ~ 300-500 km/s), with recombination seen from both the upstream and downstream of the shock surface. Additionally, constraints on the density of the upstream medium are obtained from recombination-line ratios, where brighter LRNe show deviations from Case B, consistent with denser surrounding environments. Given the outflow's velocity and surrounding density constraints, the shock luminosity is sufficient to account for the total energetics of LRNe without requiring other energy-injection mechanisms. During the plateau phase, the scattering wings are hidden and line ratios are affected by radiative transport effects, which highlights the utility of post-plateau phase spectroscopy.

1. Introduction

- Luminous Red Nova (LRN)
  - Believed to be originate from stellar mergers
  - $L \sim 10^{38} - 10^{41}$ erg/s at peak
  - Redder than classical Novae, duration; ~ weeks to several months
- LRN longer-lived plateau is likely sustained by radially distributed heating sources,
  - Shock interactions (Metzger & Pejcha 2017) ← **The authors favor this model**
  - Hydrogen recombination in various shells (Ivanova et al. 2013; Matsumoto & Metzger 2022)
  - Accretion-powered jets (Soker 2020)

2. Luminous red novae sample

- 6 LRNe are chosen; **V1309 Sco** (mainly used in this paper), V838 Mon, M101-2015OT1. NGC 4490-2011OT1. UGC12307-2013OT1, and AT2021blu

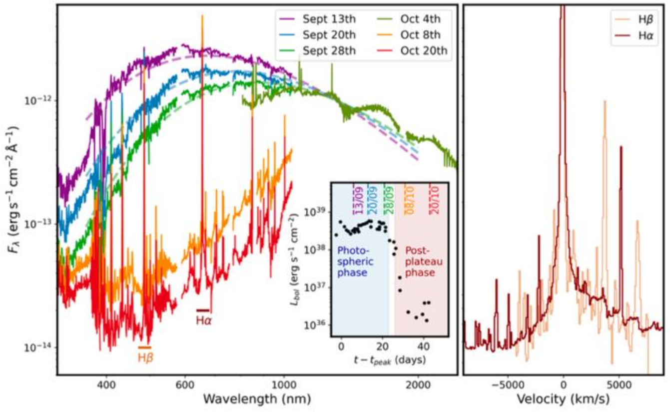


Fig.1 spectra of LRN V1309 Sco

Left
- spectra get redder
(Photospheric phase → post-plateau phase)
- $L_{\rm bol}$ suddenly drops at 20 days

Right
- narrow (~ 100 km/s, from slow CSM) + broad (> 1000 km/s, due to electron-scattering) components

3. Two energetic components in the post-plateau spectra: Blue nebular emission and a NIR star

- Two energetic components in post-plateau phase are considered (Fig.2)
  - hot ionised emission (Bound-free + recombination lines)
  - NIR stellar continuum

The authors propose two components fade coherently **because they are illuminated by the same shock front.**

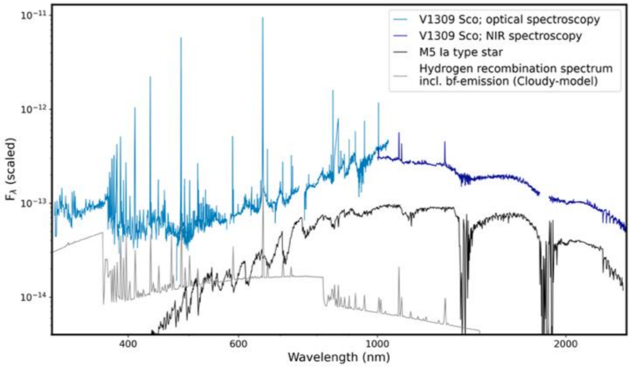
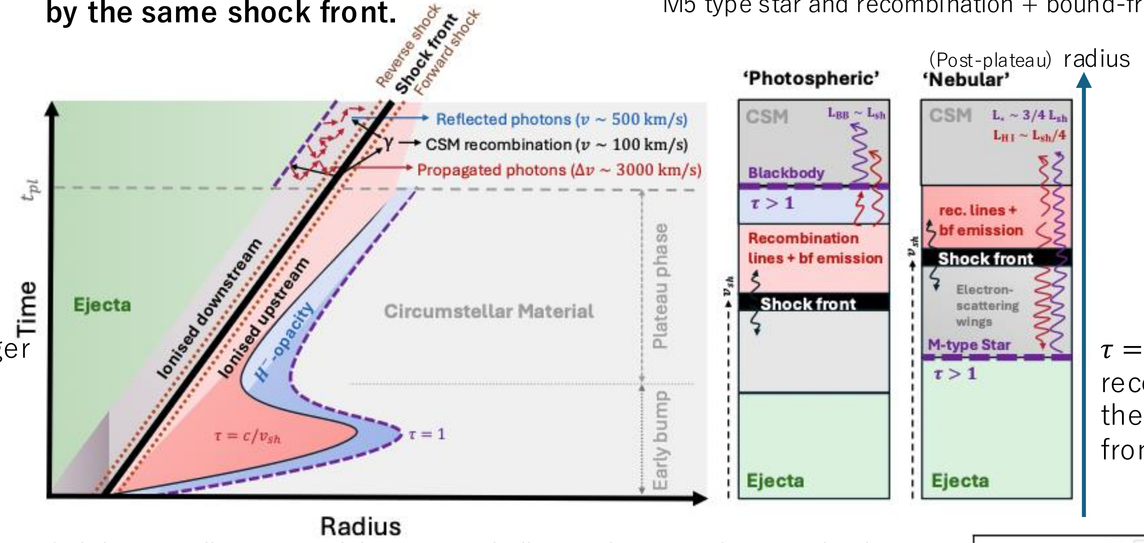


Fig.2. V1309 Sco spectra in post-plateau epochs, M5 type star and recombination + bound-free emission



$\tau = 1$ surface receding over the shock front

Fig.3. Schematic illustration of the various shells as a function of time and radius

- **upstream of the shock**, the ionised and slowly expanding CSM produces narrow recombination lines and bound-free emission, while **the dense downstream** produces an optically thick stellar surface illuminated from above.

4. Electron-scattering wings

- Broad width of Hα (>1000 km/s) is not consistent with photospheric velocity (~hundreds km/s).
- Authors suggest these are the spectral signatures of **electron-scattering** wings from a hot population of outflowing electrons, shock-heated by the collision of post-merger ejecta with the CSM formed by pre-merger ejecta. (Fig.4.)
  → They constrained N_{es} (electron column density), T_e (hot electron temperature) and v_{es} (outflow velocity)

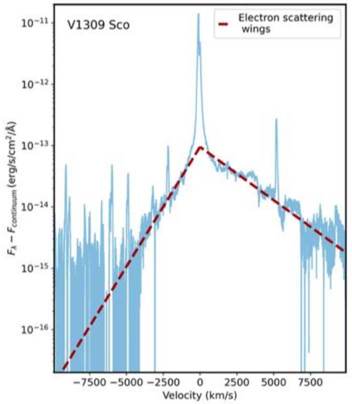


Fig.4. Hα profile

4. Electron-scattering wings (続)

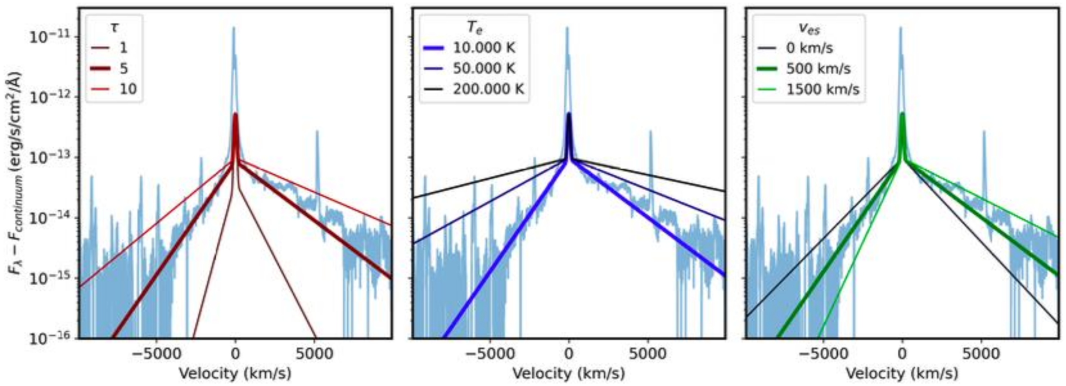


Fig.5. V1309 Sco Hα line and electron-scattering wings around an intrinsically narrow Gaussian line with varying electron-scattering optical depth (τ_{es}), electron temperature (T_e), and bulk outflow velocity (v_{es})

→ They find to be plausible physical parameters $\tau_{es} = 5, T_e = 10000\ \mathrm{K}, v_{es} = 500\ \mathrm{km/s}$

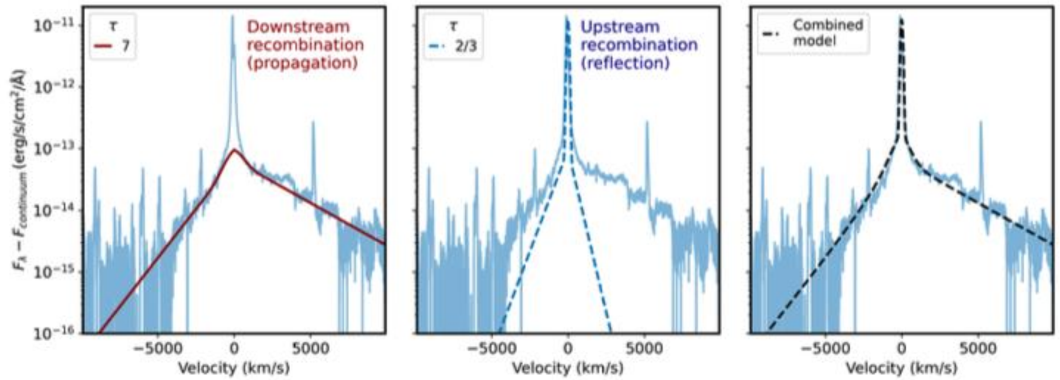


Fig.6. V1309 Sco H α line and **the two distinct scattering components** proposed in this interpretation

4.3. Luminosity from shock energetics

$$L_{\rm shock} \sim 2\pi R_{\rm sh}^2 \rho_{\rm CSM} v_{\rm rel}^3 \sim 10^{39}\,\frac{\rm erg}{\rm s}\left(\frac{\rho_{\rm CSM}}{10^{-12}\ {\rm erg/s}}\right)\left(\frac{v_{\rm sh}}{300\ {\rm km/s}}\right)^5\left(\frac{t}{30\ {\rm days}}\right)^2$$

→ the shock power is sufficient to produce the entire luminosity of LRNe.

$$L_{\rm H,upstream} \propto L_{\rm shock} \propto R_{\rm sh}^2 \rho_{\rm CSM} v_{\rm sh}^3$$
$$L_{\rm H,downstream} \propto R_{\rm sh}^2 \rho_{\rm CSM} v_{\rm sh}$$
$$L_{\rm H,upstream} \propto v_{\rm sh}^2 L_{\rm H,downstream}$$

→ the upstream-powered narrow component is therefore expected to fade faster than the downstream-powered broad component

→ The narrow and broad components are distinguished not only by velocity **but also by their temporal evolution. (Fig.8.)**

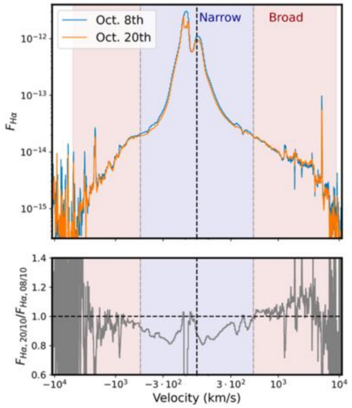


Fig.8. temporal Hα profile

5. Density from recombination line ratios

- A notable prediction of the proposed interpretation of LRNe is that collisions with a surrounding **low-density medium are sufficient to provide the observed luminosities**. (in Section 4)
- They test predicted low densities against $\rho_{\rm CSM}$ from recombination line ratios

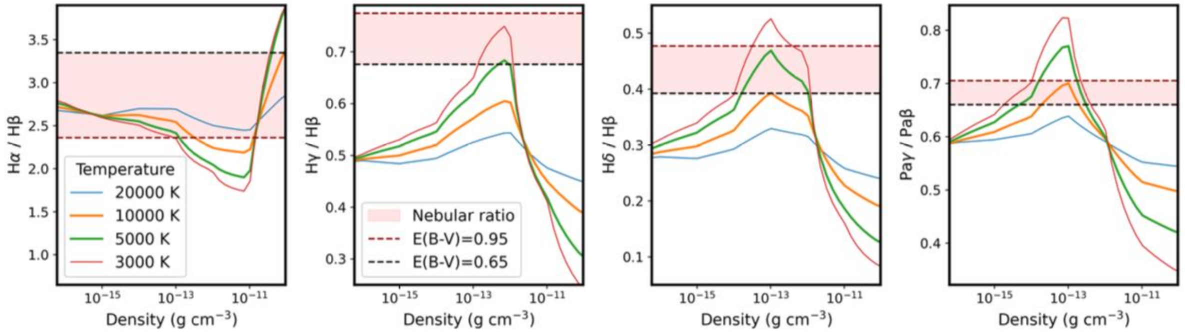


Fig. 9. Selected recombination line ratios from PyNeb calculations

→ $\rho_{\rm CSM} \sim 10^{-13} - 10^{-12}\ {\rm g/cm^3}, {\rm T} \sim 5000 - 10000\ {\rm K}$ for V1309 Sco , which are consistent with predicted shock interpretations

- As for bright LRNe, line ratios are deviated from case B recombination (H β /H α ≈0.3 − 0.4) and they have denser $\rho_{\rm CSM} \sim 10^{-11}\ {\rm g/cm^3}$ than non-deviated LRNe like V1309Sco

6. Discussion and Summary

- LRNe post-plateau phase
  - M type red-continuum
  - Recombination + free-bound emission

→ Two components are illuminated by a common shock surface because two fade coherently.

- Two electron-scattering components in H β and H α
  - narrow (~100 km/s) lines from slow CSM
  - Broad (>1000 km/s) lines from multiple scattered downstream photons
- Shock-powered model can explain the overall LRNe luminosity and their diversity of LNRe can be explained by $\rho_{\rm CSM}$.

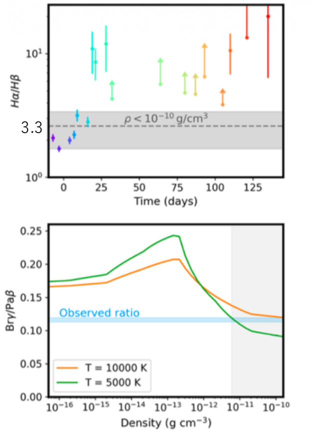


Fig.10. (top) the Balmer decrement as a function of time for AT2021blu and (bottom) the ratio of NIR hydrogen lines