MODELING THE 2006 NOVA OUTBURST OF RS OPHIUCHI: COLLIMATED OUTFLOWS AND JET-LIKE EJECTIONS

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Outline

- Scientific background
- The Chandra/HETG observations of the 2006 nova outburst
- 3D hydrodynamic model of the nova outburst
- Results and comparison with the observations
- Summary and conclusions

The symbiotic star RS Ophiuchi

Symbiotic recurrent nova

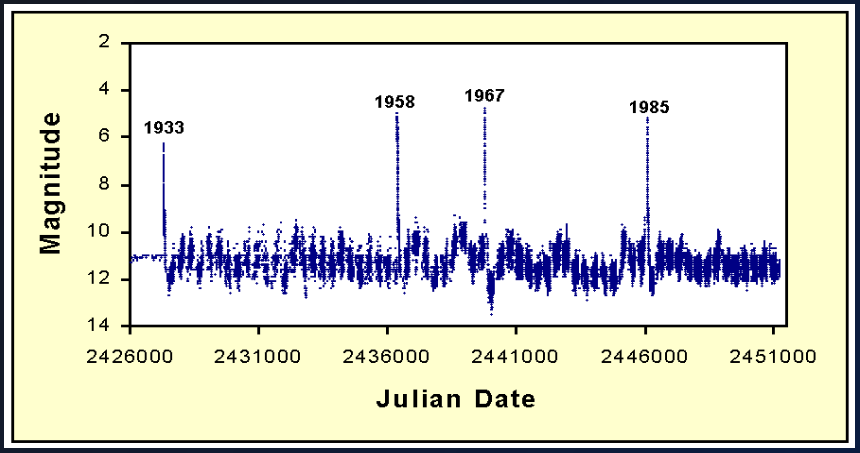
- Latest outburst: February 2006 (Narumi et al. 2006)
- Previous outbursts: 1898, 1933, 1958, 1967, 1985 (Rosino 1987)

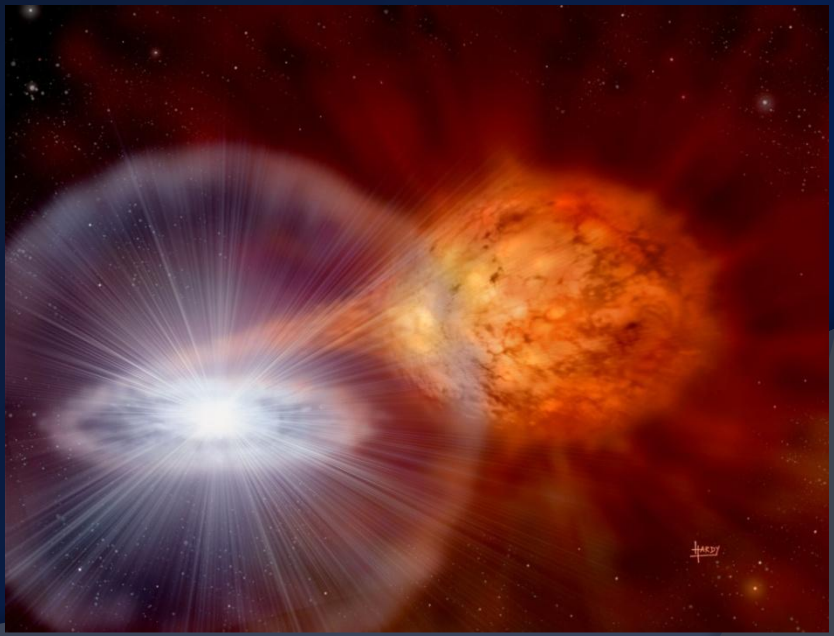
Binary system, comprising

- a red giant star that does not fill its Roche lobe
- a white dwarf of mass near the Chandrasekhar limit

See Sokoloski's talk

Are recurrent novae progenitors of SNe Ia?

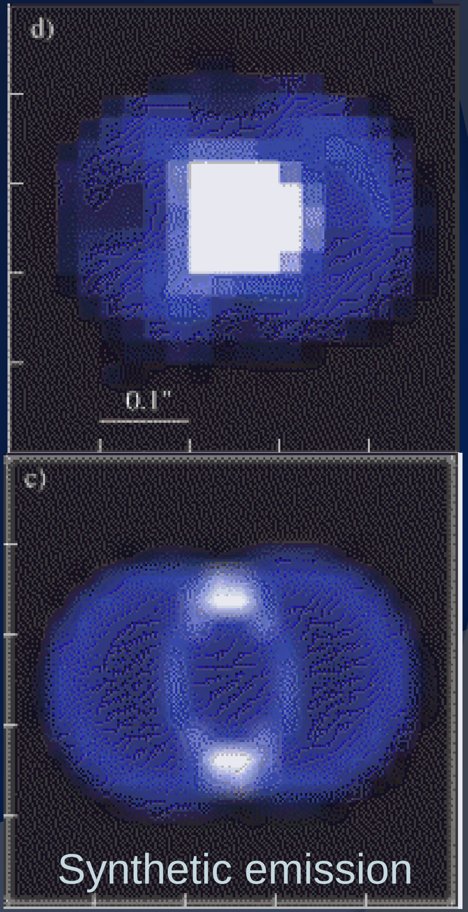




The 2006 Nova Outburst

- During the 2006 outburst an intensive international observing campaign was organized since early phases of evolution
- Observations range from radio to X-ray wavelengths

HST ACS/HRC
(Bode et al. 2007)



X-ray Band

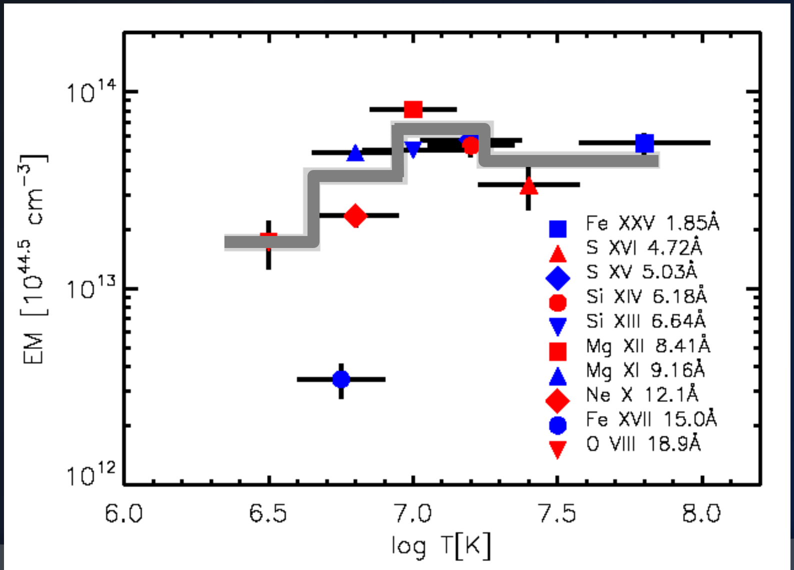
- Hot gas
  - ~ 10 keV few days after eruption
  - ~ 4 keV 19 days after optical maximum
- Shock-heated outer atmosphere of the red giant

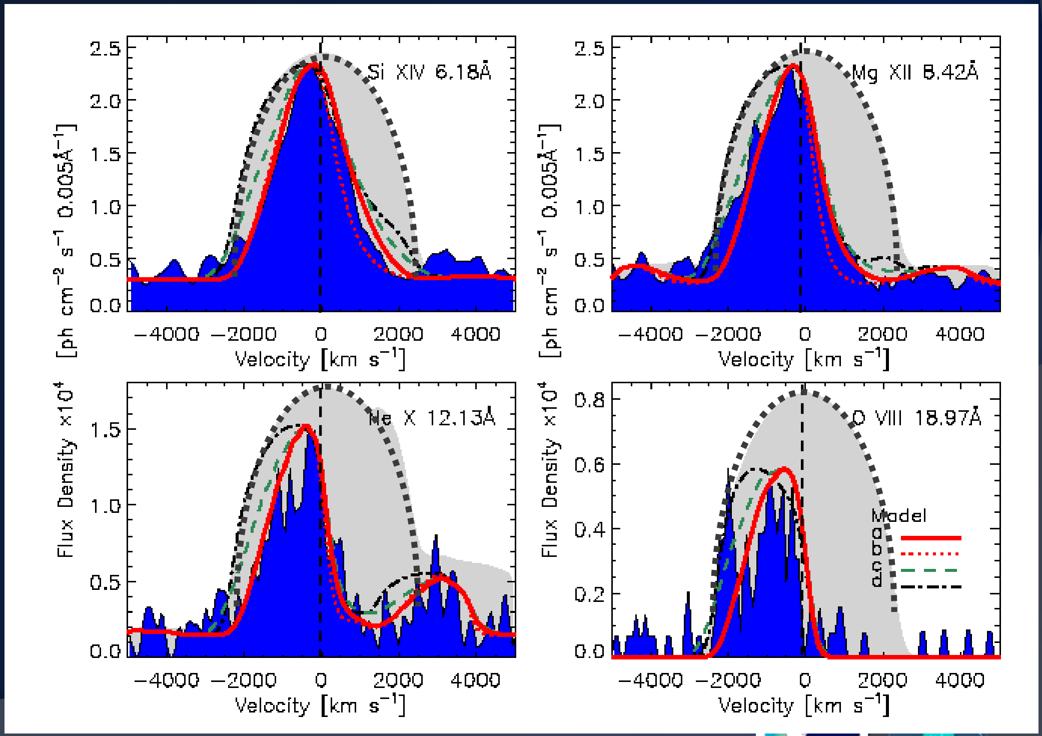
Sokoloski et al. 2006 (nature); Bode et al. 2006; Ness et al. 2007; Nelson et al. 2008; Drake et al. 2008

The Chandra/HETG Observations

Observations at day 13.9 (Drake et al. 2008)

- Rich spectrum of emission lines
  - Emitting plasma with 3 MK < T < 60 MK
- Lines too strongly peaked to be explained by a spherically symmetric shock
  - Collimation mechanism of X-ray emitting plasma perpendicularly to LoS
- Lines asymmetric and slightly blue-shifted





The Chandra/HETG Observations

Open Questions:

1) Where does the X-ray emission originate during the early phase of evolution?
2) How does the collimation mechanism of X-ray emitting plasma work?
3) Which is the mechanism responsible of line asymmetries and blue-shift?

The Model

AIMS
Investigate the origin of X-ray emission and of observed asymmetries and broadening of emission lines

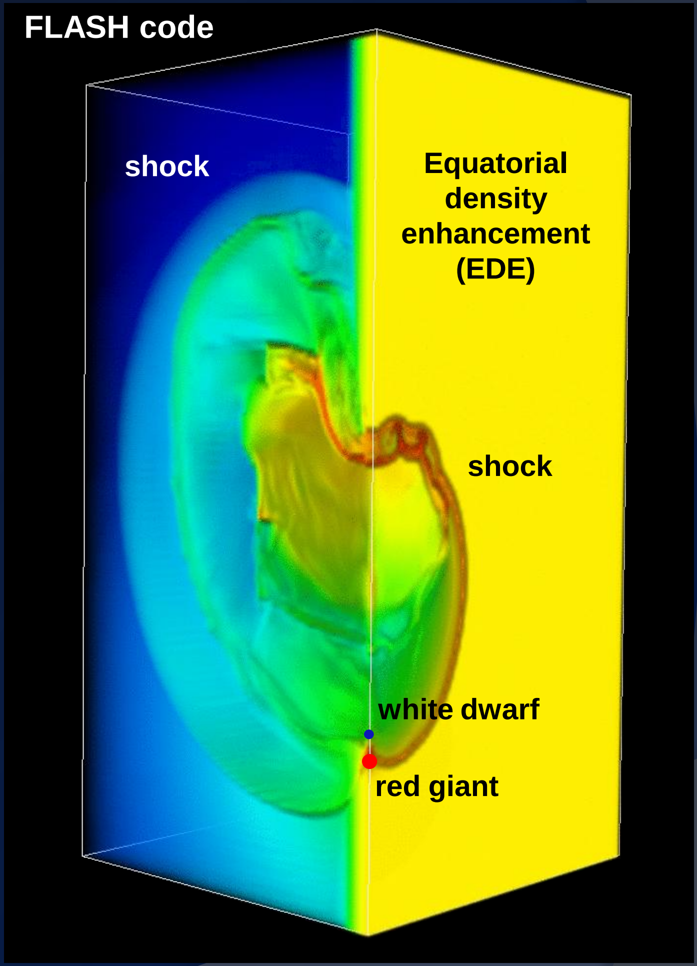
- Thermal conduction (+ heat flux saturation)
- Radiative cooling

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0\,, \qquad \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \rho \mathbf{v}\mathbf{v} + \nabla P = 0$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{v} = -\nabla \cdot q - n_e n_H \Lambda(T)$$

$$E = \epsilon + \frac{1}{2}|\mathbf{v}|^2\,, \quad P = (\gamma - 1)\rho\epsilon\,, \quad q = \left(\frac{1}{q_{\rm spi}} + \frac{1}{q_{\rm sat}}\right)^{-1}\,,$$

$$q_{\rm spi} = -\delta_{\rm T}\epsilon 20 \left(\frac{2}{\pi}\right)^{3/2} \frac{(k_b T)^{5/2} k_b}{m_e^{1/2} e^4 Z \ln(\Lambda)} \nabla T \qquad q_{\rm sat} = -{\rm sign}\,(\nabla T)\; 5\phi\rho c_s^3$$



Orlando et al. 2008

Hydrodynamic Evolution

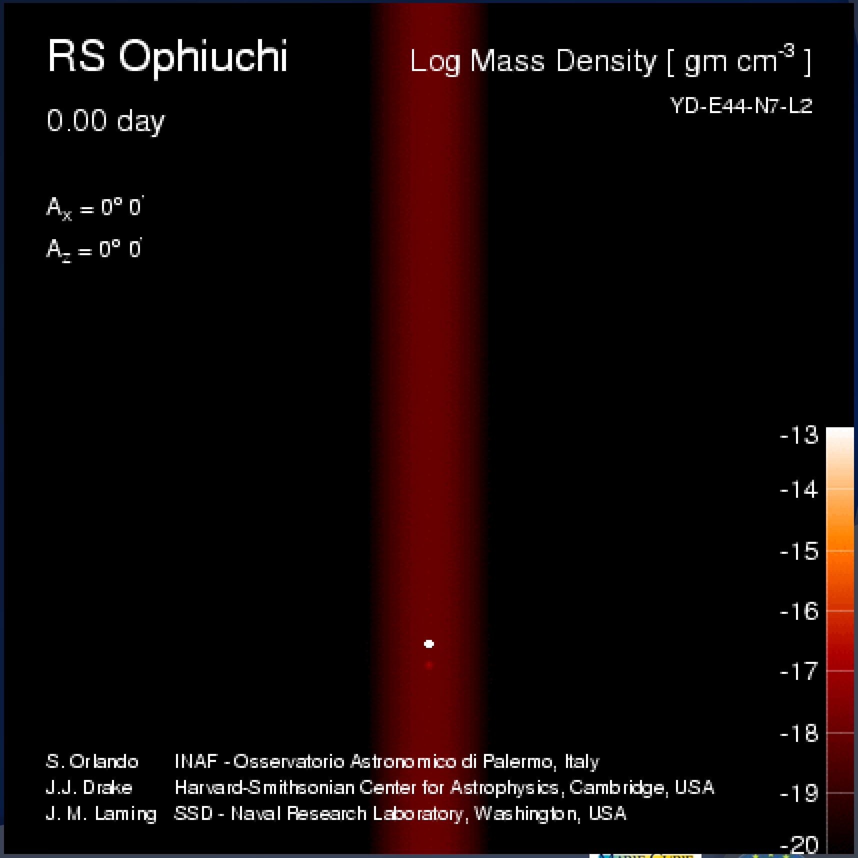
Radiative shock propagating through an inhomogeneous medium:

- Fast expansion of the shock with T ~ 10-80 MK
- development of dense and cold regions dominated by radiative cooling

Explored models with or without EDE

In models with EDE:

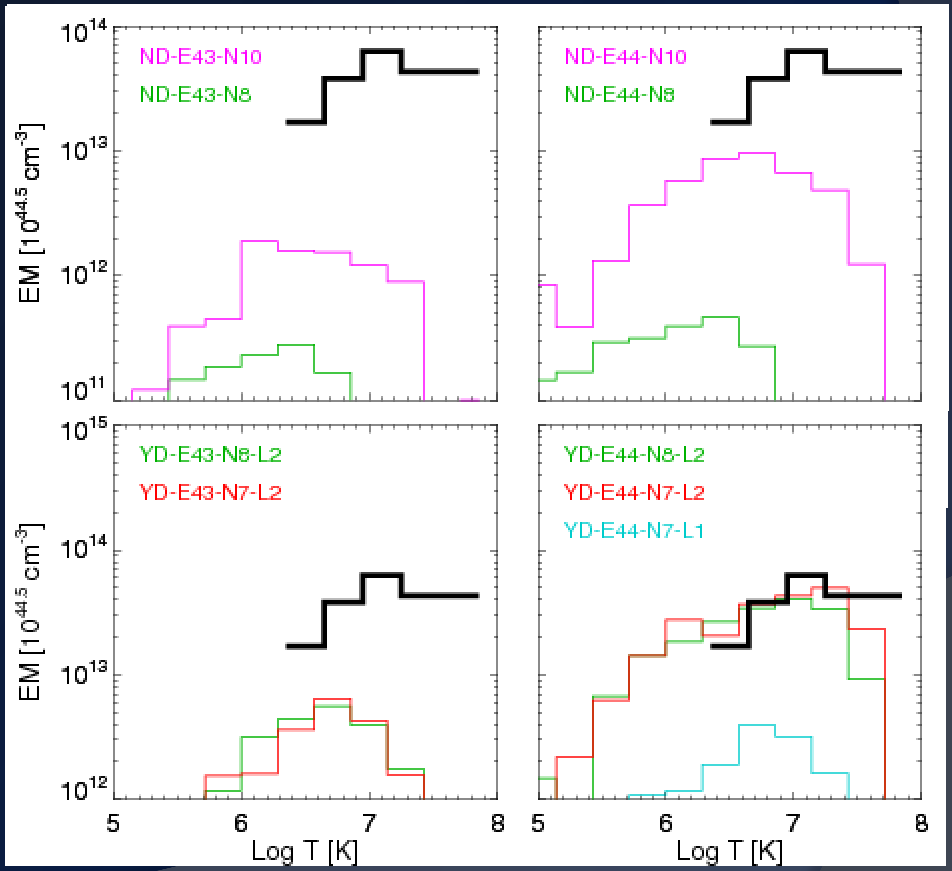
- Aspherical shock morphology
- EDE determines the shock collimation perpend. to the plain of the orbit
- Bipolar shock morphology distorted (by the off-set red giant wind) and converging on the side away from the red giant



Emission Measure vs. Temperature

Models without EDE:

- EM(T) characterized by a bump at T between 1 and 5 MK
- Even with E = 10^{44} erg and red giant wind with largest density, the model fails in reproducing the observed EM(T)



Models with EDE:

- EM(T) characterized by a bump at T ~ 10 MK
- EM of the bump depends on the initial energy of the outburst
- Observed EM(T) distribution well reproduced with E = 10^{44} erg and $M_{ej} = 10^{-6}$ M_{sun}

X-ray Emission

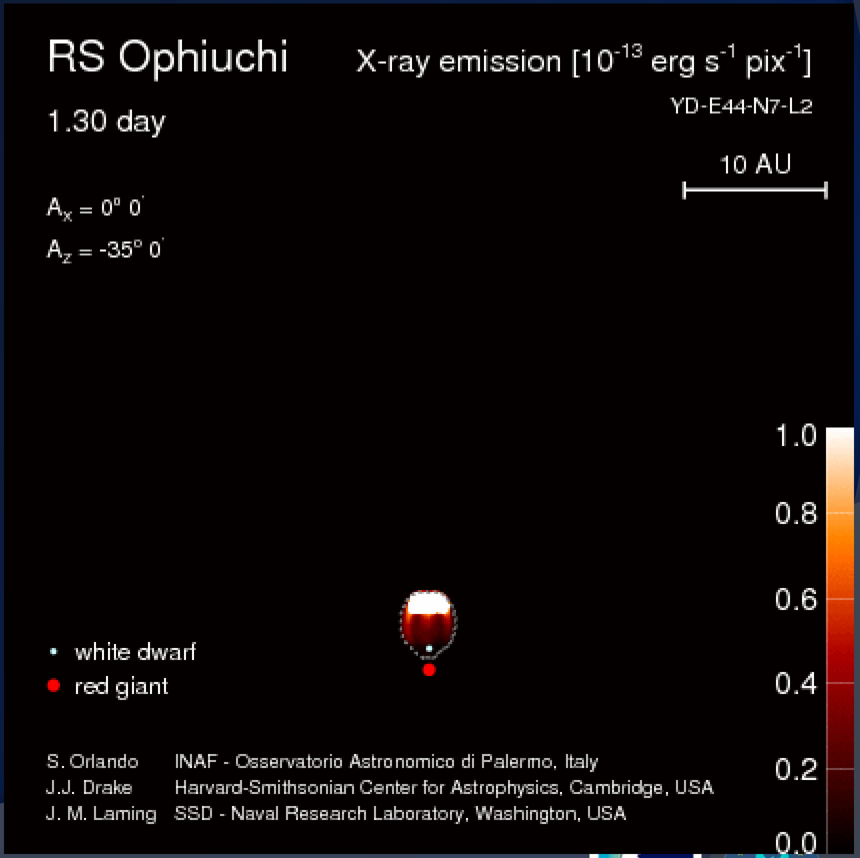
Synthesis of X-ray emission in the [0.6, 12.4] keV band

- Thermal broadening of emission lines
- Doppler shift of lines due to velocity along the LoS
- Absorption due to shocked CSM and ejecta

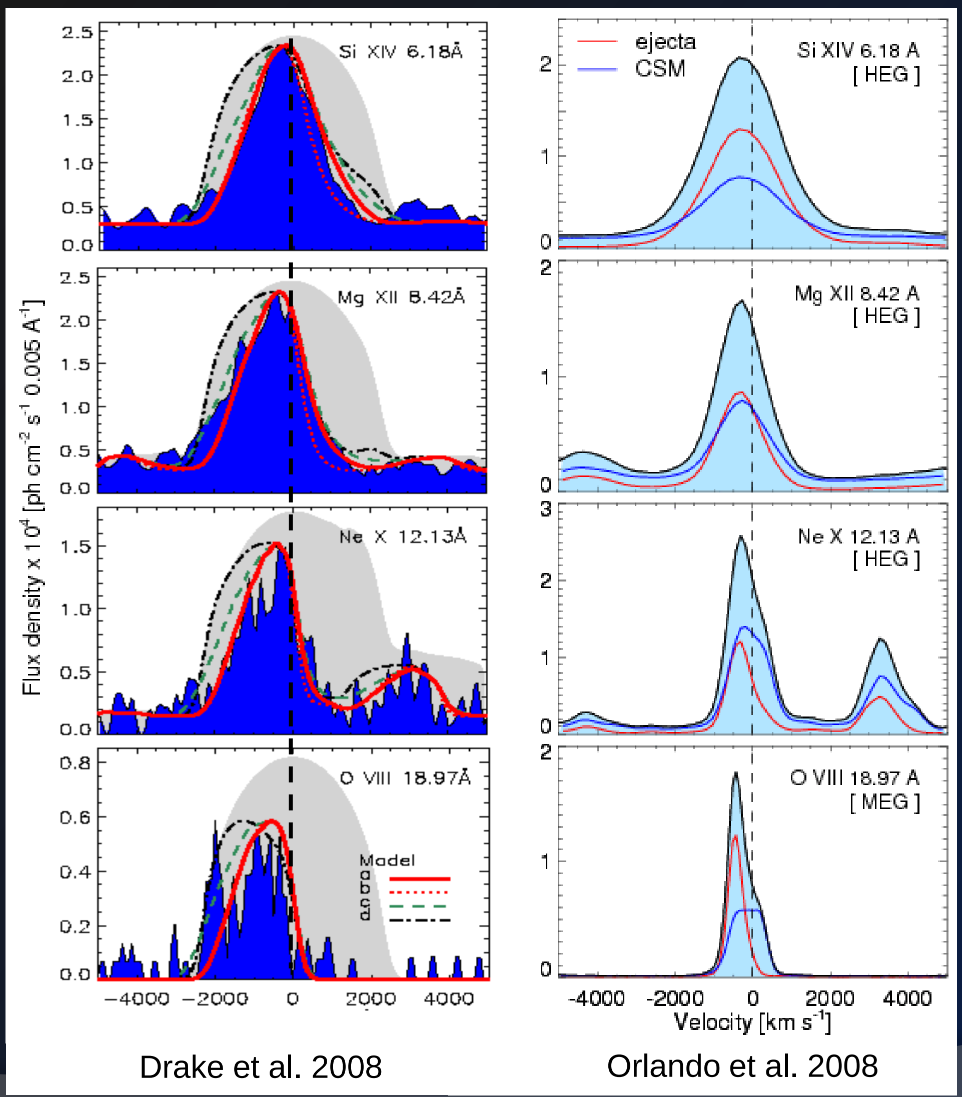
Plane of the orbit inclined by 35º to the LoS

Best-fit model with EDE:

- Most of the X-ray emission originates from an irregular jet-like structure with a size of ~10 AU
- The X-ray source is due to interaction between the blast wave and the EDE and propagates perpendicularly to the LoS



Line Profile Analysis



Best-fit model with EDE:

- The synthetic line profiles are more peaked than expected for a spherically symmetric shock
- Line profiles asymmetric and slightly blue-shifted; Asymmetries due to X-ray absorption of red-shifted emission by ejecta material
- Shocked CSM and shocked ejecta contribute to observed X-ray emission

Summary

- Simulated nova remnant highly aspherical;
  - blast wave efficiently collimated by the inhomogeneous CSM
- The model reproduces the observed X-ray emission in a natural way if the CSM is characterized by an equatorial density enhancement
- Most of the early X-ray emission originates from a small region localized at the interaction front between the blast wave and the EDE
- The model predicts asymmetric and blue-shifted line profiles remarkably similar to those observed
  - Asymmetries due to substantial X-ray absorption of red-shifted emission by ejecta material