Magnetar Wind-Driven Shock Breakout Emission

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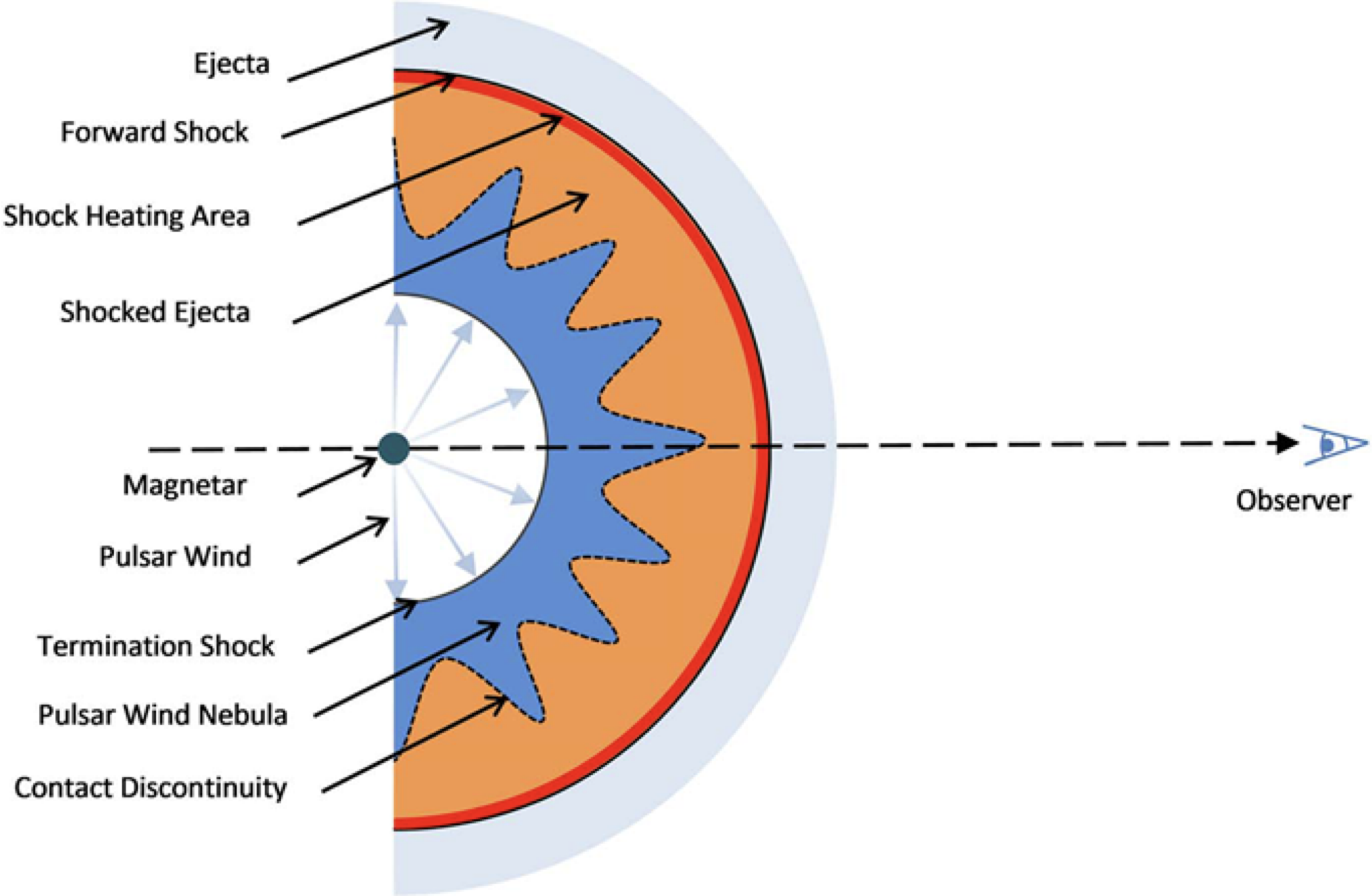

Ejecta
Forward Shock
Shock Heating Area
Shocked Ejecta
Magnetar
Pulsar Wind
Termination Shock
Pulsar Wind Nebula
Contact Discontinuity
Observer

Heating zone

- $\frac{dU_{heating}}{dt} = H_{sh} - P_{heating}\frac{d\left(V_{heating}\right)}{dt} - L_{SBO}$
- $H_{sh} = \frac{1}{2}\left[v_{sh} - v_{ej}(r_{sh}, t)\right]^2 \frac{dM}{dt}$
- $\frac{L_{SBO}}{4\pi r_{sh}^2} = c\frac{\partial P_{heating}}{\partial \tau}, P_{heating} = \frac{U_{heating}}{3V_{heating}}$
- $V_{heating} = \epsilon V_{\mathrm{sh}}$

Residual part

- $\frac{dU_{res}}{dt} = L_{inj} - P\frac{dV_{sh}}{dt} - L_{SN/MN},$
- $L_{inj} = L_{Ni\&Co} + L_{sd}$
- $\frac{L_{SN}}{4\pi r_{sh}^2} = c\frac{\partial P_{res}}{\partial \tau}$
- $V_{res} \approx V_{sh} = \frac{4\pi}{3} r_{sh}^3$

Energy injection

- $L_{sd} = L_{sd,0}\left(1 + \frac{t}{\tau_{sd}}\right)^{-2}$
- $L_{sd,0} = \frac{B^2 R_{ns}^6 \Omega_0^4 \sin^2 \chi}{6c^3}$
- $\tau_{sd} = \frac{6 I_{ns} c^3}{B^2 R_{ns}^6 \Omega_0^2}$

- $L_{NiCo} = L_{Ni} + L_{Co}$
- $\frac{dN_{ni}}{dt} = \lambda_{Ni} N_{Ni}$
- $\frac{dN_{co}}{dt} = \lambda_{Ni} N_{Ni} - \lambda_{Co} N_{co}$
- $N_{Ni} = N_0 e^{-\lambda_{Ni} t}$
- $N_{co} = \frac{\lambda_{Ni} N_0 (e^{-\lambda_{Ni} t} - e^{-\lambda_{Co} t})}{\lambda_{co} - \lambda_{Ni}}$
- $L = \lambda N(t) Q$

Shock Dynamics

- Total energy of shocked region:
- $E = \frac{1}{2} M v_{sh}^2 + U$ (1)
- Total energy variation:
- $dE = \left(L_{inj} - L_{SBO} - L_{SN/MN}\right) dt + \frac{1}{2} v_{ej}^2 (r_{sh}, t) dM$ (2)
- d(1)=(2)$\Longrightarrow \frac{dv_{sh}}{dt} = \frac{1}{M v_{sh}} \left[\left(L_{inj} - L_{SBO} - L_{SN}\right) - \frac{1}{2}\left(v_{sh}^2 - v_{ej}^2\right) \frac{dM}{dt} - \frac{dU}{dt} \right]$

Density & Velocity Distribution

- (Nagakura et al. 2014)

$$\rho_{\rm ej}(r,\,t) = \frac{(\delta-3)M_{\rm ej}}{4\pi r_{\rm max}^3}\left[\left(\frac{r_{\rm min}}{r_{\rm max}}\right)^{3-\delta} - 1\right]^{-1}\left(\frac{r}{r_{\rm max}}\right)^{-\delta}, \qquad (1)$$

and

$$v_{\rm ej}(r,\,t) = v_{\rm max}\frac{r}{r_{\rm max}(t)}, \quad \text{for} \quad r \leqslant r_{\rm max}(t), \qquad (2)$$

- δ: 3∼4

Result

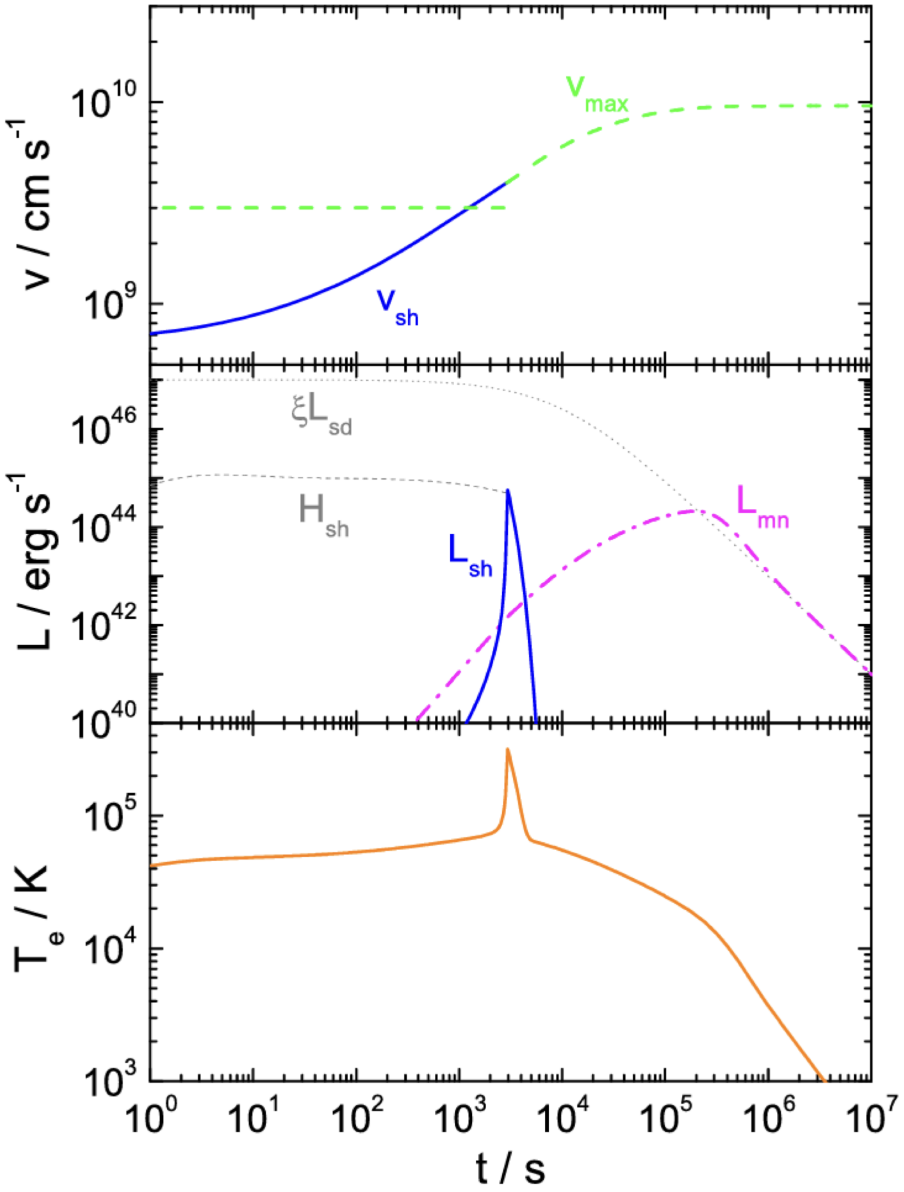


Figure 1. Evolutions of velocities (top), bolometric luminosities (middle), and emission temperature (bottom). In the middle panel, the injected spin-down luminosity ($\xi L_{\rm sd}$) and the shock heating rate ($H_{\rm sh}$) are also presented for reference. The model parameters are taken as $\xi L_{\rm sd,i} = 10^{47}$ erg s^{-1}, $t_{\rm md} = 10^4$ s, $\Delta t = 2$ s, $M_{\rm ej} = 0.01 M_\odot$, $v_{\rm max} = 0.1c$, $\delta = 3.5$, and $\kappa = 10$ cm^2 g^{-1}.

Blackbody Spectrum

- $T_{eff} = \left(\frac{L_{SBO}+L_{SN}}{4\pi r_{max}^2 \sigma}\right)^{1/4}$
- $\nu L_\nu = \frac{8\pi^2 r_{max}^2}{h^3 c^2} \frac{(h\nu)^4}{\exp\left(\frac{h\nu}{kT_{eff}}\right)-1}$

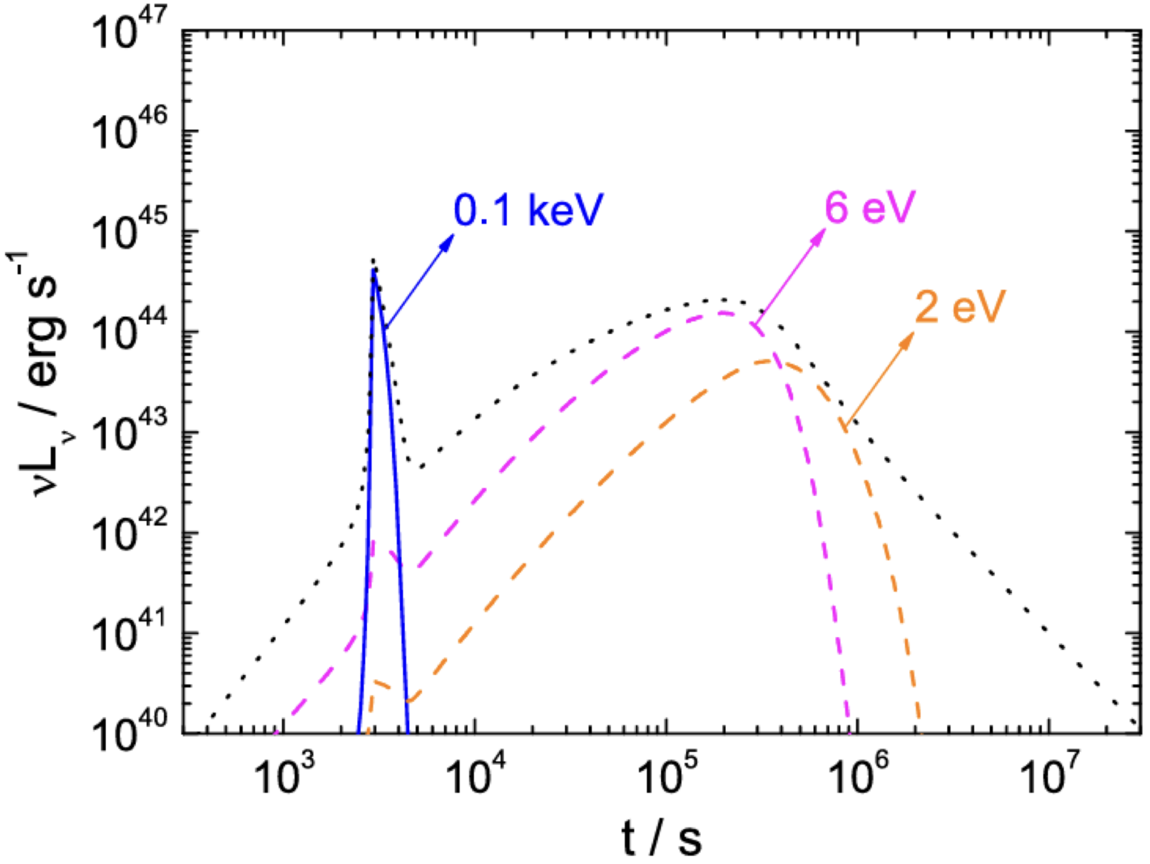
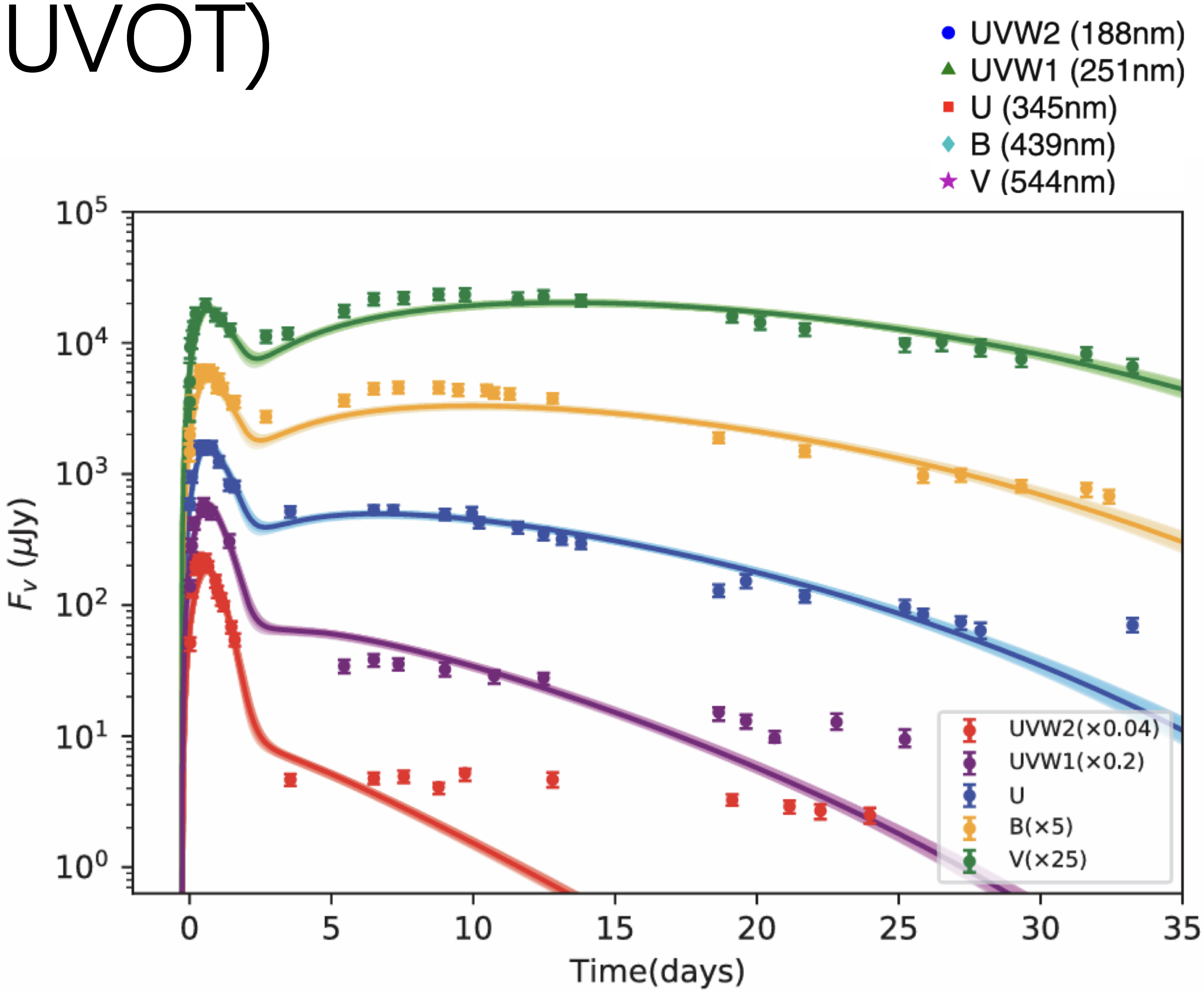


Figure 2. Three chromatic light curves for photon energies of $h\nu = 0.1$ keV (soft X-ray; solid), 6 eV (UV; dashed), and 2 eV (optical; dash–dotted), respectively, where the bolometric light curve (dotted) is presented as a reference.

SN 2006aj (Swift UVOT)

- (Density distribution: Liu et al. 2018)



Conclusion

- Magnetar central engine could explain the light-curves of double-peak supernovae/mergernovae.
- The discovery of magnetar-powered transients could substantially modify and expand our conventional understandings of dynamics, radiation mechanism, and properties of newborn magnetars.

Thank you