INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

FAPESP

γ-ray emission from RS OPh

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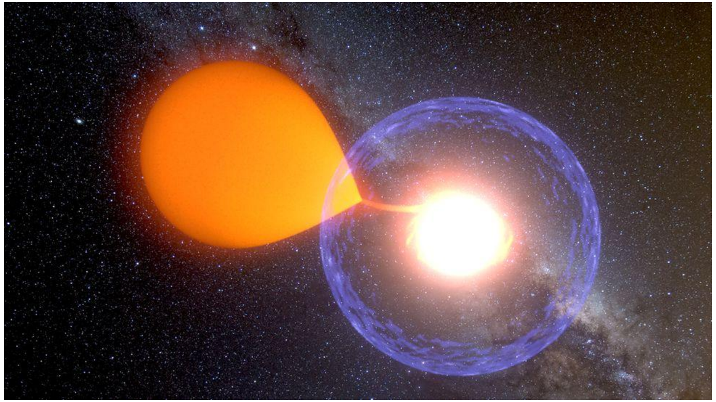
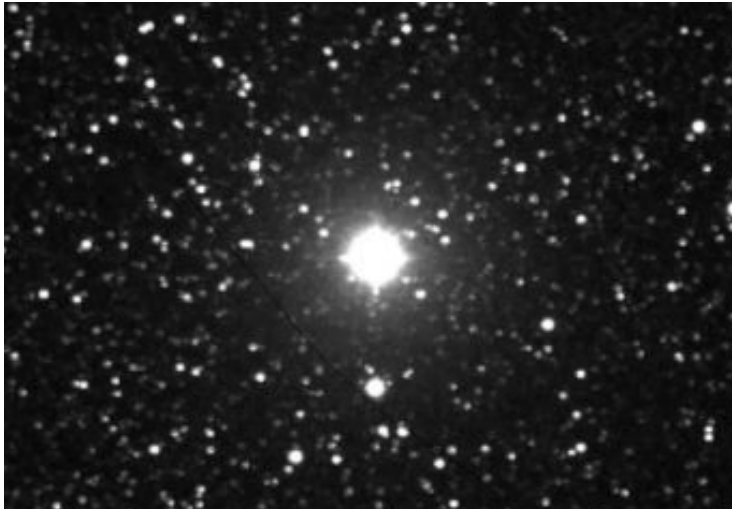
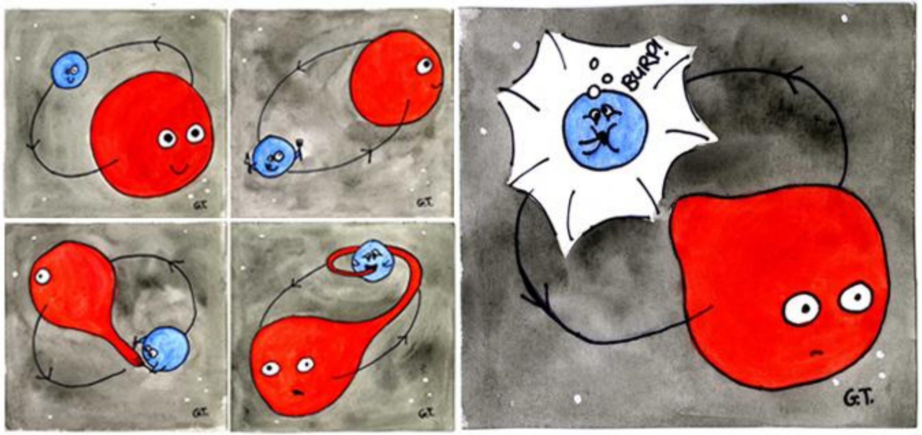
Novae

- Among the brightest transients in the sky
- Binary system: WD plus non-degenerate stellar companion
- Accreted layer accumulates on the WD surface
- Density and temperature at its base rise
- Layer can undergo unstable (“runaway”) nuclear burning once it reaches a critical mass
- After the thermonuclear runaway, a shell of gas is expelled



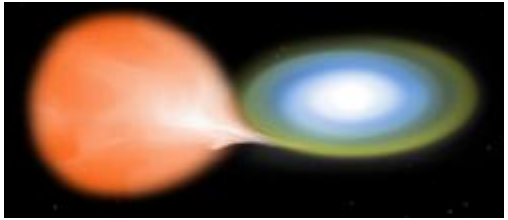


Classification



Cataclysmic Variable: mass-transferring binary system: WD + main sequence secondary overflowing its Roche lobe.

Classical Nova: Thermonuclear eruption (main sequence or moderately evolved)

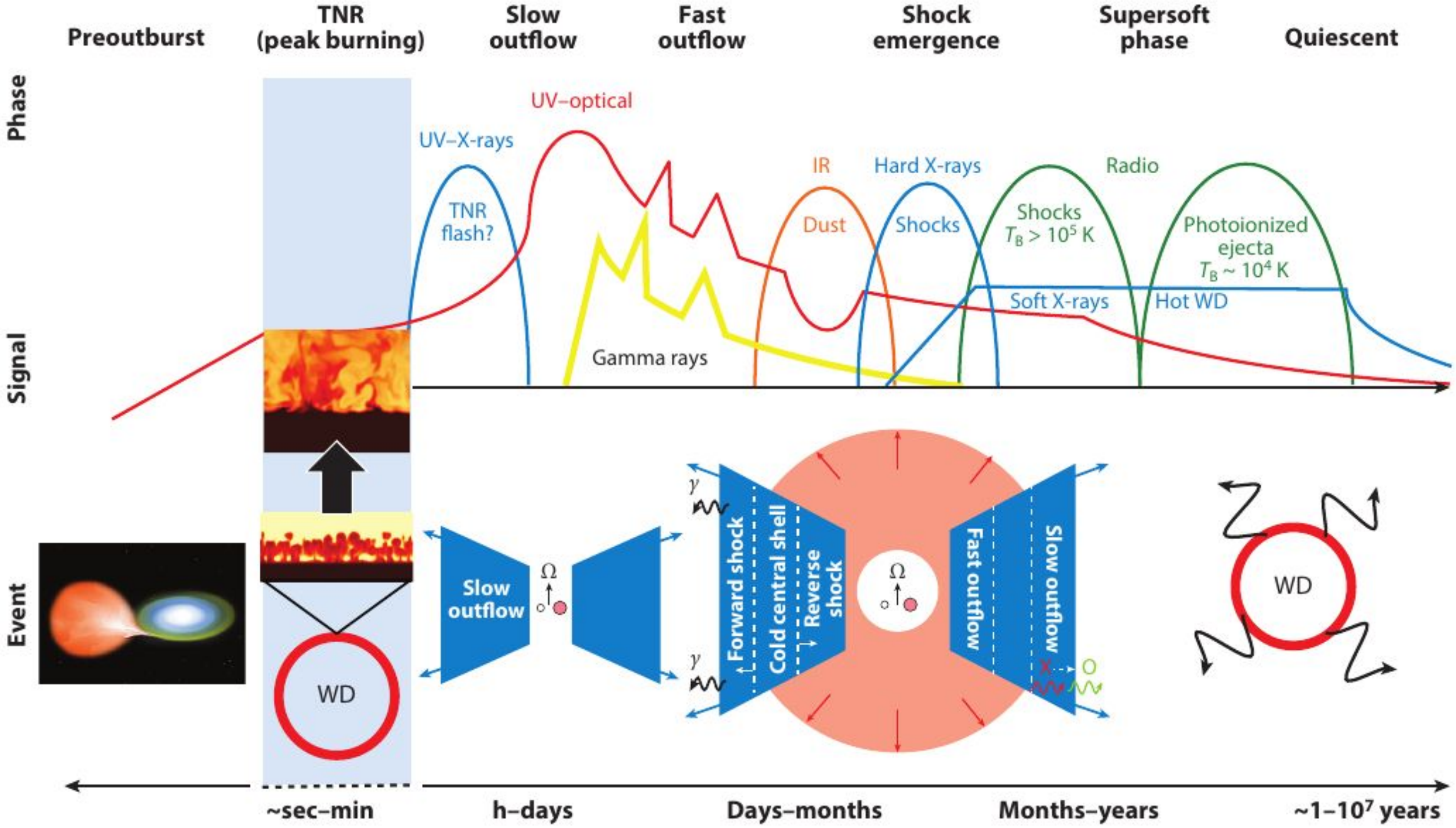


Embedded Nova: WD accretes from giant companion usually via wind accretion.

Recurrent Nova: A nova observed to undergo more than one eruption

Evolves slowly: **Symbiotic Novae**

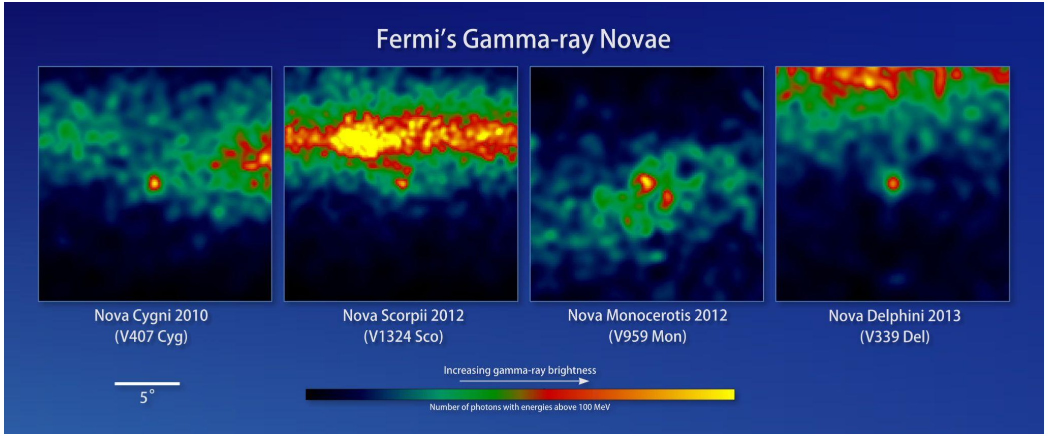
Light curve

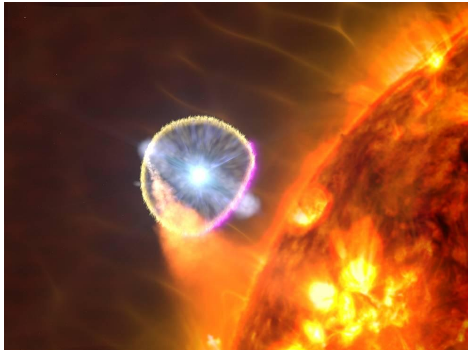


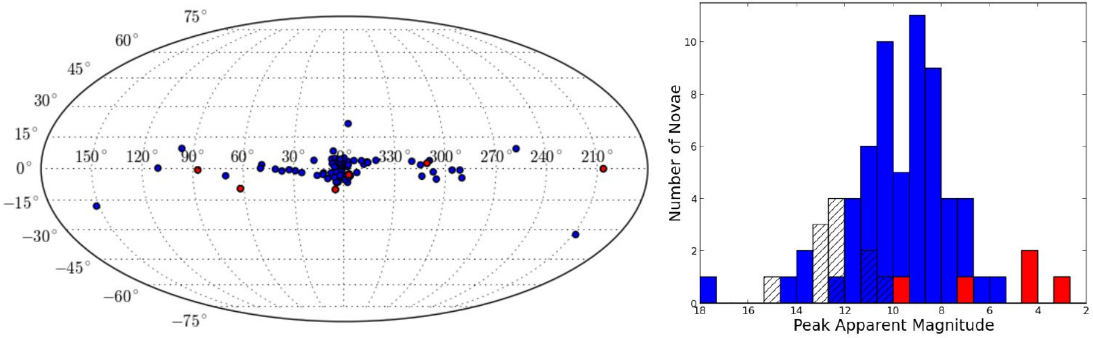
Chomiuk et al. 2020

Gamma emission!

- Unexpected new class of gamma-ray source
- Fermi's LAT first nova detection, V407 Cygni, March 2010
- 17 detected + 5 candidates



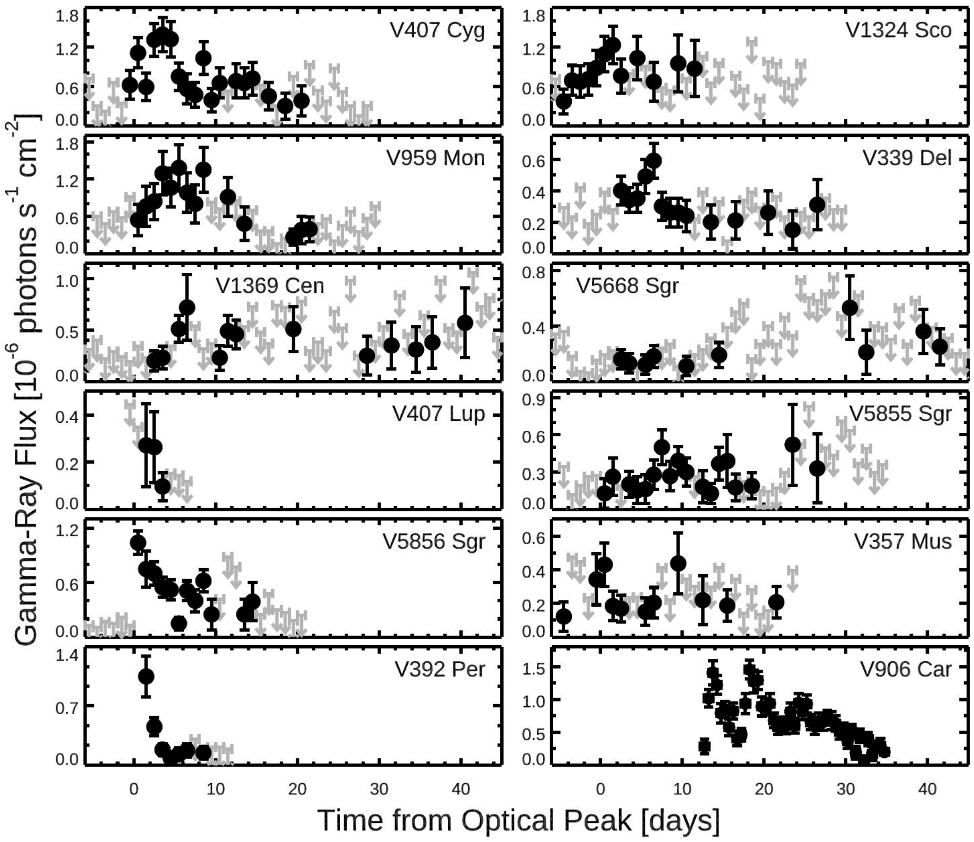




Franckowiak et al. 2018

Gamma emission properties

- E ~ 0.1 - 1 GeV
- L_γ ~ 10^34 - 10^36 erg / s
- E_γ ~ 10^41 - 10^42 erg
- Nearby novae 2 - 5 kpc
- Detected for a few weeks



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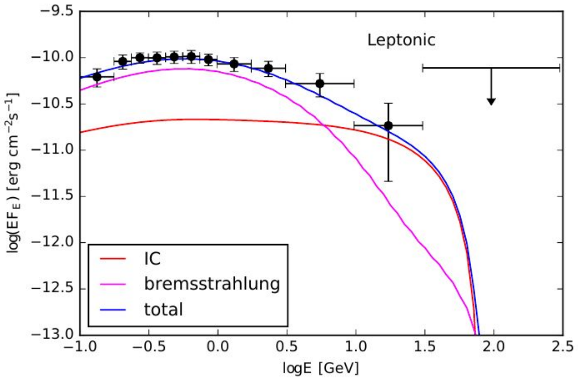
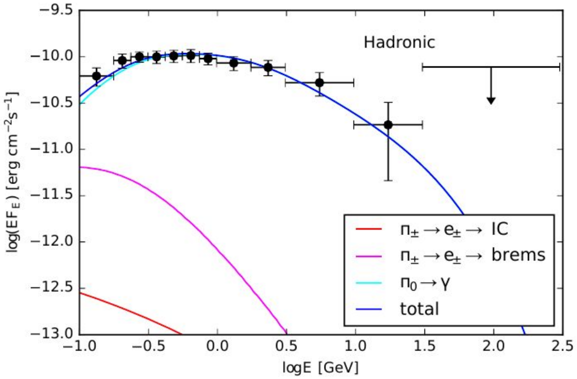
Leptonic:
e + n , e + γopt

Hadronic:
p+p





Chomiuk et al. 2020

Shocks

Cs ~ 10 km /s

Ejecta velocity 100 -1000 km /s

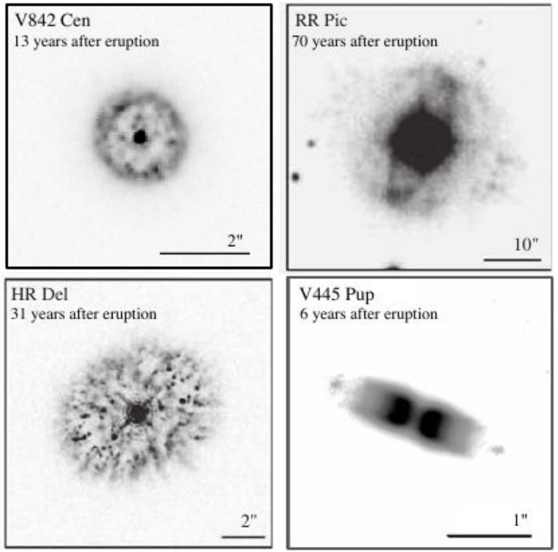
Observational signatures

Shocks in embedded novae:

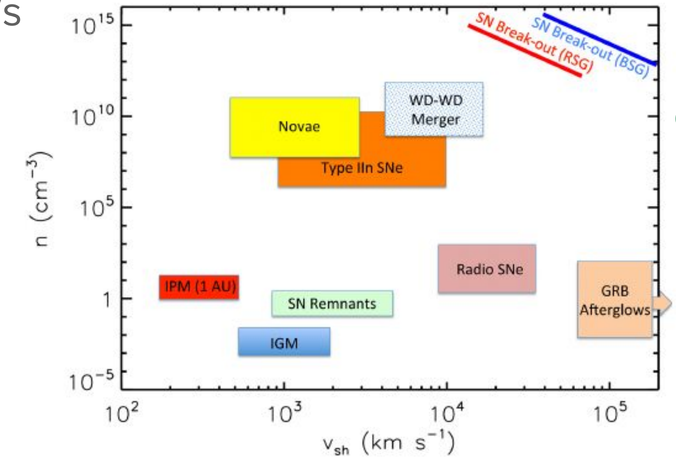
ejecta + companion wind

Classical novae:

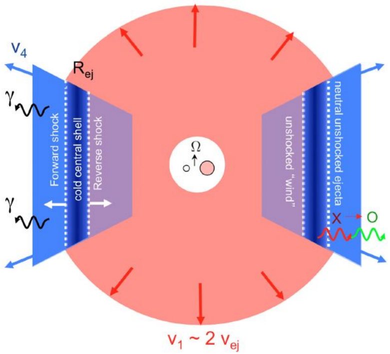
ejecta + previously ejected material



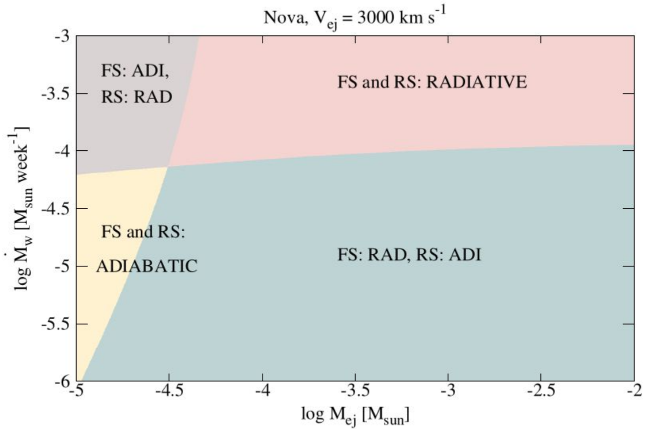
Woudt et al. 2009



Metzger et al. 2016



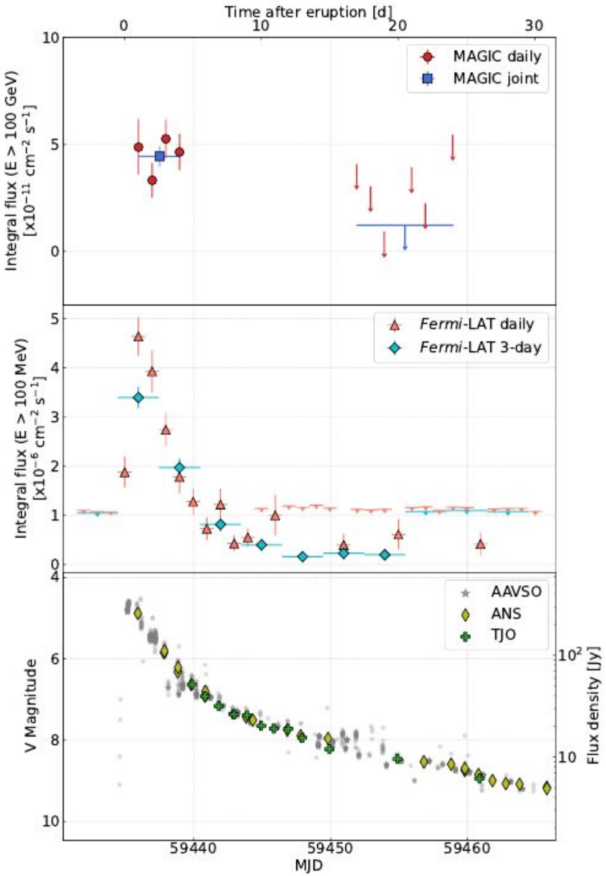
Metzger et al. 2014



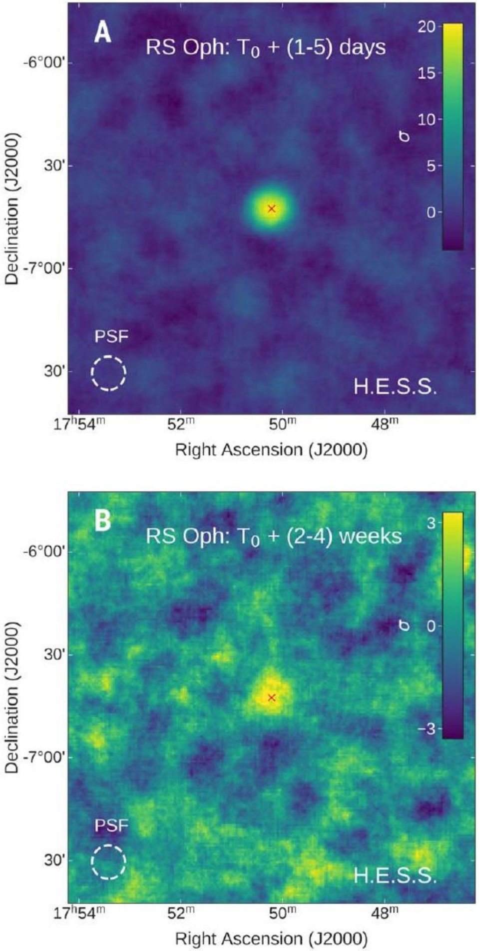
del Valle et. al 2022

Detection at VHE! by MAGIC and H.E.S.S.

- 8 of August outburst
- 9 of August both
- 5 days, 4 days
- Decay 1 order of magnitude
- 2 week period
- Up to 2.5 TeV



MAGIC collab. 2022

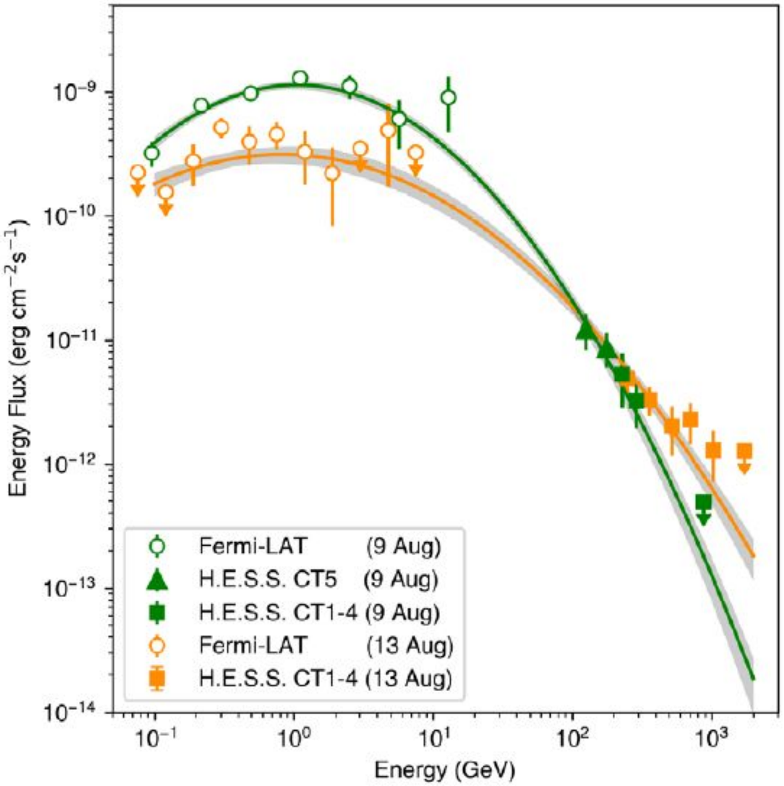


H.E.S.S collab. 2022

Detection at VHE

The observation of the August 2021 outburst of RS Oph introduces a new class of sources as VHE gamma-ray emitter: (symbiotic) novae.

MAGIC collab. 2022



H.E.S.S collab. 2022

RS Oph

Recurrent nova, outbursts every 15-20 years

WD + red giant

d ~ 1.4 kpc

Ekin ~ 10^43 erg

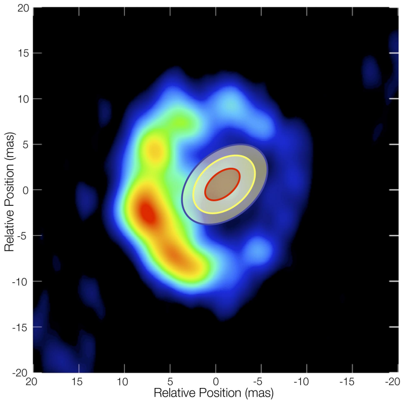
Separation of 1.5 AU

8 outburst 1898-2006

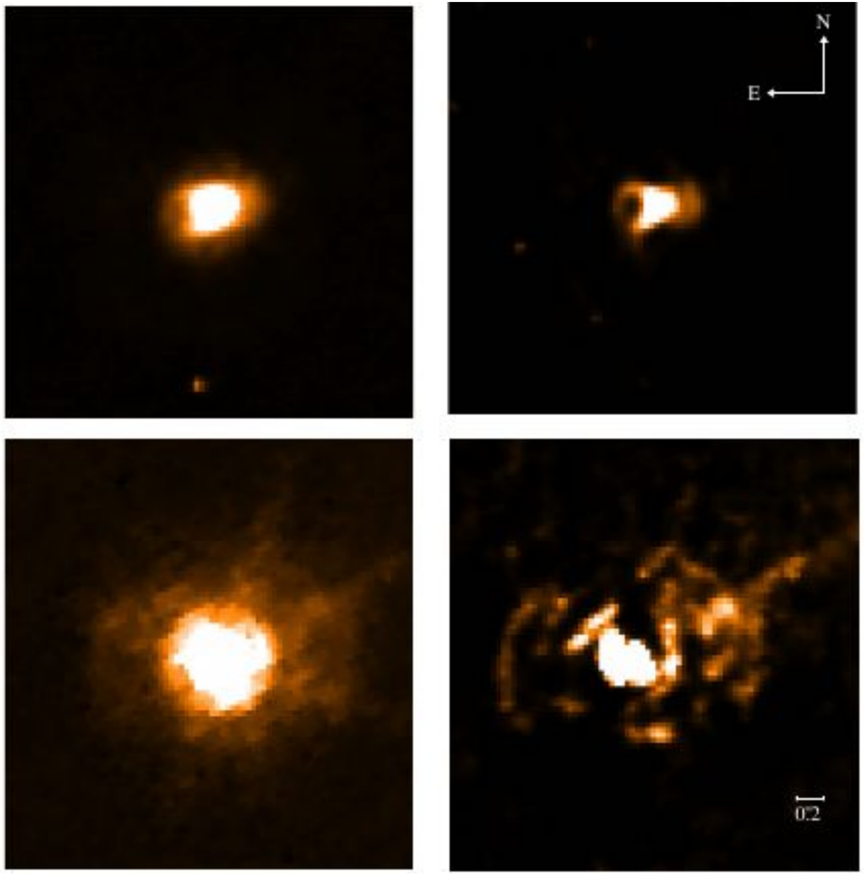
Fermi detected in 2021

Radio synchrotron

Hot X-ray emission



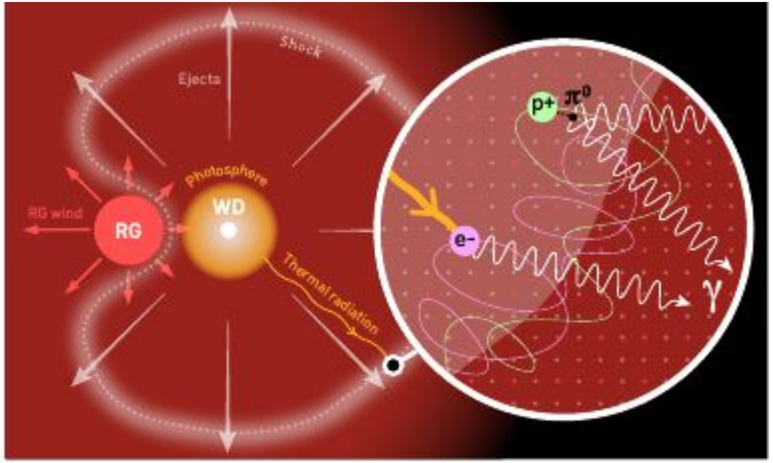
Credit: ESO



Ribeiro et al. 2006

Modelling RS Oph

The physical scenario



MAGIC collab. 2022

Ejecta moves inducing a shock in CSM

Shock velocity different regimes:

- Steady: V ~ V , for t < 10 days
- Sedov: V ~ V t^-⅓, for ~115 days
- Radiative: V ~ Vt^-1/2

e.g, Bode & Kahn 1985

Assume steady shock velocity ~ 5 days

$$\frac{\partial N_p}{\partial t} = D(E)\left[\frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2\frac{\partial N_p}{\partial R}\right) + \frac{1}{R^2 \operatorname{sen}\theta}\frac{\partial}{\partial \theta}\left(\operatorname{sen}\theta\frac{\partial N_p}{\partial \theta}\right)\right] - \frac{\partial}{\partial E}\left(P(R,\theta,E)\,N_p\right) + Q_p(R,\theta,E,t).$$

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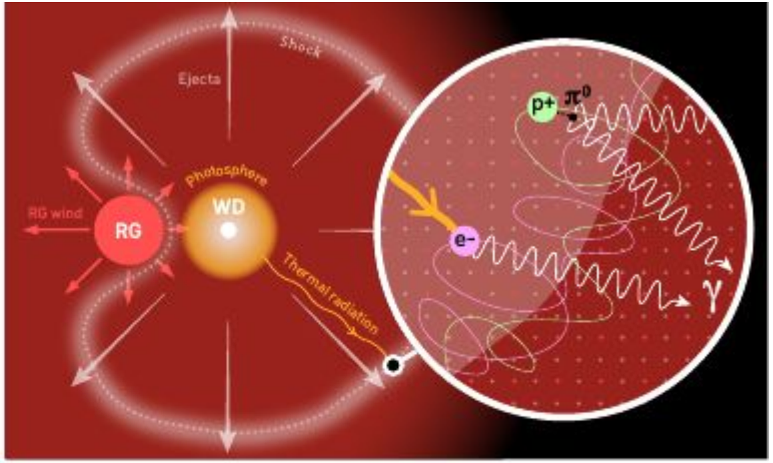
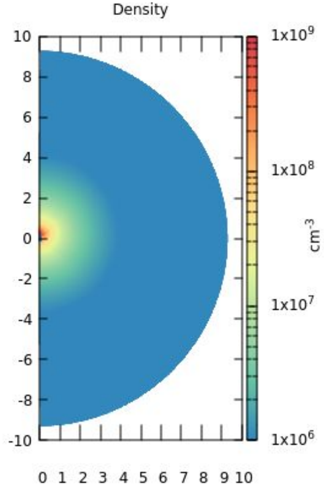


MAGIC collab. 2022

$$n_{RG} = \frac{\dot{M}_{RG}}{4\pi R_{sh}^2 v_{RG} m_p}$$

Initial density



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Calculations & parameters

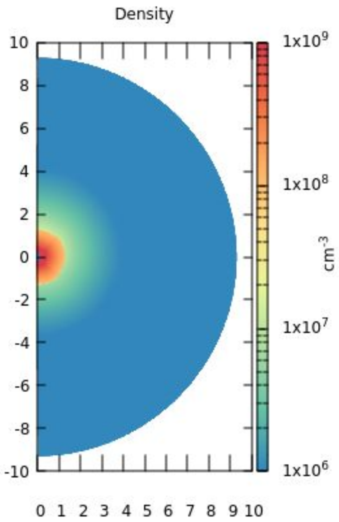
Shock velocity depends on density

ratio chi = (nej / n_RG)^0.5

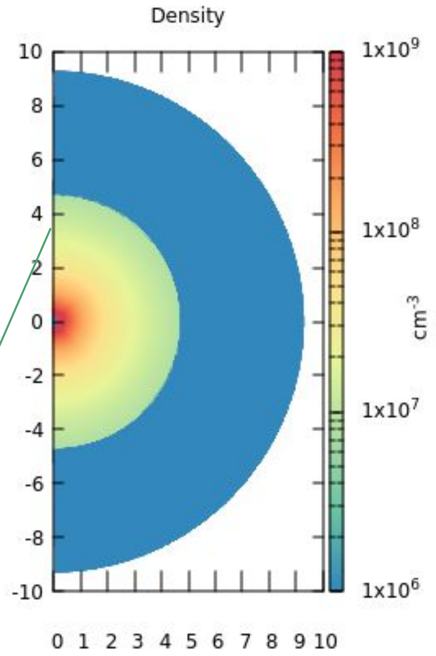
Vs = 1.33*V_ej / (1.0 + 1./chi)

$$n_{RG} = \frac{\dot{M}_{RG}}{4\pi R^2 \, v_{RG} m_p} \qquad n_{ej} = \frac{M_{ej}}{4\pi h R^3 \; m_p}$$

Vej x time



ejecta



Injection and power

Injection is made at shock position

$$\frac{dN_{\rm inj}}{dEdt} = \begin{cases} A_{e/p} E^{-\alpha_{e/p}} \exp\left[-\left(\frac{E}{E_{\max,e/p}}\right)^{\beta_{e/p}}\right] & E \geq E_{\min,e/p} \\ 0 & E < E_{\min,e/p}\,. \end{cases}$$

Shock power depends on rho(r,th) and Vs(r,th)

$$L_{\rm sh} = 2\pi R^2 \rho_1 u_{\rm sh}^3\,.$$

Particles escape due to diffusion.

Assuming:

D > Dbohm , D0 << Dgalactic

D(E) = D0 (E / 10 GeV)^0.5 cm^2 / s

Maximum energy of injected particles depends on each injection cell position:

Acceleration time (B, Vsh) (Bohm diffusion) equated to:

min{t physical integration time

or losses,

for electrons:

tsyn,

tic,

for protons:

tpp}

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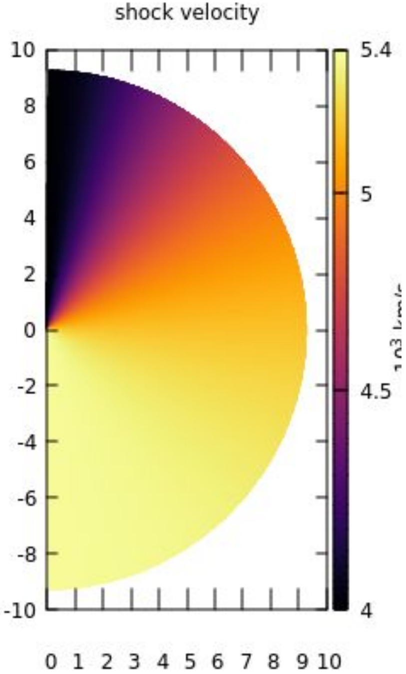
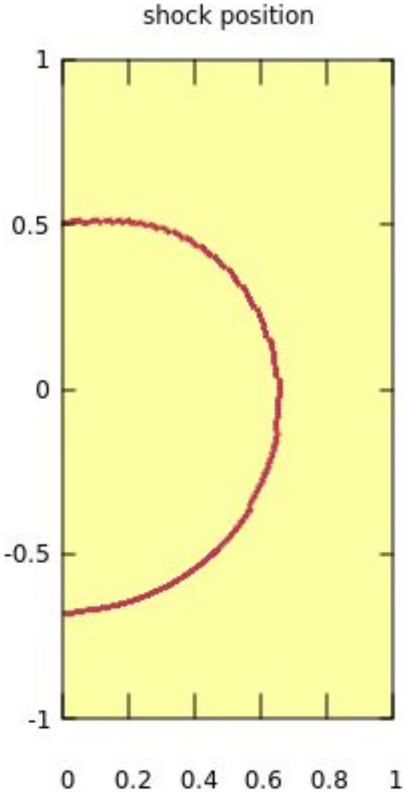
Vej x time

Vs ~ 4000 km/s





Calculations & parameters

Target photons

Photosphere

$$u_{ph} = 0.14 \frac{(R_{ph}/200\,R_{\odot})^2 (T_{ph}/8460\,\mathrm{K})^4}{(v_{sh}/4500\,\mathrm{km\,s^{-1}})^2 (t/3\,\mathrm{d})^2} [\mathrm{erg\,cm^{-3}}]$$

$$\epsilon_{ph} = 2.2 (T_{ph}/8460\,\mathrm{K})\,[\mathrm{eV}].$$

MAGIC Collab. 2022

Magnetic field

1 G

$$B_{\mathrm{w}}(R) = B_* \left(\frac{R}{R_*}\right)^{-2}$$

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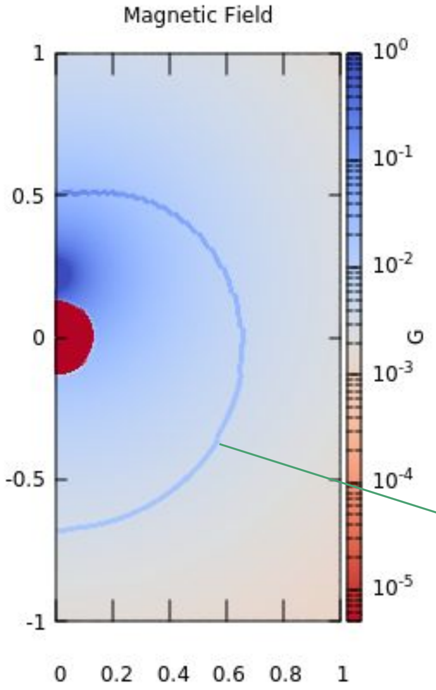
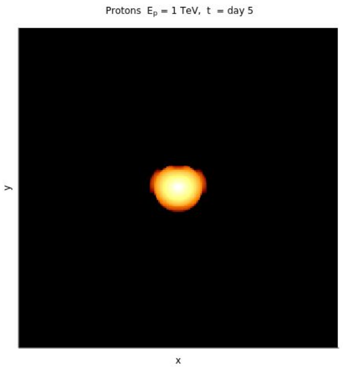
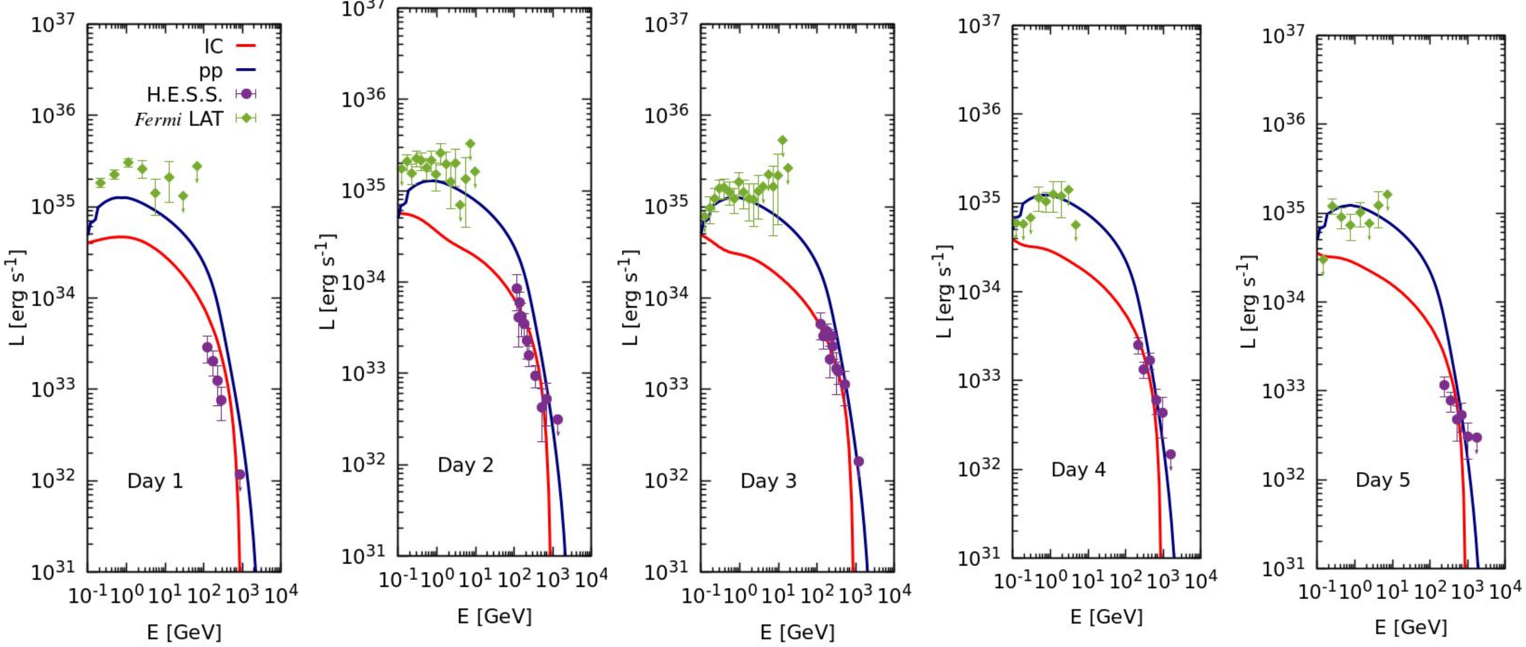


factor of 10



Results

eta_e = 12%
eta_p = 50%
alpha,e = 2.4
alpha,p = 2.2
Cuttoff = 0.5
D0 = 10^20 cm^2/s



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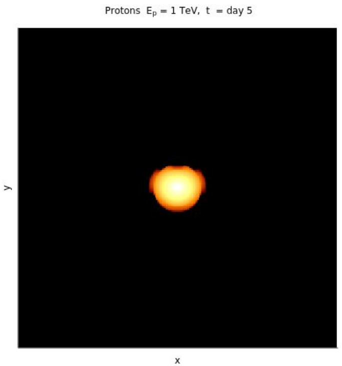

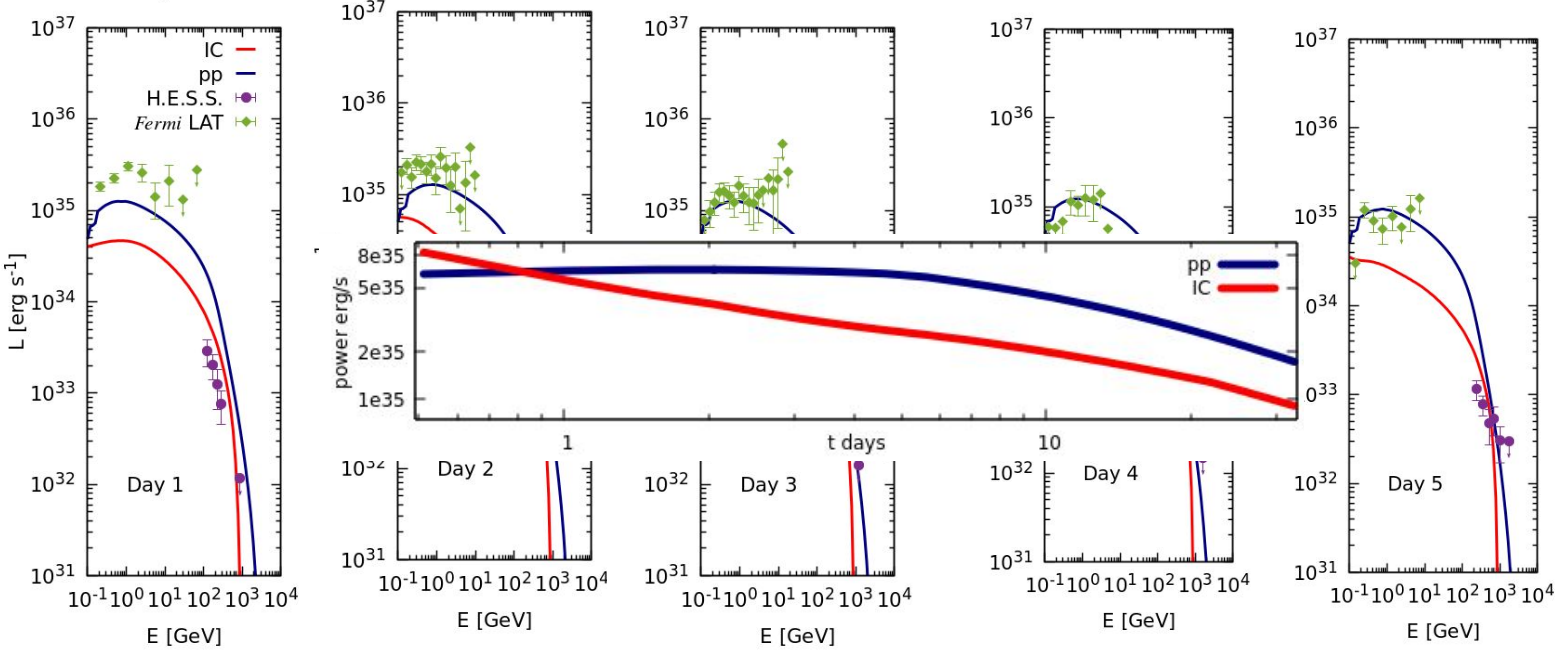

Conclusions

(preliminar)

- Both e and p might fit the data
- Ep_max ~ 10 Ee_max
- Escape by diffusion important
- Substantial fraction of Ps required to fit data
- Difficult d > 1.4 kpc

Thanks!

Parameter	Symbol, unit	p	e
Injection index electrons	α_e	–	2.2
Injection index protons	α_p	2.2	–
Cutoff exponent electrons	β_e	–	0.5
Cutoff exponent protons	β_p	0.5	–
Fraction of energy in electrons	κ_e		12%
Fraction of energy in protons	κ_p	50%	
Diffusion coefficient	D_0	10^{20}	–
RG surface magnetic field	B_*, G	1.	
RG radius, au	R_*, au	0.35	
RG mass-loss rate	$\dot{M}$, $M_\odot$ yr^{-1}	10^{-7}	
WD orbit radius	r_{orb}, au	1.48	
Distance from Earth	kpc	1.4	
Ejecta speed	v_{ej}, km s^{-1}	4500	
Ejecta mass	m_{ej}	$10^{-6} M_\odot$	