RS Ophiuchi: The Many Faces of a Remarkable Nova

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Why This talk?

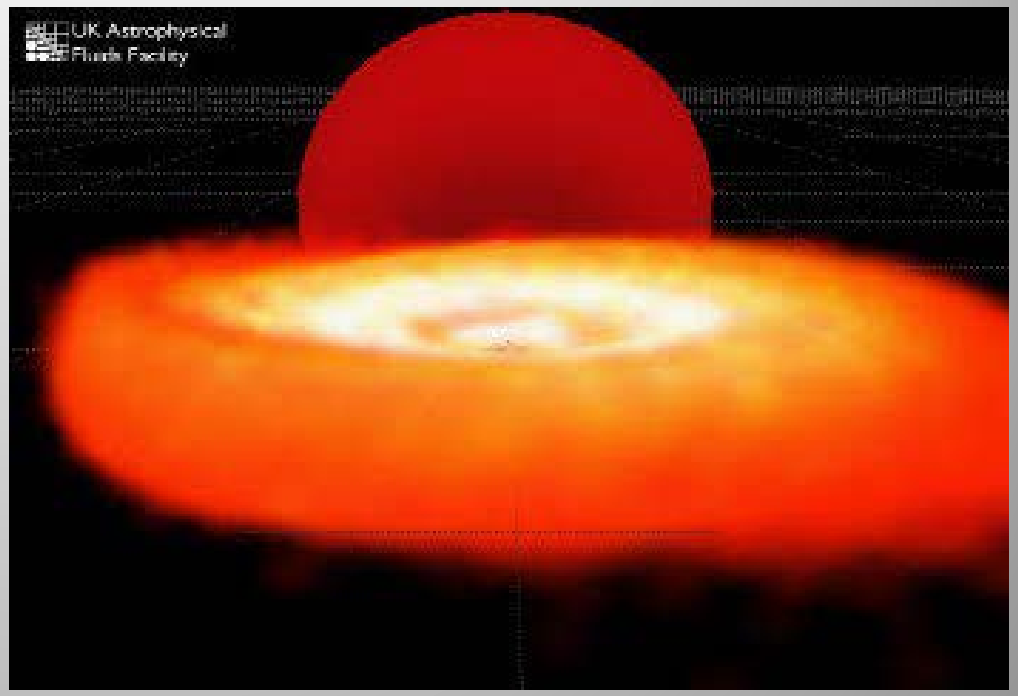
- An object of wide interest
- Properties of WD particularly important
- Remind those who know
- Illuminate those who don’t
- 10 years this week since Keele conference
- Margarita was there – and has made significant contributions to our understanding
- ‘Warm-up’ for next talk
- ‘Hocus Pocus’ re nova outburst and meetings!

"IT'S SOMEWHERE BETWEEN A NOVA AND A SUPERNOVA... PROBABLY A PRETTY GOOD NOVA."

Classical Nova Vital Statistics

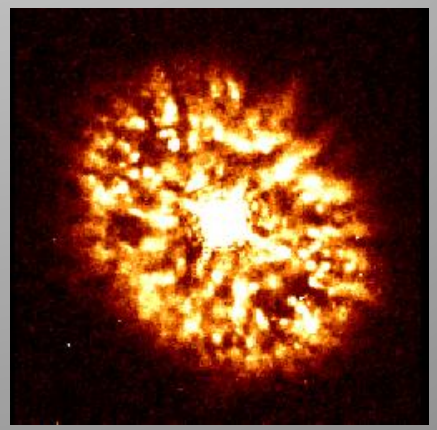
Central System:

- WD (CO or ONe) + late-type MS star, P ~ 1.5-8(+) hrs
- $\dot{M}_{acc} \sim 10^{-9}\ M_\odot yr^{-1}$
- $L_{qu} \sim L_\odot$



At Outburst (TNR on WD):

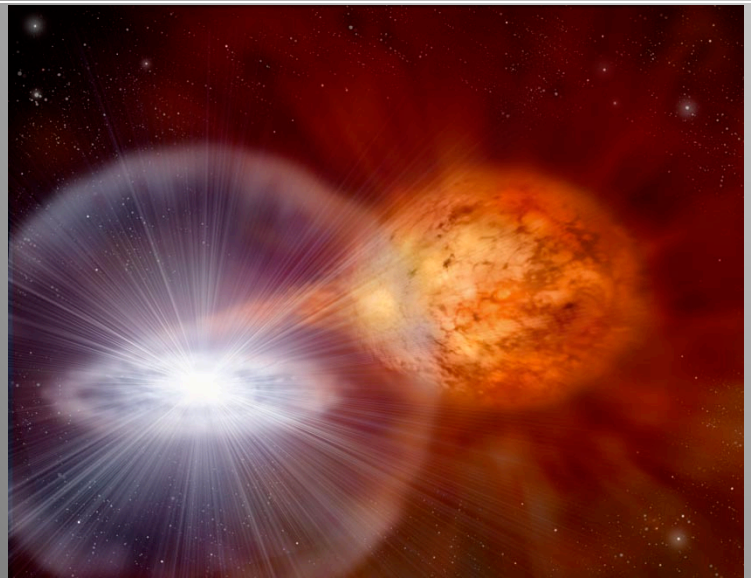
- L ~ few x $10^4\ L_\odot$ (~ L_{Edd})
- $M_{ej} \sim 10^{-5} – 10^{-4}\ M_\odot$
- v_{ej} ~ few 100 - several 1000 km/s
- Inter-outburst period: ~10^3–10^5 yrs (~ 1000 o/b's?)



Recurrent Novae

- Inter-outburst period: ~1–100 yrs
- TNR on WD (high mass + high accretion rate)
- Candidate for single degenerate channel SNIa progenitors
- 3 possible sub-types (Anupama 2008; Galactic e.g.s):

T CrB, RS Oph, V3890 Sgr, V745 Sco
Red giant secondary, P ~ few 100d
M_{WD} ~ M_{Ch}
Very fast optical decline, v_{ej} >~4000 km/s
M_{ej} ~ 10^{-7} – 10^{-6} $M_\odot$



U Sco, V394 CrA , Cl Aql (+V2487 Oph?)
Evolved/sub-giant secondary, P ~ day
M_{WD} ~ M_{Ch}
Very fast optical decline, v_{ej} ~10,000 km/s
M_{ej} ~ 10^{-7} $M_\odot$

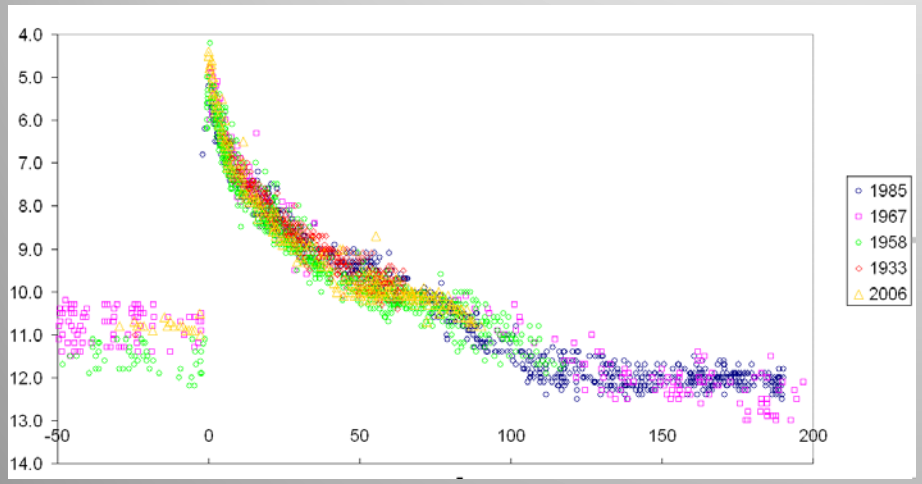
T Pyx, IM Nor
MS/sub-giant secondary, P ~ hrs - day
M_{WD} < M_{Ch}
Slower optical decline, v_{ej} ~800-2500 km/s
M_{ej} ~ 10^{-5} $M_\odot$, spectral development as CN

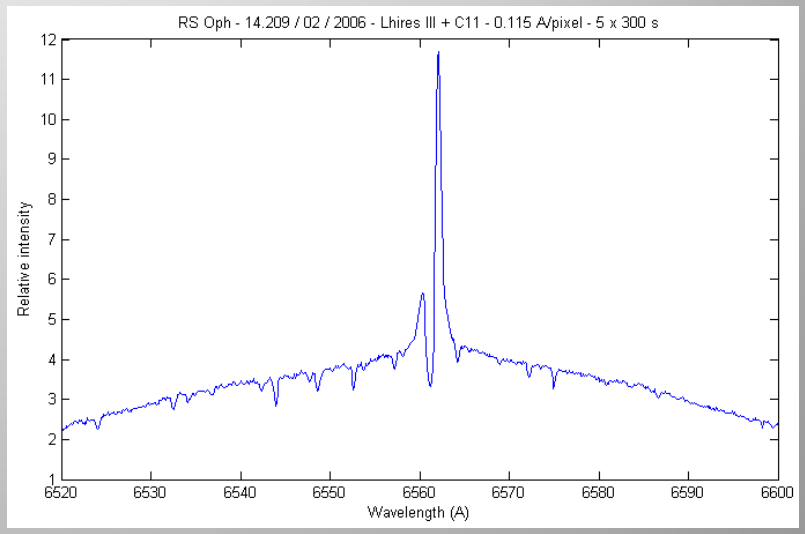
RS Oph: Vital Statistics

- Recurrent Nova – outbursts 1898, (1907), 1933, (1945), 1958, 1967, 1985, 2006
- Central system – high mass WD + Red Giant (M0-2III); P = 453.6 days
- $d = 1.6 \pm 0.3$ kpc, $N_H = 2.4 \pm 0.6 \times 10^{21}$ cm^{-2}
- Prior to 1985, spectroscopic evidence for red giant wind, systematic reduction in velocities post-outburst, and emergence of coronal lines, led to suggestion of ejecta (v_0 ~ 4000 km s^{-1}) interaction with RG wind (u = 20 km s^{-1})
- 1985 outburst first to be observed beyond the visible, but radio imaging and X-ray observations sparse (and no HST of course!)
- Shock models by Bode & Kahn (1985), O'Brien, Bode & Kahn (1992)

2006 Outburst

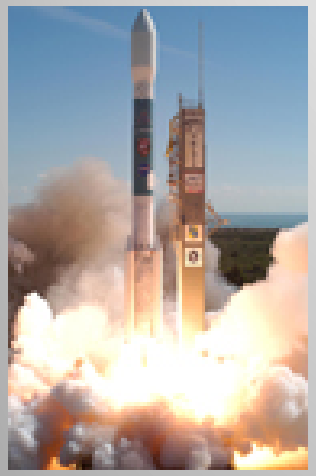
- Discovered Feb 12.83 UT (t = 0)
- Very similar optical behaviour to previous outbursts





- Within 2 days, ToO's granted on *Swift*, *XMM*, *Chandra*, *RXTE*, *MERLIN*, *VLA*, *VLBA*, *EVN*, *LT*, *UKIRT*, plus *GMRT*, *Ryle*, *Spitzer* a few days later, and *HST* at 155d

Swift Gamma Ray Burst Mission

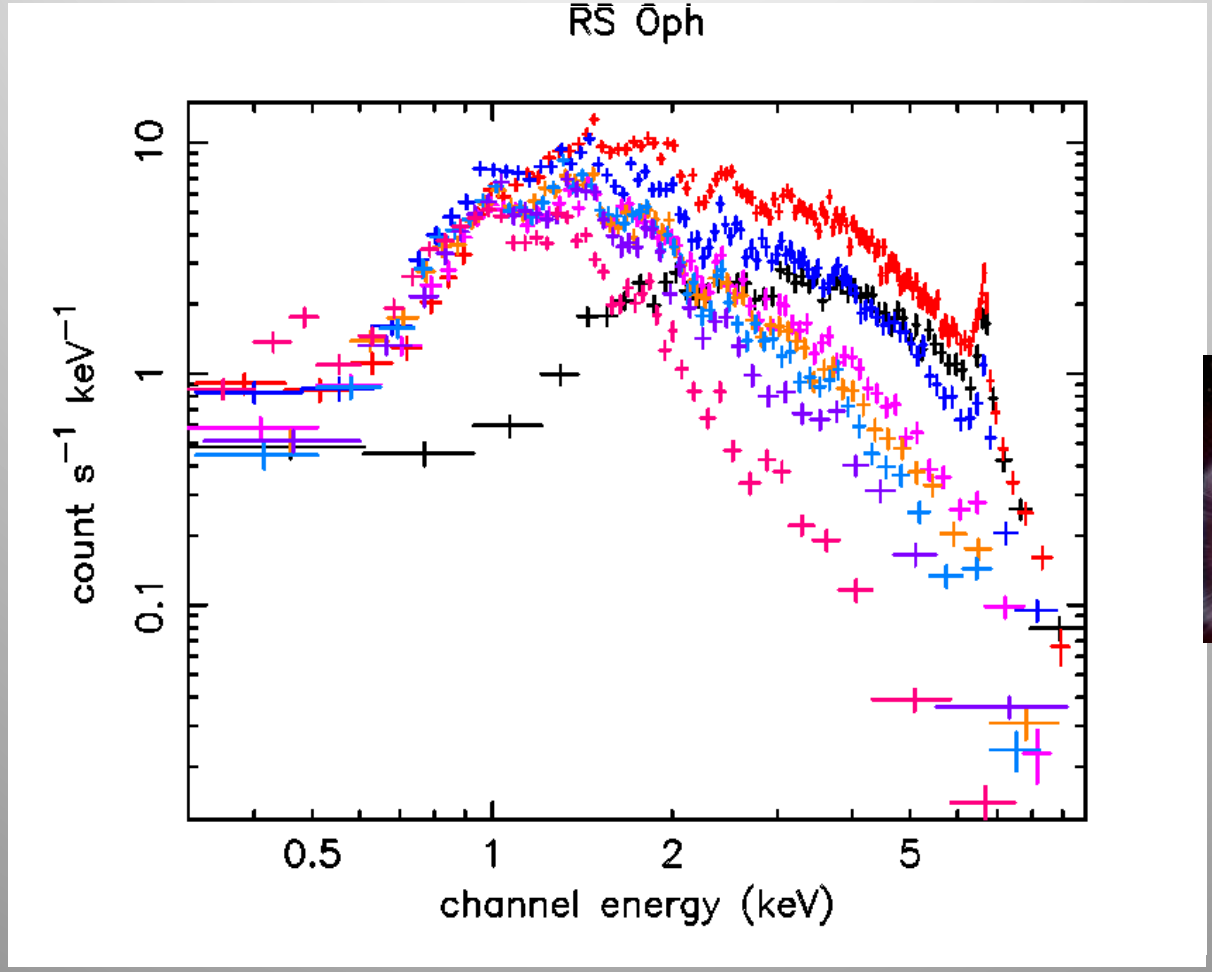


Launched November 2004

- Burst Alert Telescope (BAT)
  (14 – 190 keV in 3 channels)
- X-Ray Telescope (XRT)
  (0.1 – 10 keV)
- UV-Optical Telescope (UVOT)
  (imaging plus grisms)

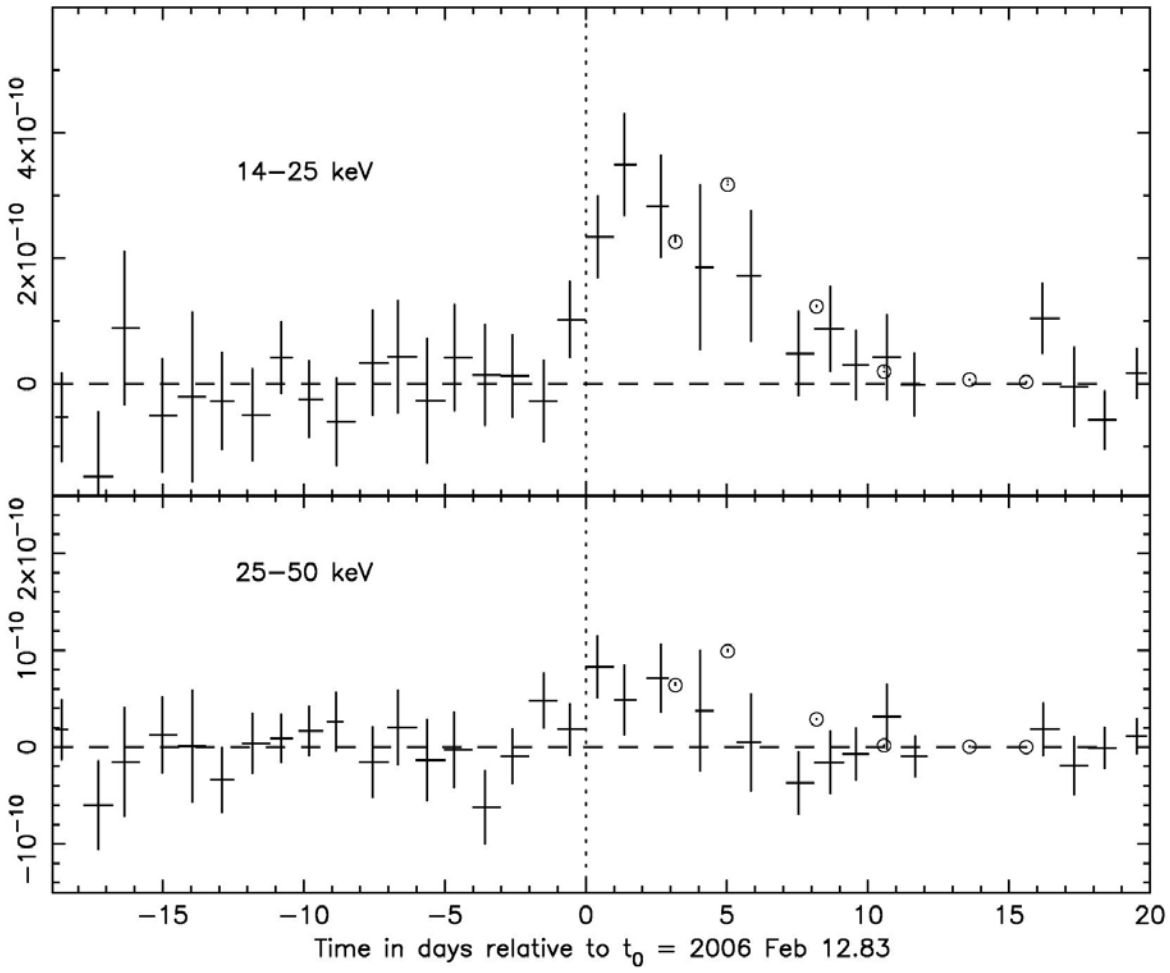
2006 Outburst: *Swift* XRT: First 26 days

day
3.17
5.03
8.18
10.99
13.60
15.61
18.17
25.99



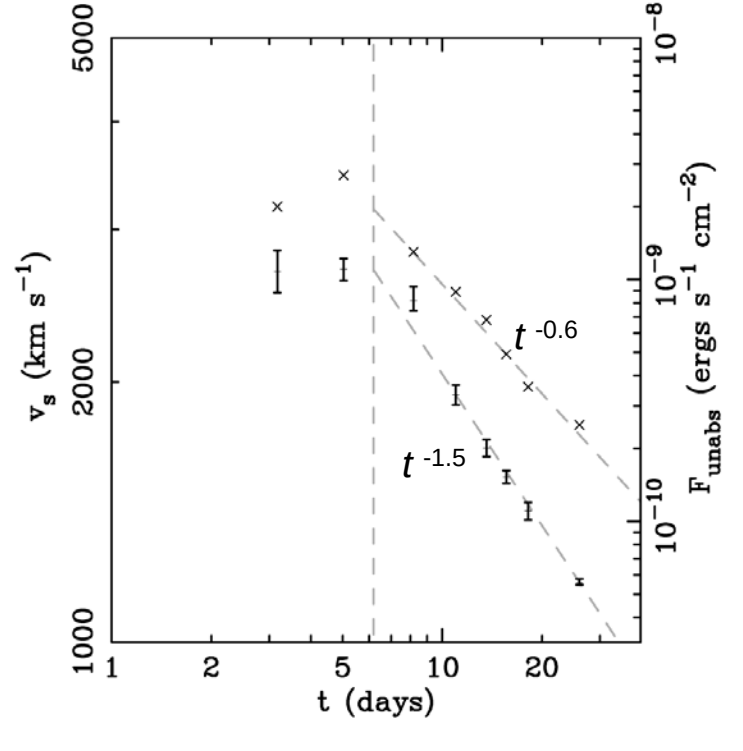
(see also Sokoloski et al. 2006 for RXTE observations + Nelson et al. 2008, Drake et al. 2009, Ness et al. 2009 for XMM/Chandra)

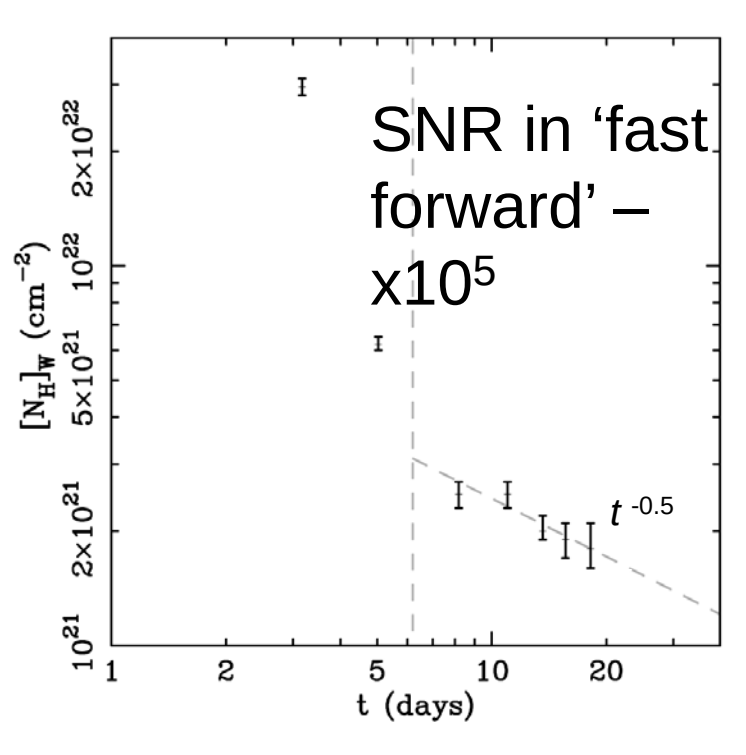
+ Detection with BAT at Outburst



Comparison with Models

XRT spectra fitted with single temperature *mekal* model. v_s from kT; interstellar N_H fixed and overlying wind N_H *a* free parameter (expect $[N_H]_W \propto r_s^{-1}$ here - Bode et al. 2006, ApJ)

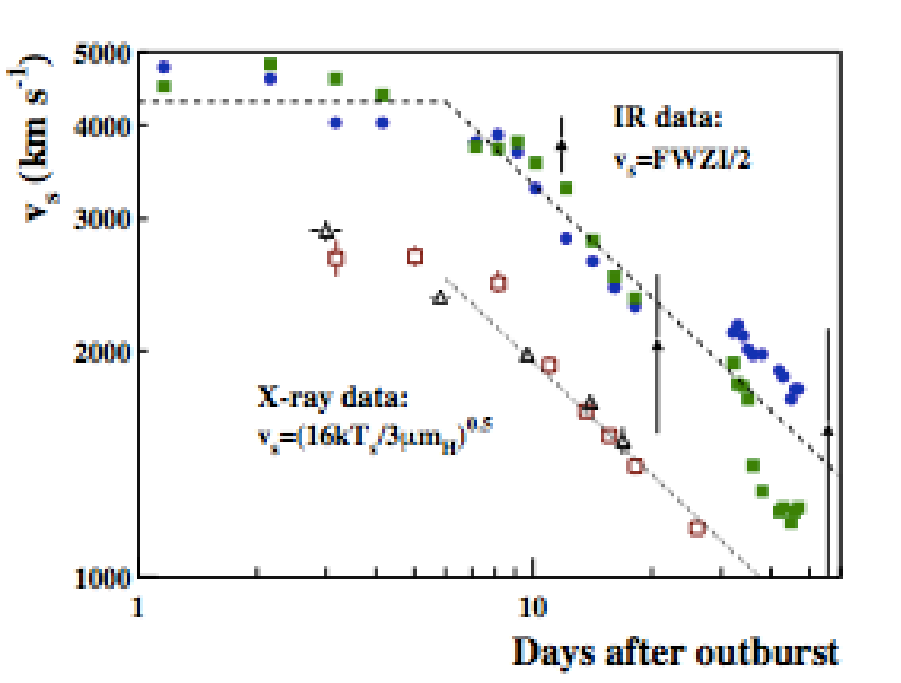




SNR in 'fast forward' – x10^5

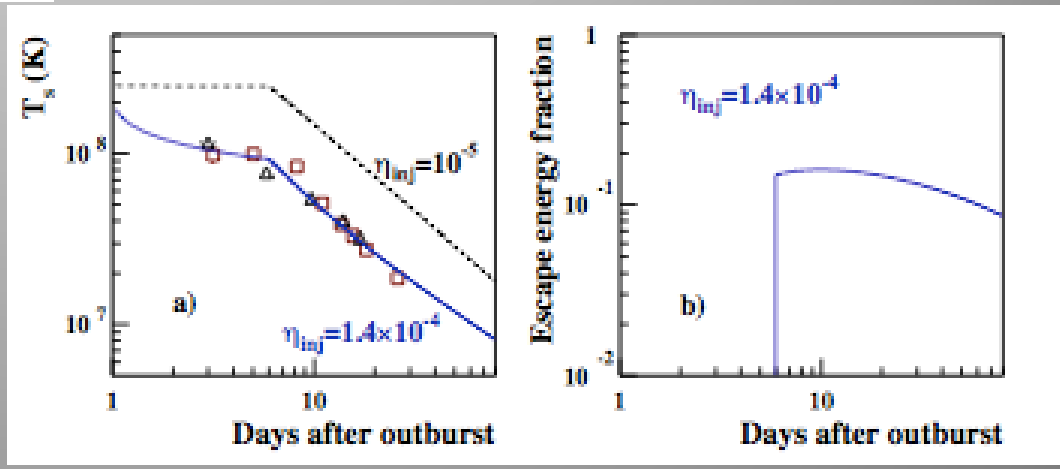
Appears to settle into stable pattern after ~6 days (cf. end Phase I) but rapidly evolves to what looks more like Phase III behaviour. Detailed models: e.g. Orlando+ (2009), Vayet+ (2010, 2011)

Shock Acceleration of Cosmic Rays

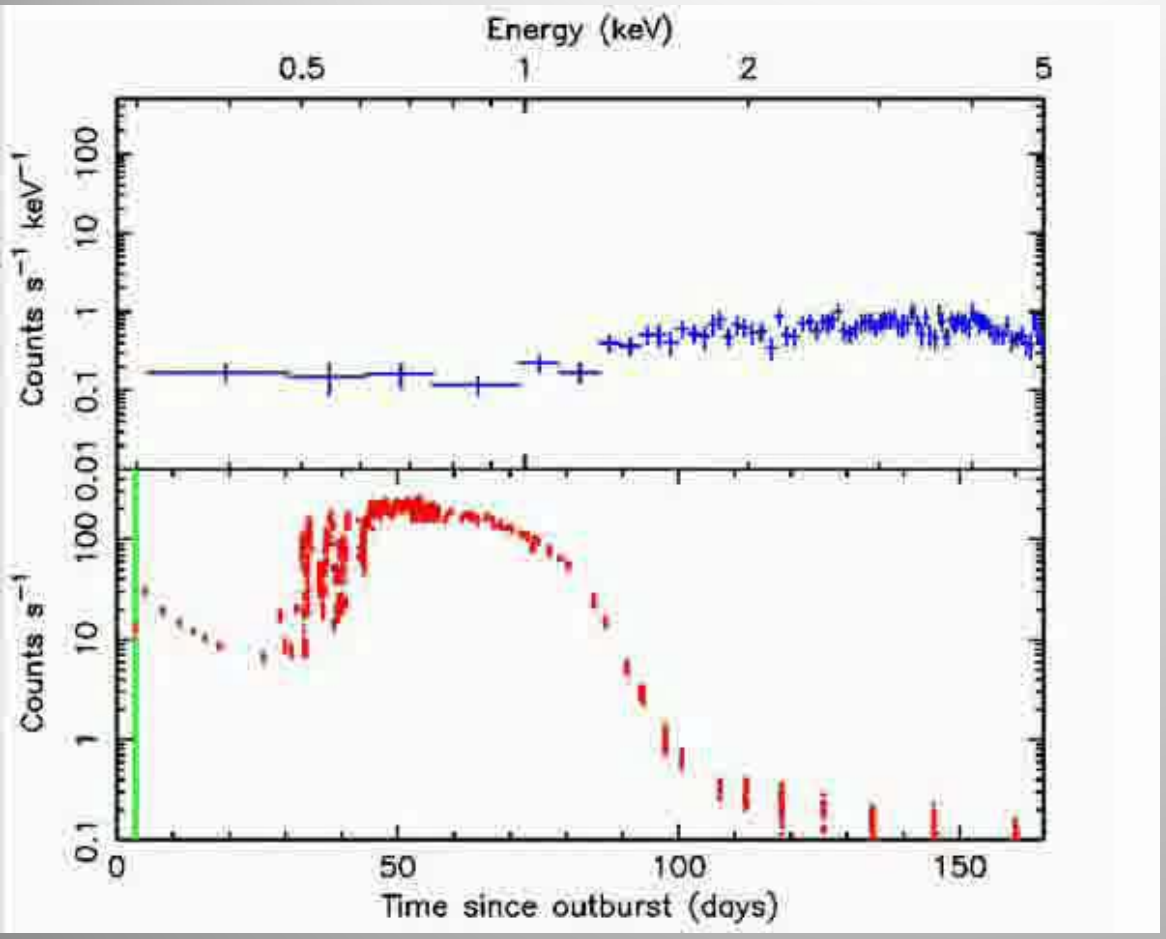


Non-linear diffusive shock acceleration of particles – additional source of energy loss. Can explain non-agreement of velocities derived from IR and X-ray, plus also rapid ‘Phase III’ transition (Tatischeff & Hernanz 2007)

Further conclusion is RS Oph would have been detected by Fermi/LAT if flying then (from neutral pion decay – Hernanz & Tatischeff 2012)



SSS phase – nuclear burning unveiled



SSS from t ~ 26 days

Initially highly variable

~35s periodicity seen

SSS emergence and decline suggests M_{WD} ~ M_{Ch} + M_{acc} > M_{ej}

→ SN Ia?? (next slide)

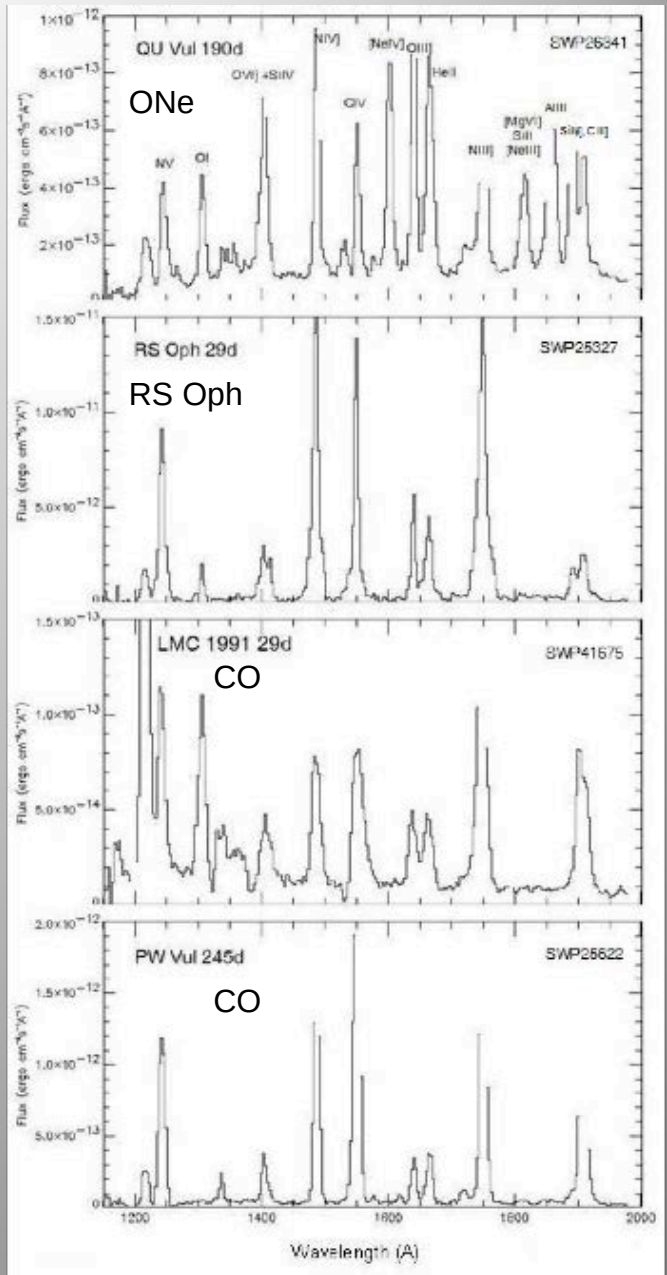
(Osborne+ 2011; see also Hachisu+ 2007; Orio+, 2008; Hernanz & Jose 2008)

• SSS evolution since observed in detail for LMC 2009a (Bode+ 2016), KT Eri, U Sco, V2491 Cyg, V458 Vul etc… – see e.g. Schwarz+ 2011; JO & KP talks)

Further Evidence for Fate as SNIa

Mikolajewska & Shara (2017):

- Simulations of high mass transfer through many many cycles show He 'ash' retained and WD grows, e.g. M_{WD} = 0.8 M_{Sun} -> M_{Ch} in ~10^6 yrs (Hillman et al. 2016)
- Optical spectroscopy gives most likely orbital solution as M_{hot}= 1.2-1.4 M_{sun} (Brandi et al. 2009), plus outburst characteristics (e.g. Hachisu & Kato 2001; Yaron et al. 2005)
- UV spectra cf ONe and CO novae at similar phase strongly suggest CO WD
- As $[M_{WD}]_{CO}$<1.1 M_{Sun} from stellar evolution, WD must have grown, and still grows -> SNIa (see MD & MH talks)

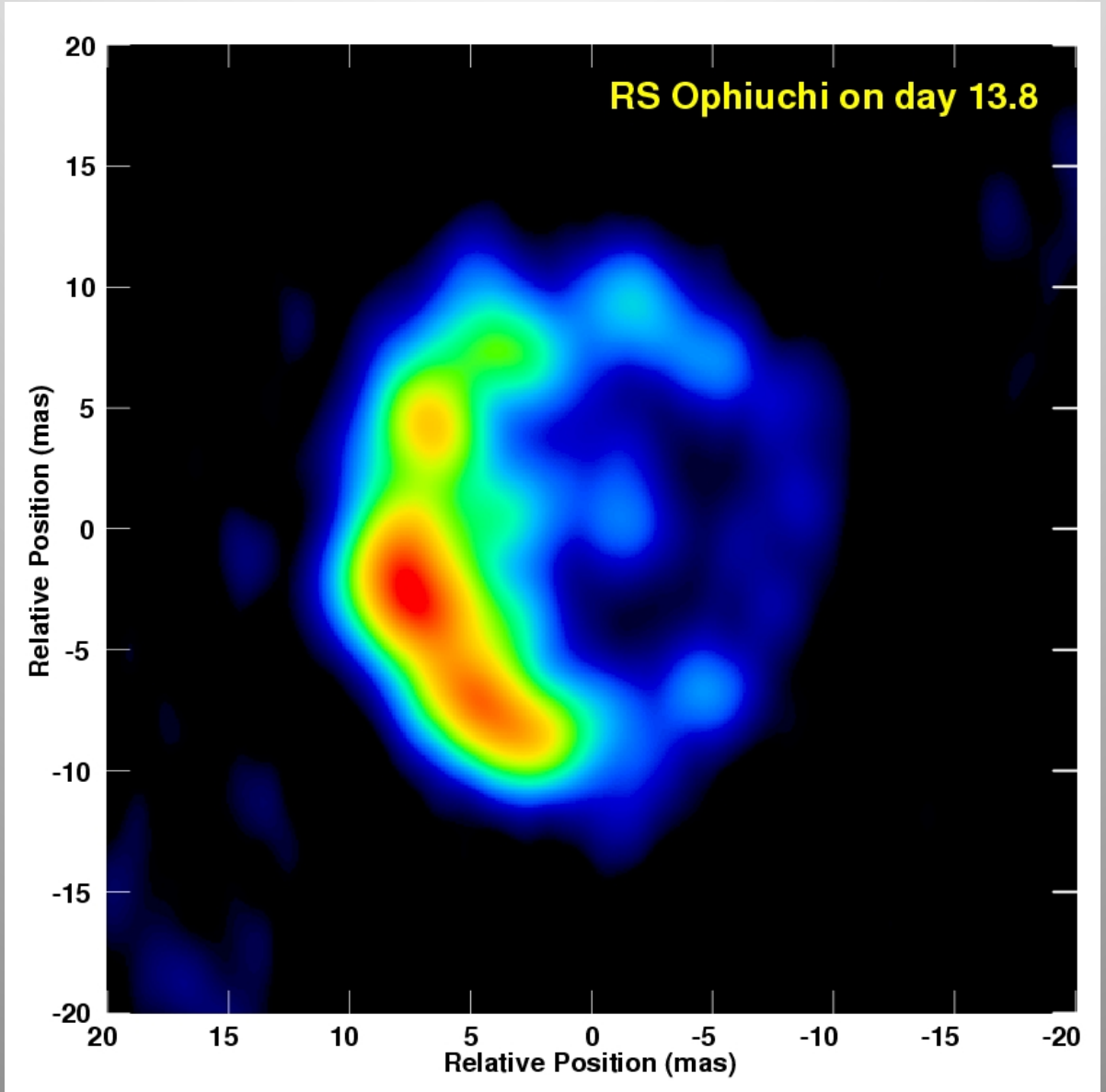


First VLBA image – Day 13.8

Res'n ~ 3 mas

Peak T_b~5x10^7K

Significant contribution from non-thermal synchrotron emission i.e. particles accelerated in shock wave. Radius consistent with X-ray results



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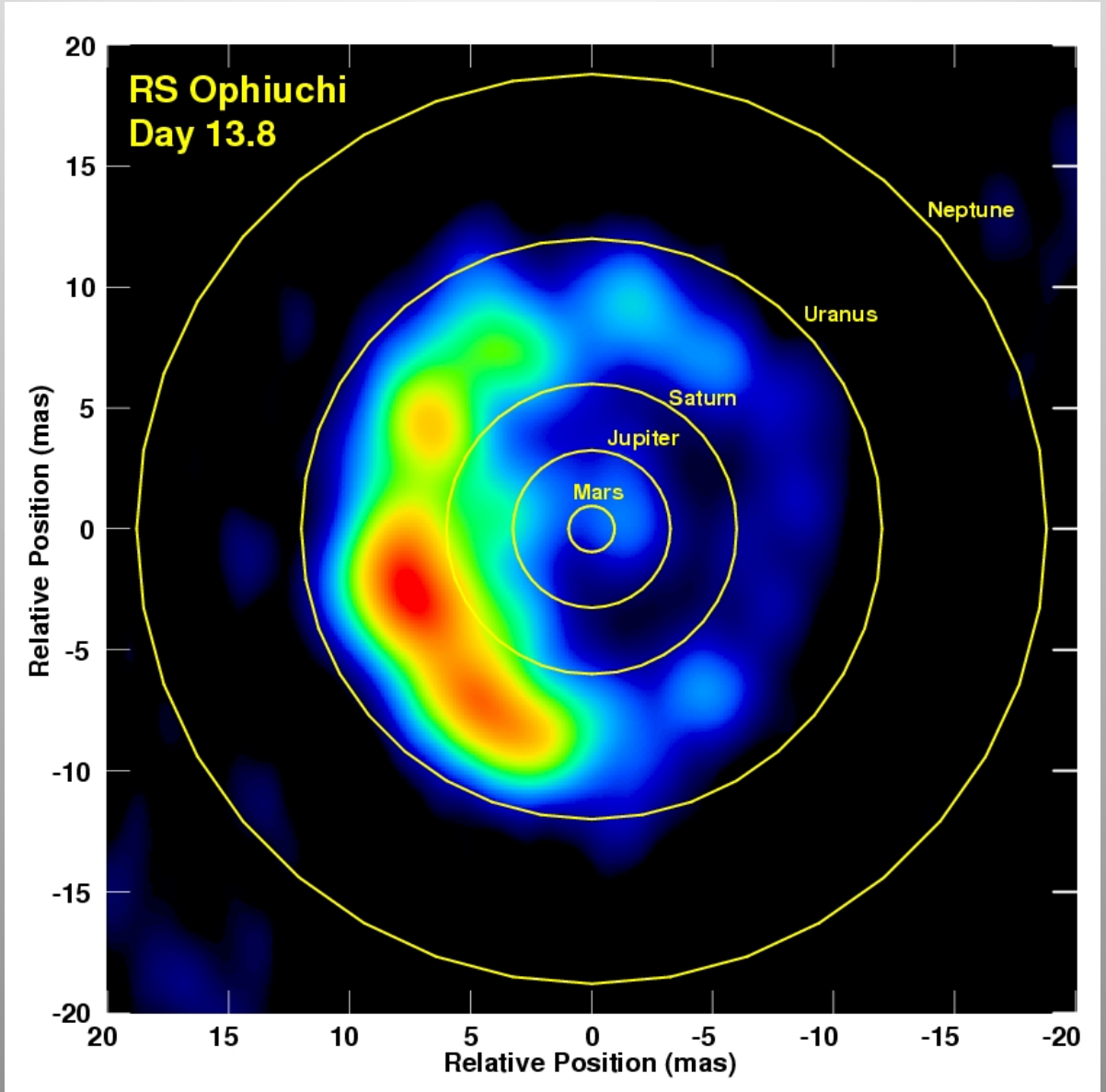
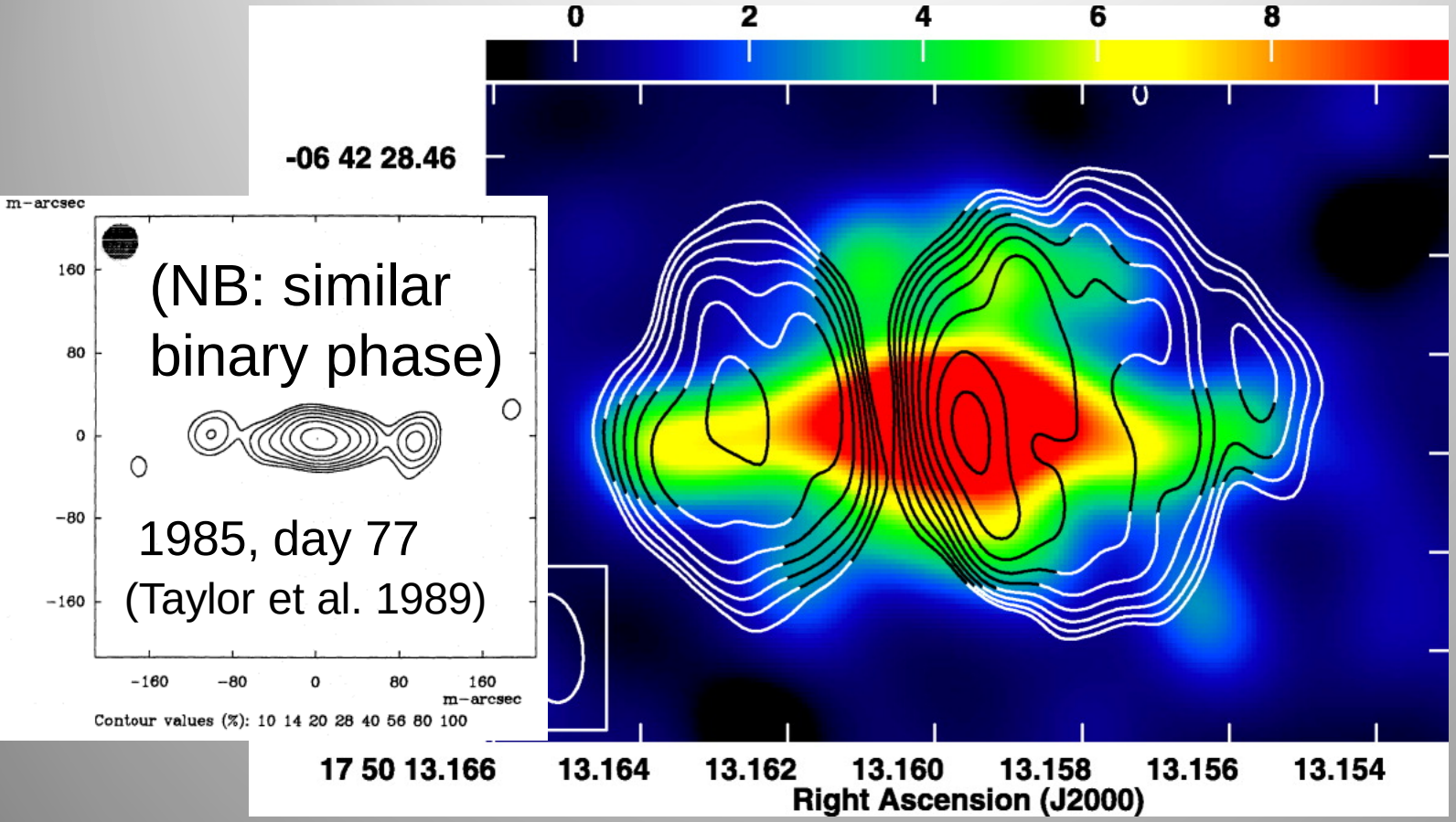


O'Brien, Bode et al. 2006

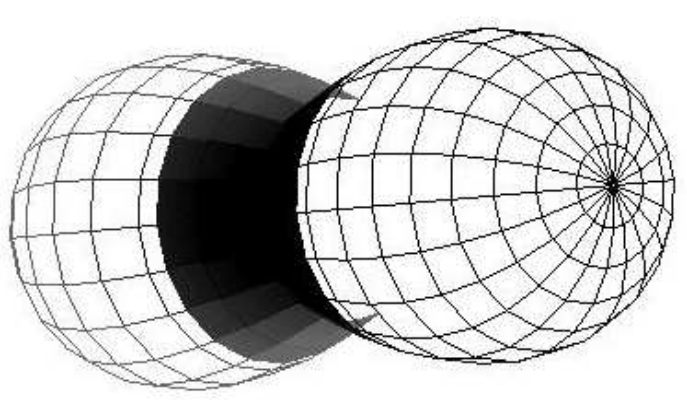
Evidence of Radio ‘Jet’

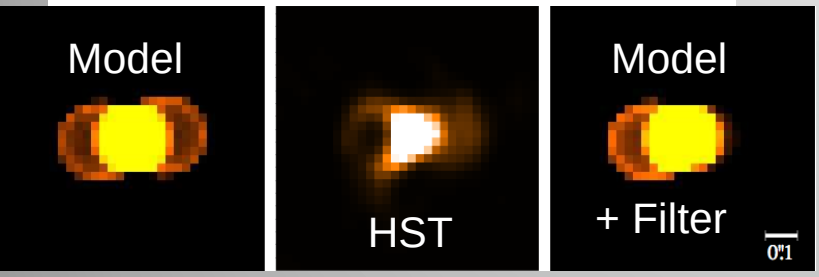


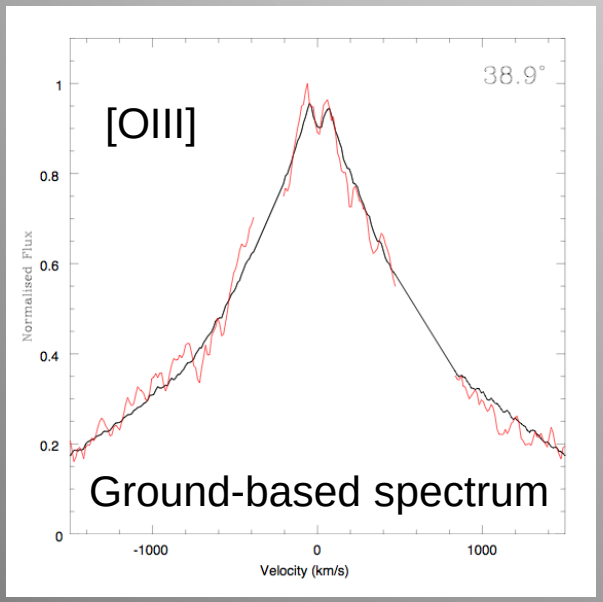
(day ~50)

1.7 GHz VLBA (contours - largely synchrotron) vs
43 GHz VLA (colour image - thermal dominates)
(Sokoloski et al. 2008, Rupen et al. 2008)

Remnant Structure







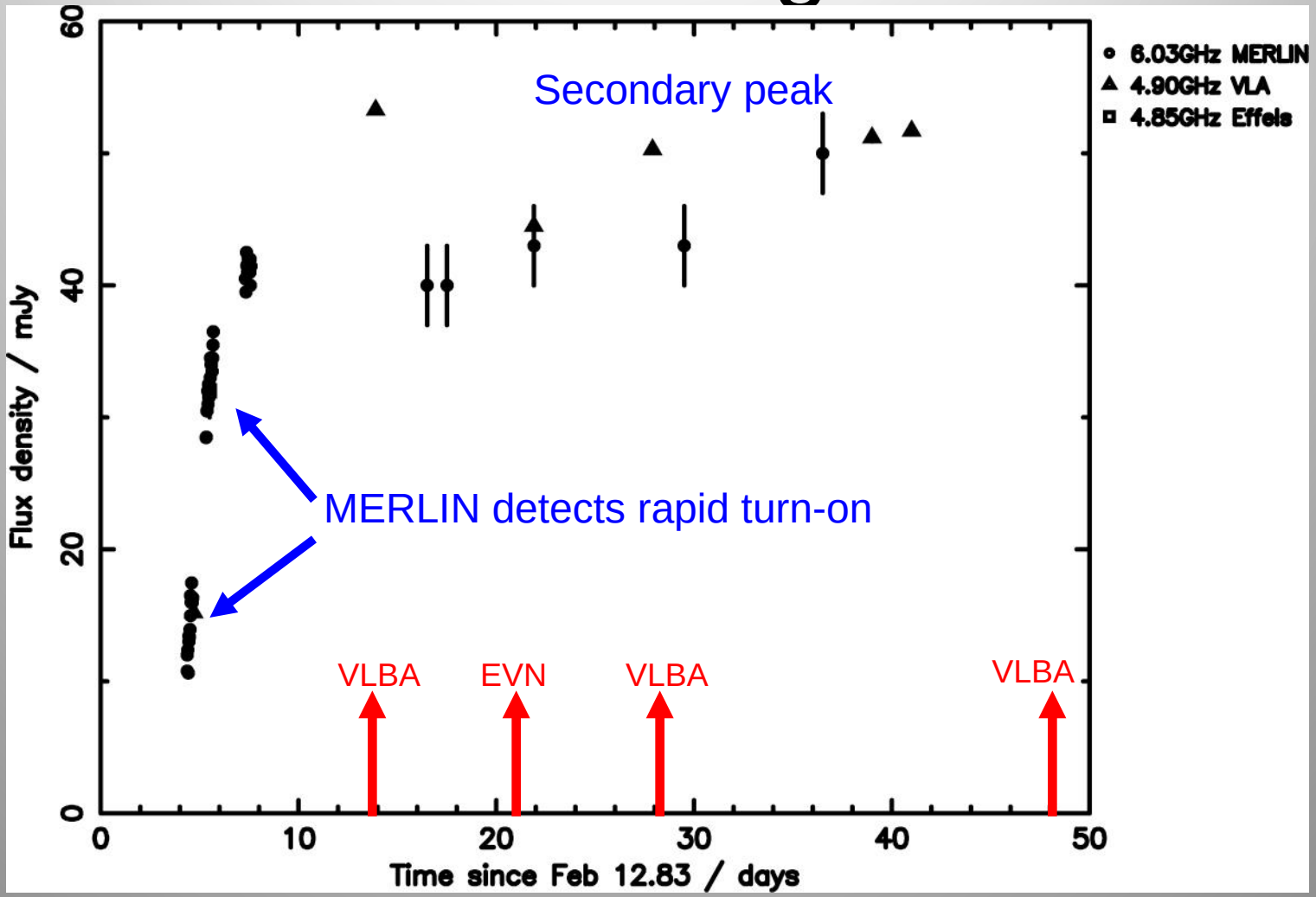
- O'Brien, Bode et al. (2006) suggested VLBI evolution modelled by bipolar structure
- Used *Shape* to model t=155d HST images + ground-based spectra
- Outer dumbbell and inner hourglass: latter containing lower velocity, denser material
- West lobe is approaching observer
- $i = 39^{o\ +1}_{-10}$ (v_0 = 5100 km/s)
  → binary orbital plane in "waist"
- Consistent with early-time infrared interferometry, VLBI, X-ray, plus survival of circumstellar dust (Spitzer data - Evans et al. 2007)

(Ribeiro, Bode et al. 2009)

Summary

- Study of RS Oph is important more widely in terms of tests of TNR; SNR analogue (particle acceleration); collimation of jets; SNIa channel…
- Outbursts 1898, (1907), 1933, (1945), 1958, 1967, 1985, 2006 – now ~11.5 years since last one – are we ready? Monitoring at quiescence?
- Next outburst: more systematic, earlier and frequent radio and optical/IR (HST/JWST) hires imaging, plus optical/IR interferometry; ditto optical and X-ray spectroscopy; gamma ray obs…
- Hats off to Margarita!

Initial 5-6 GHz lightcurve



- Different behaviour from 1985.