FG Sge, V605 Aql, Sakurai – Facts and Fictions

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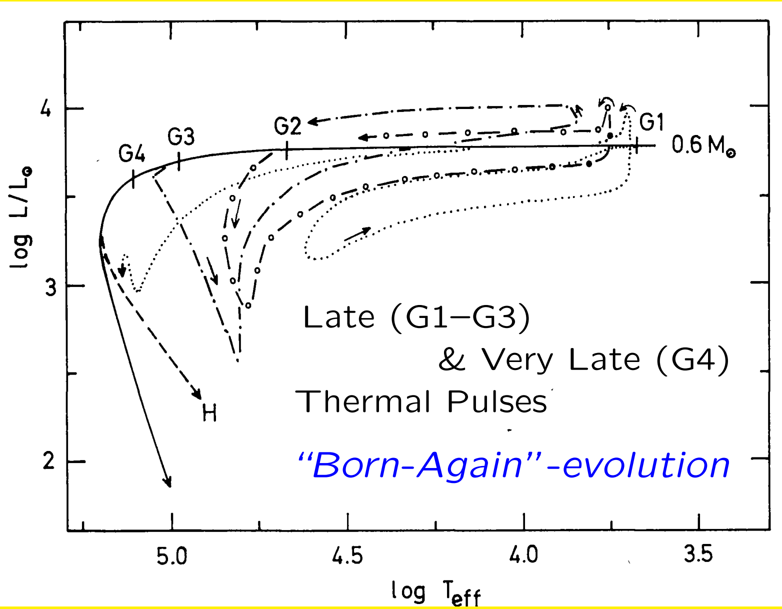
- Introduction
- Time-dependent effects
- FG Sge, V605 Aql, Sakurai
- Summary

Introduction (1)

Post-AGB evolution of an 0.6 $M_\odot$ AGB remnant with *mass loss*: *Schönberner 1979*

Post-AGB duration ≈1/10 of thermal-pulse cycle period!
i.e. ≈10 000 vs. ≈100 000 years



Loop duration ≈ mean thermal time scale of envelope *above He shell*:

G1: 2×10^3 yr / 10^3 yr
G3: 1×10^3 yr / 2×10^2 yr

No contact between He-rich & H-rich matter

LTP

G4: At position H
Mixing between He-rich & H-rich matter

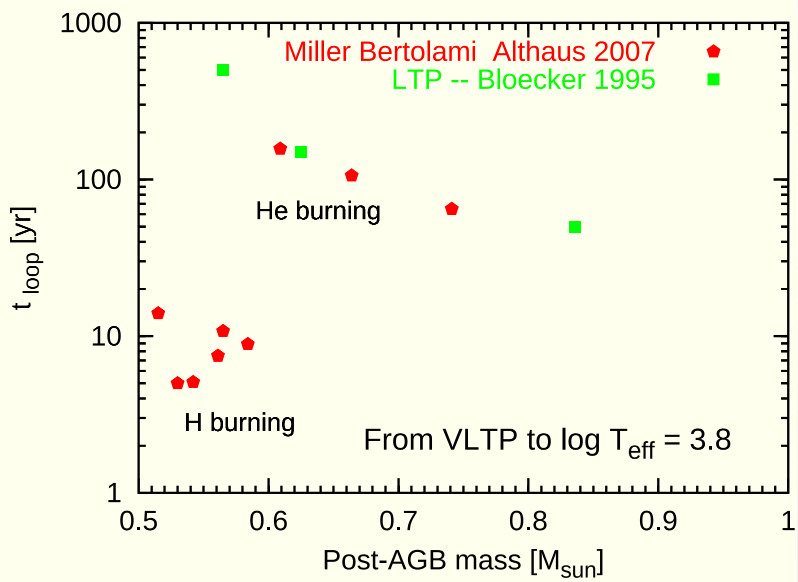
VLTP

Predicted by *Fujimoto 1977* & first shown by *Schönberner 1979*!

Introduction (2)

VLTP :

- Burning and mixing *must* be treated *simultaneously*!
- Radial position of H-burning shell where $\tau_{\rm mix} \approx \tau_{\rm burn}$
- Loop duration $\approx$ mean thermal timescale of envelope *above H-burning shell*, $\tau_{\rm VLTP} \ll \tau_{\rm LTP}$



Miller Bertolami & Althaus 2007:

- H-burning driven loop, $M < 0.6$ M$_\odot$, + He-loop
- He-burning driven loop, $M \gtrsim 0.6$ M$_\odot$ only *one* loop
- *For all masses, surface virtually H-free after H burning & mixing* (In contrast to the LTP cases !)

Introduction (3)

So far 3 bona-fide born-again-objects known :

- **FG Sagittae** — LTP prior to ∼1890
- **V605 Aquilae** — VLTP 1919
- **Sakurai's Object** (V3443 Sgr) — VLTP prior to 1996

Challenges for modelling late stages of stellar evolution & benchmarks for the models:

- Real-time stellar evolution with $\tau_{\mathrm{evol}} \lesssim \tau_{\mathrm{human}}$
- Time-dependent modelling necessary for solving the stellar energy budget
- 'Stellar archaeology', using old plates and/or old spectra, & analysing line emission from low-density nebulae

Introduction (4)

Rapid central-star evolution,

$\Longrightarrow$ *PN in ionisation equilibrium ?*

$\Longrightarrow$ *PN in thermal equilibrium ?*

Prerequisites for application of photo-ionisation codes like e.g. CLOUDY

Question rarely addressed so far for PNe :

Harrington & Marionni 1976,	*application for FG Sge*
Tylenda 1979, 1980,	*application for FG Sge*
Tylenda 1983, 1986,	*recombination halos*
Marten 1993 (PhD thesis, unpub.),	*general considerations*
Marten 1993,	*non-eqilibrium halo ionisation*
Marten 1995,	*general considerations*
Kifonidis 1996 (Diplom thesis, unpub),	*application for FG Sge*
Marten & Szczerba 1997,	*general considerations*
Corradi et al. 2000,	*recombination halos*

Analysing nebular spectra around born-again objects
should rely on time-dependent methods

Time-dependent effects (1)

Assumption normally made:
Records of previous hot stellar phases from nebular line emission, provided $\tau_{\rm evol} \ll \tau_{\rm rec}$

However,
this condition is NOT SUFFICIENT

Rather we must have also $\tau_{\rm evol} \ll \tau_{\rm ion}$

Timescale τ for a species to reach a particular ionisation stage consists of *two* parts:
Marten 1993: $1/\tau = 1/\tau_{\rm ion} + 1/\tau_{\rm rec}$

- $$\frac{1}{\tau_{\rm ion}} = \frac{1}{4\pi r^2}\int_{\nu_1}^{\infty} \frac{L_\nu}{h\nu} \exp(-\tau_\nu)\, a_\nu \, {\rm d}\nu$$ ionising photon flux
- $$\frac{1}{\tau_{\rm rec}} = n_{\rm e}\, \alpha$$ electron density

Time-dependent effects (2)

Examples for hydrogen :

- Luminous central star (6 000 $L_\odot$), middle-aged PN $\tau_{\rm ion}^{\rm H} < 1{\rm yr}$
- In contrast $\tau_{\rm rec}^{\rm H} = n_{\rm e}\alpha^{\rm H} \simeq 10^5/n_{\rm e}$

$\Longrightarrow$ Under standard conditions in PNe: $\tau_{\rm ion}^{\rm H} \ll \tau_{\rm rec}^{\rm H} \lesssim \tau_{\rm evol}$

Ionisation equilibrium good approximation

(Similar estimates holds for other species as well)

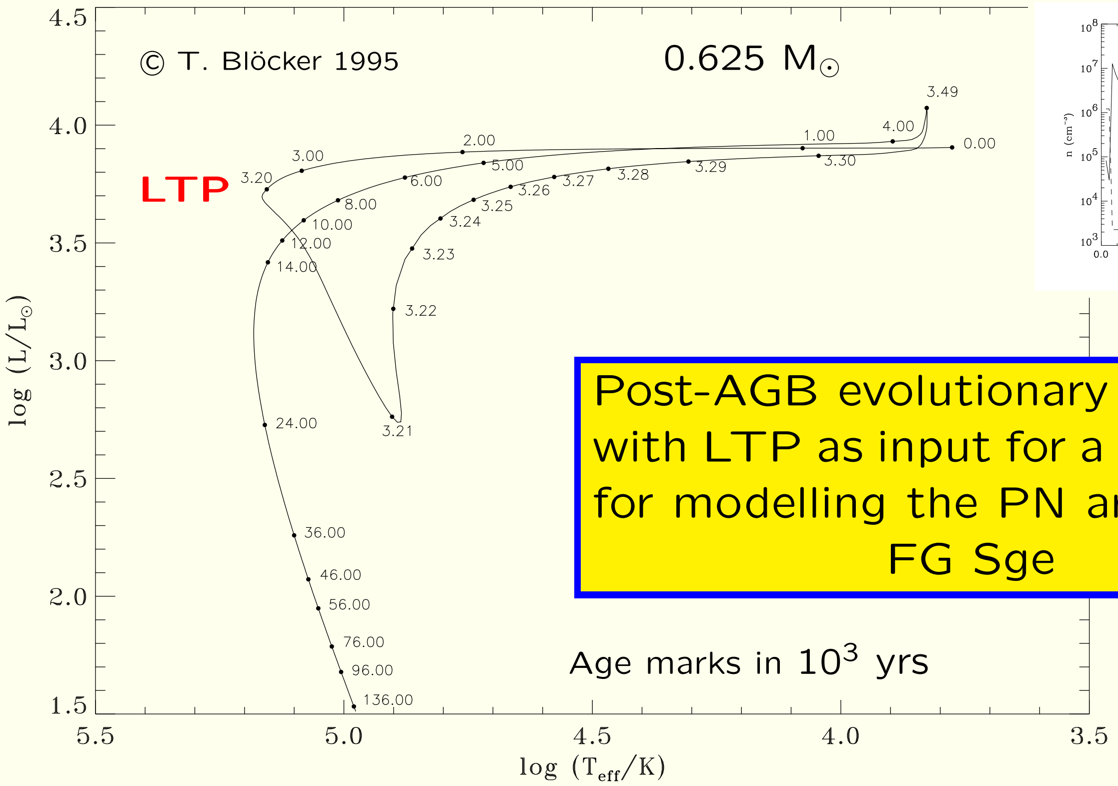
At large ionising photon fluxes, $\boxed{\tau = \tau_{\rm ion}}$

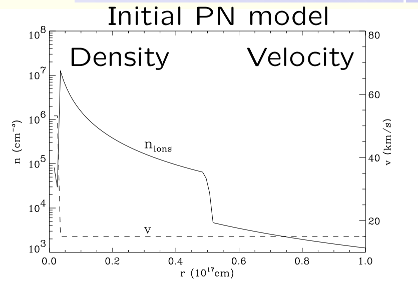
PNe are generally ruled by ionisation in equilibrium,
even if the photon flux increases very rapidly,

Only if ionising photon flux is suddenly shut-off, $\boxed{\tau \simeq \tau_{\rm rec}}$
recombination dominates

Time-dependent effects (3)

A model of FG Sge & its nebula He 1-5 : *Kifonidis 1996*

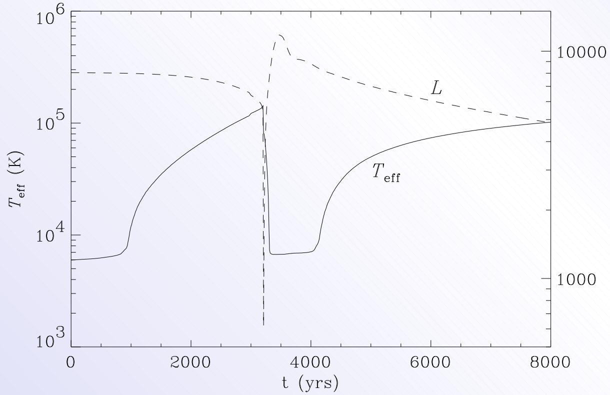


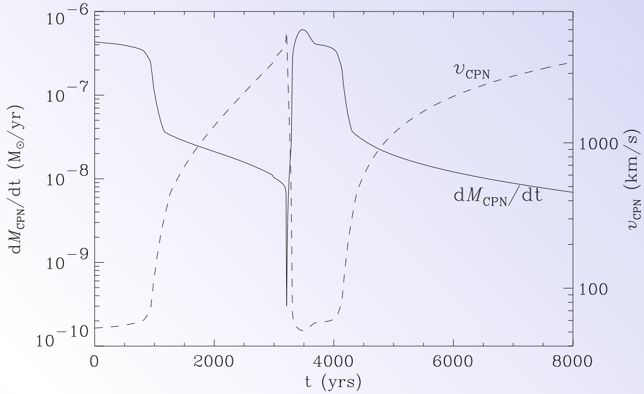


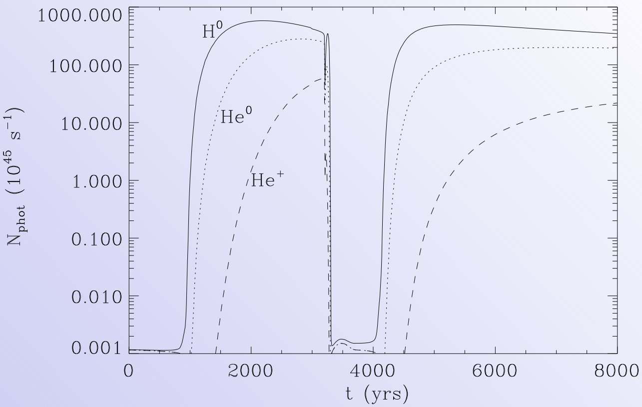
Post-AGB evolutionary models with LTP as input for a RHD code for modelling the PN around e.g. FG Sge

Time-dependent effects (4)

Boundary conditions for RHD computations
extremely time dependent: *Kifonidis 1996*





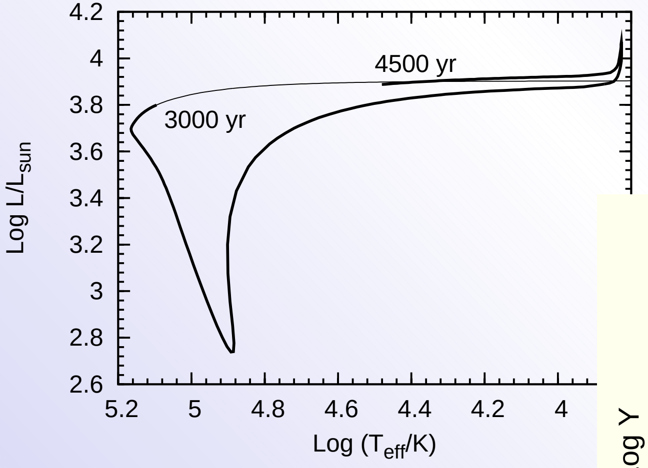


- *Ionisation/recombination in PN shell is treated fully time-dependently for 9 species (H, He, C, N, O, Ne, Cl, S, Ar) with up to 12 ionisation stages*
- *Cooling is computed for the actual values of density & temperature from all the ions involved*

Time-dependent effects (5)

Recombination vs. ionisation :

Nebular evolution across the thermal pulse, *Kifonidis 1996*

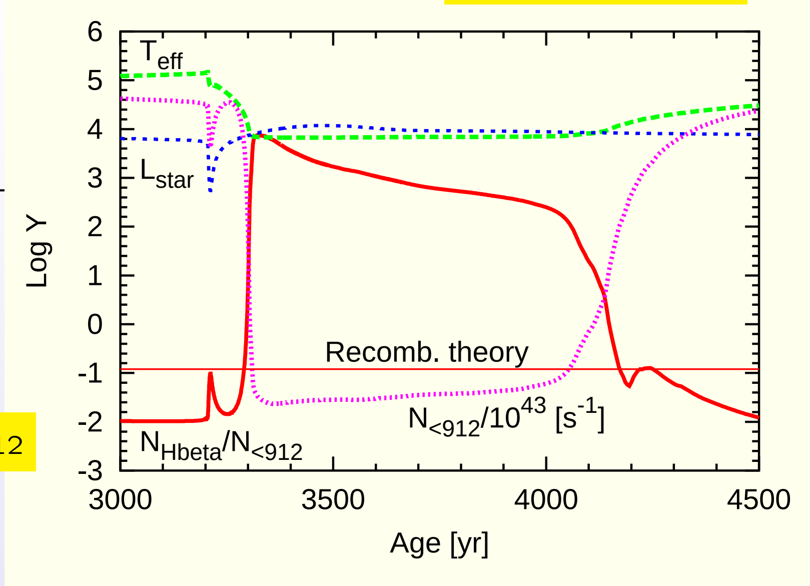


Post-flash re-ionisation, recombination to H^0 *only if*

$T_{\rm eff} \lesssim 20\,000$ *K*

Recombination theory, ionisation eqilibrium:

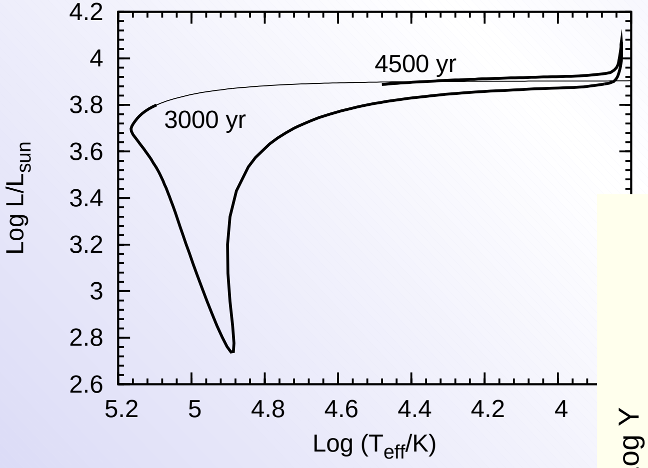
$N_{\mathrm{H}\beta} = 0.12\, N_{<912}$



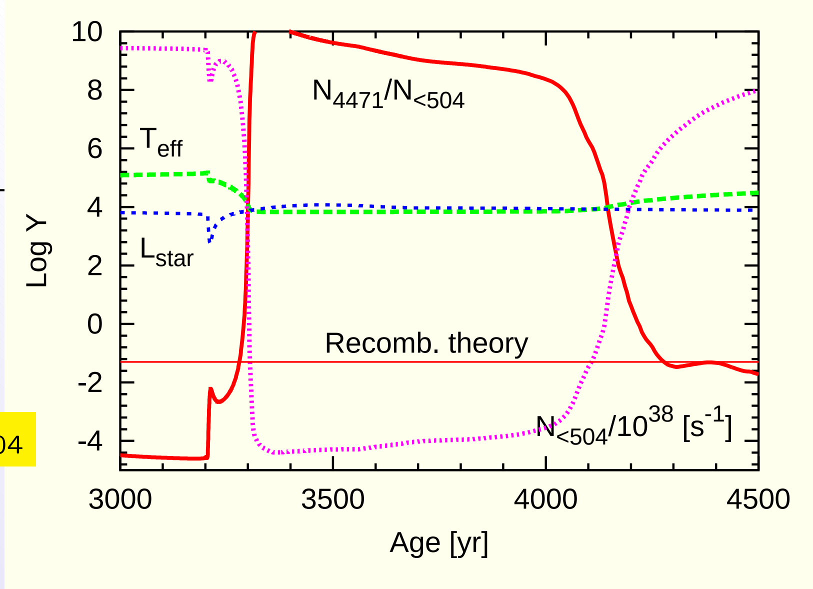
Time-dependent effects (6)

Recombination vs. ionisation (2):

Nebular evolution across the thermal pulse, *Kifonidis 1996*



Post-flash ionisation, recombination from He$^+$ *to* He^0 *only if* $T_{\rm eff} \lesssim 30\,000$ *K*

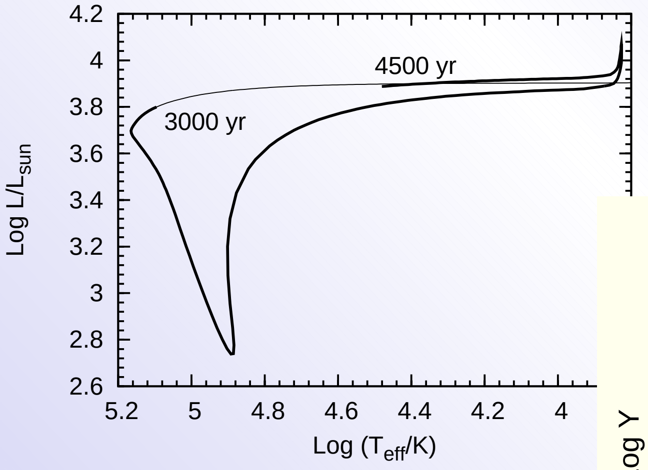


Recombination theory, ionisation eqilibrium: $N_{4471} = 0.05\, N_{<504}$

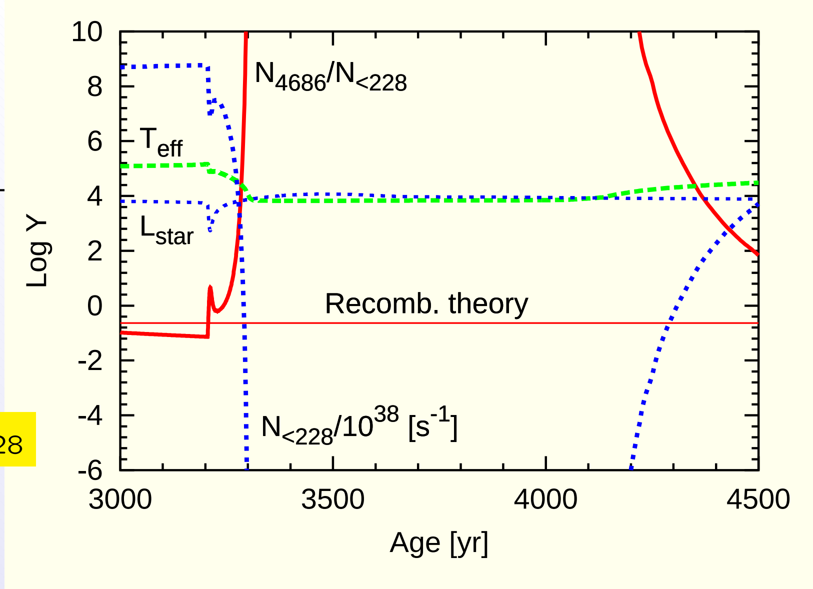
Time-dependent effects (7)

Recombination vs. ionisation (3) :

Nebular evolution across the thermal pulse, *Kifonidis 1996*



Post-flash ionisation, recombination He^{+2} *to* He^{+} *from beginning of LTP*

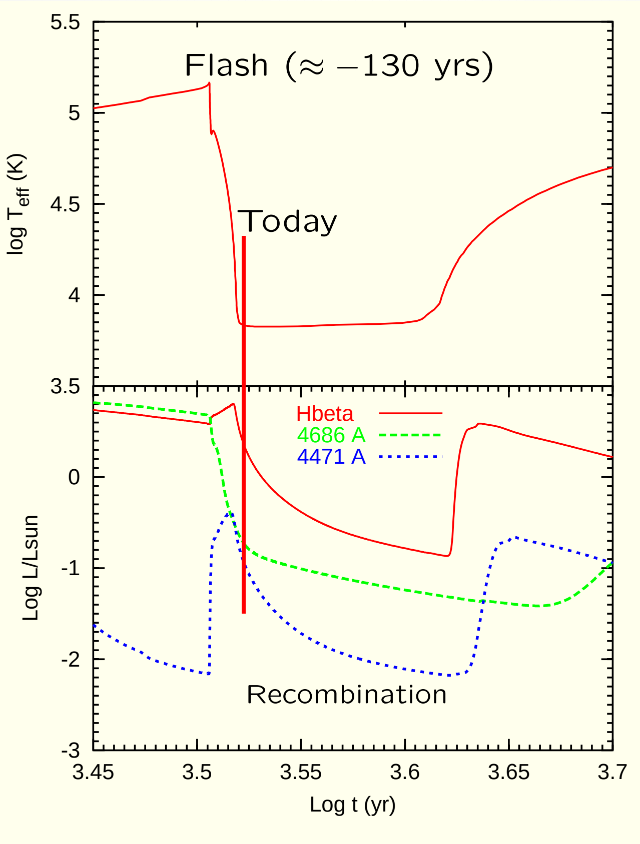


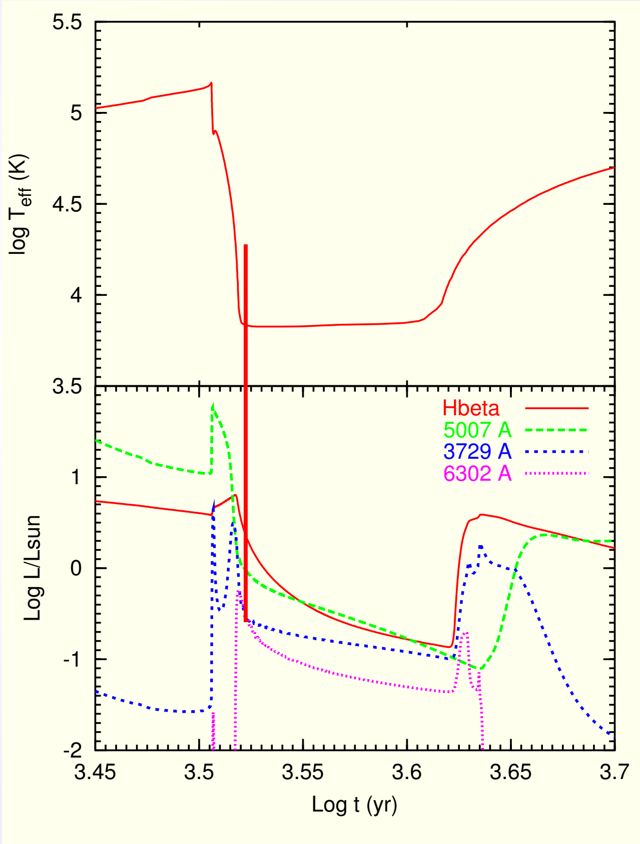
Recombination theory, ionisation eqilibrium:

$$N_{4686} = 0.23\, N_{<228}$$

Time-dependent effects (8)

Records from flashing position of FG Sge? *Kifonidis 1996*





Time-dependent effects (6)

Records from the TP event in the PN spectrum? *Kifonidis 1996*

- $\Longrightarrow L_{\mathrm{min}}$: Rapid recombination towards lower ionisation
- $L \Uparrow$: Ionisation adjusting to stellar temperature, $\tau \simeq \tau_{\mathrm{ion}} \lesssim \tau_{\mathrm{evol}}$
- $T_{\mathrm{eff}} \lesssim 30\,000$ K: Most ions already recombining, $\tau \simeq \tau_{\mathrm{rec}} \gtrsim \tau_{\mathrm{evol}}$
- **N.B.**: *Hβ not const: 3.8 $L_\odot$ (pre-flash) – 5.7 $L_\odot$ – 1.93 $L_\odot$ (today)!*
  During final recombination, T_{e} falls below 4000 K!

Time	Hβ	447 nm	468 nm	658 nm	373 nm	501 nm	387 nm
Pre-flash	**100**	–	**124**	**4**	**1**	**293**	**11**
L_{min} (+7 yr)	100	*2*	*84*	*216*	*154*	*1234*	*146*
$T_{\mathrm{eff}} = 40\,000$ K	100	7	10	36	30	345	26
$T_{\mathrm{eff}} = 30\,000$ K	100	7	7	108	67	167	12
$T_{\mathrm{eff}} = 20\,000$ K	100	6	5	240	72	38	4
1980 (+100 yr)	100	5	7	108	28	33	5
Today (+130 yr)	100	5	9	90	23	45	7

Time-dependent effects (7)

Records from TP event in the PN spectrum (2) ?

Kifonidis 1996

We conclude from our simulations :

Pre-flash ionisation status rapidly wiped out by post-flash evolution because of the small ionisation time scales

Consequence:

The position of a LTP or VLTP event in the HR diagram cannot not be inferred from nebular line analysis

FG Sge (1)

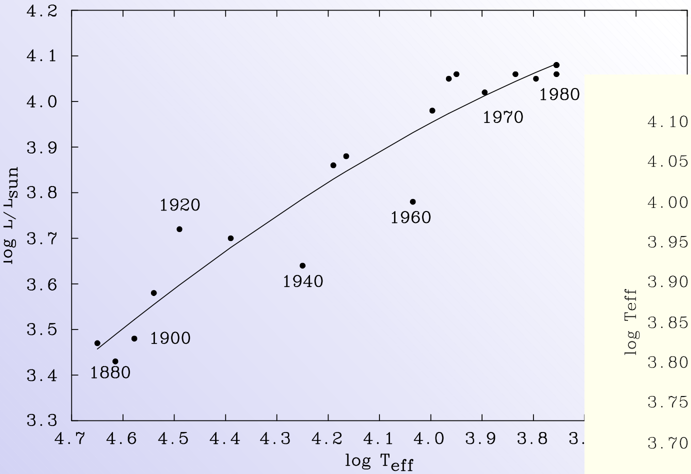
Best-studied object in a thermal pulse phase, PN: He 1-5

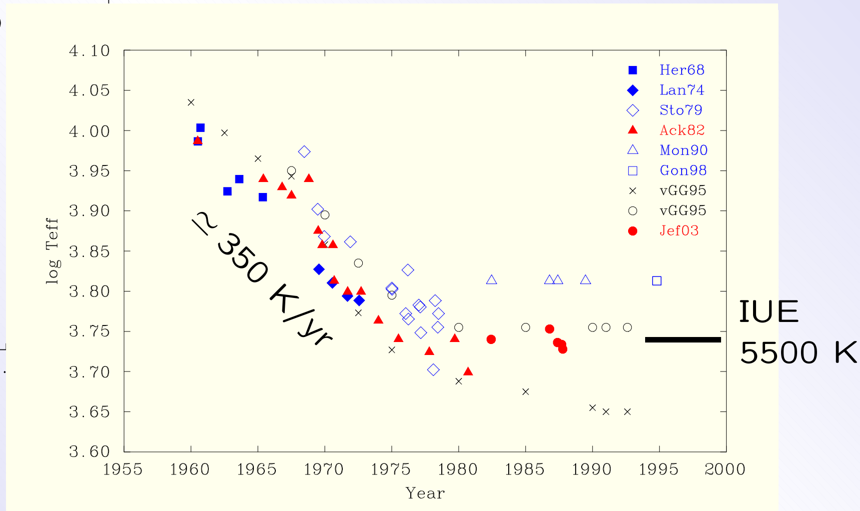
born-again red supergiant since ≈1970

left AGB a few 1 000 yrs ago with PN formation

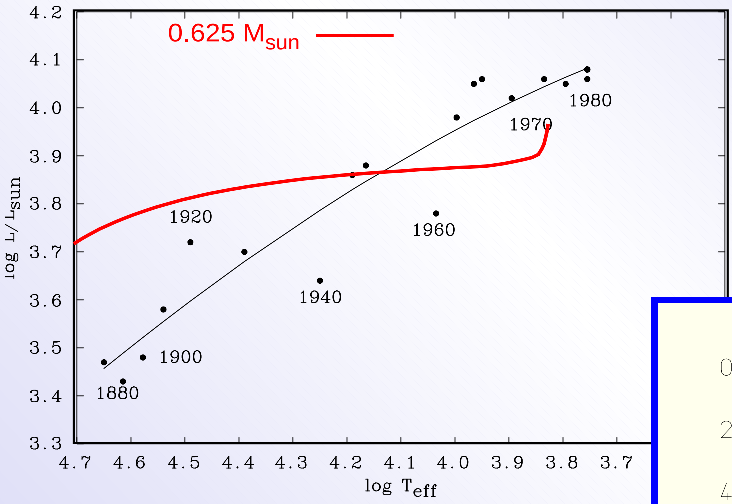
Recent ‘archaeological’ study: *Jeffery & Schönberner 2006*

Luminosity/temperature evolution of the last 100/45 years – after *van Genderen & Gautschy 1995*



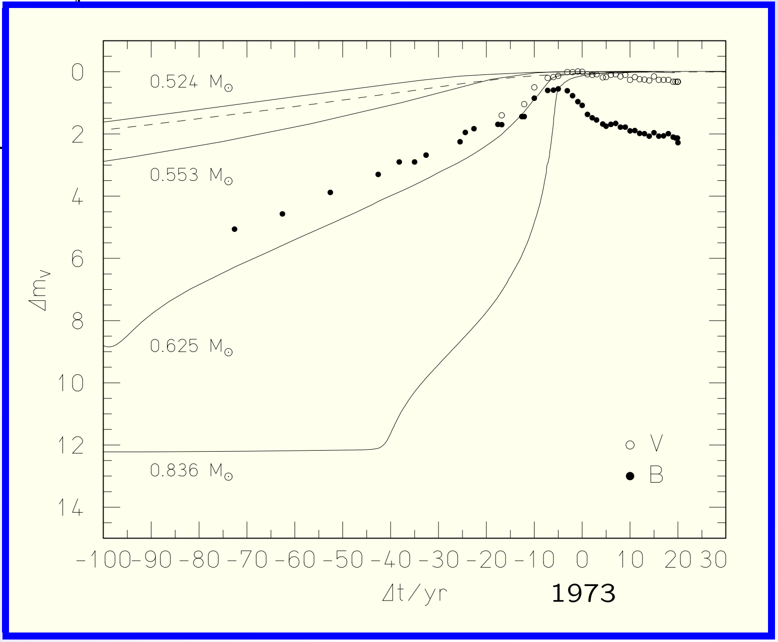


FG Sge (2)



Van Genderen & Gautschy 1995, with 0.625 $M_\odot$ LTP model of *Blöcker 1995*

Post-flash brightness evolution



Mass of FG Sge :

$\boxed{0.61\ M_\odot}$ $\pm 0.04\ M_\odot$

Blöcker & Schönberner 1997

FG Sge (3)

AIP

Abundances (1):

Pre-flash abundances from nebular spectrum (He 1-5)
by plasma diagnostics *Hawley & Miller 1978*

Based on $T_\mathrm{e} = 8\,000$–$10\,000$ K (assumed):

- He/H = 0.12
- N: solar
  O: +0.3 dex
  Ne: +0.7 dex

The only reliable result:
He/H $\simeq$ 0.1

Comparison with our hydro simulation ($\simeq$ solar abundances, no fit!) :

Time	Hβ	447 nm	468 nm	658 nm	373 nm	501 nm	387 nm
$\simeq$ 1975 (+ 95 yr)	100	5	6	121	27	31	4
Today (+ 130 yr)	100	5	9	90	23	45	7
Obs. ($\sim$ 1975)	100	5	<3	294	687/200	209	42

- $\tau_\mathrm{cool} \propto (\mathrm{density})^{-2} \lesssim 0.2\,\tau_\mathrm{rec}$, $T_\mathrm{e}^\mathrm{model} \simeq 5\,000$ *K*, $T_\mathrm{e}^\mathrm{He\,1-5} = ??$
- *Ionized halo contributes strongly to emission along line-of-sight !*

FG Sge (4)

Abundances (2) :

Post-flash abundances from stellar photosphere,

Herbig & Boyarchuk 1968, Jeffery & Schönberner 2006

Main conclusions :

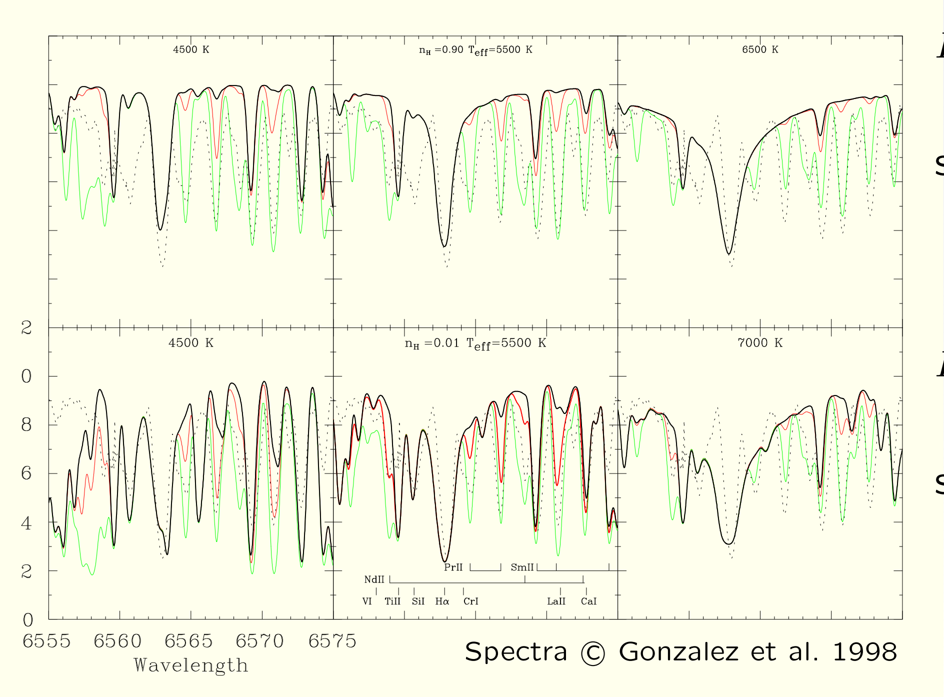
- He/H $\simeq 0.1$ (Agreement with nebular analysis)
- C and O: $\simeq$ solar
  Possibly C/O > 1
  Sr, Ba, Eu: $\simeq +1$ dex
  (Confirmed later by occurrence of C_2 bands)
- Iron group slightly underabundant

Dredge-up processes on late AGB with carbon and s-process enrichment

No mixing/burning of hydrogen at thermal pulse
$\Longrightarrow$ *Late Thermal Pulse*

FG Sge (5)

Abundances (3): *Jeffery & Schönberner 2006*



$L/M = 10^4$

$n_{\mathrm{H}} = 0.90$

s-process: normal (black)
+1 dex (red)
+3 dex (green)

$L/M = 10^4$

$n_{\mathrm{H}} = 0.01$

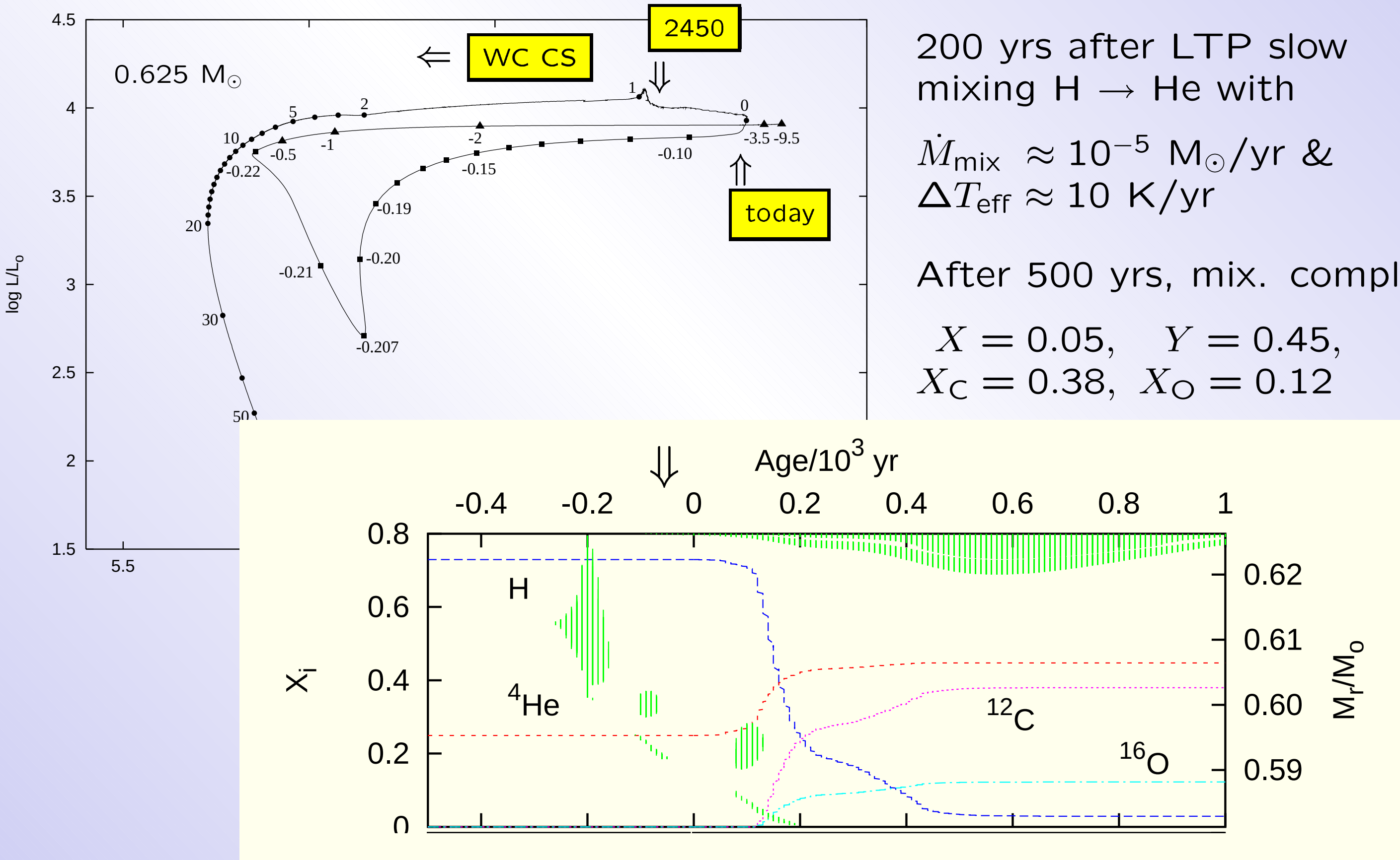
s-process: normal (black)
+1 dex (red)
+2 dex (green)

By 1992:

- *Hydrogen apparently reduced by a factor of about 100*
- La, Nd, Pr, Sm: +(1–2) dex

FG Sge (6)

Theoretical model of FG Sge : *Blöcker 2001*



200 yrs after LTP slow mixing H $\rightarrow$ He with

$\dot{M}_{\rm mix} \approx 10^{-5}$ $M_\odot$/yr &
$\Delta T_{\rm eff} \approx 10$ K/yr

After 500 yrs, mix. compl.

$X = 0.05, \quad Y = 0.45,$
$X_{\rm C} = 0.38, \quad X_{\rm O} = 0.12$

FG Sge (7)

Final assessment of FG Sge : *Jeffery & Schönberner 2006*

- Still H-rich by 1960's — *Late TP with no mixing & burning*
- Apparently H-poor by 1990's — *(?) Indirect measurement, no concomitant blueward evolution observed !*
- s-process $\approx$+1 dex consistently — *Typical for AGB 3rd dredge-up*

FG Sge (8)

Problem : *Iben 1984*

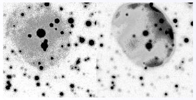
From PN age, evol. time scale & surface abundance $\Longrightarrow$

FG Sge example of LTP

BUT

- LTP predicts hydrogen depletion by 3rd dredge-up *not before* deep penetration of envelope convection ($= T_{\rm eff}^{\rm min}$) is reached, lasting $\simeq$400 yrs with a concomitant increase of $T_{\rm eff}$
- Provided FG Sge reached already $T_{\rm eff}^{\rm min}$, then hydrogen depletion occurred *too rapidly* & *without* a concomitant *increase* of $T_{\rm eff}$

V605 Aql (1)



Central star of the old PN A 58

- $\approx 10^4$ yrs ago PN (A 58) formation *Clayton & de Marco 1997*
- $\sim$ 1917 final helium shell flash of central star
- 1919 brightness peak at $m_{\rm pg} = 10.2$ or $M_B \sim -4.7$ ($d = 3.5$ kpc), spectrum like a cool R CrB star *Lundmark 1921, Clayton & de Marco 1997*
- 1985 central, H-poor knot discovered *Seitter 1985, Pottasch et al. 1986*
- 1991 H-deficient central flow, $\approx$100 (200?) km s^{-1} *Pollaco et al. 1992*
- 2006 central star of spectral type [WC] *Clayton et al. 2006*

  $T_{\rm eff} \simeq 95\,000$ K, $\dot{M} \simeq 1 \times 10^{-7}$ M$_\odot$ yr^{-1}, $v \simeq 2500$ km s^{-1}, ($\log L/L_\odot = 4$)

  abundances: mass ratio He:C:O = 54:40:5

Mass of the H-deficient knot? 80 yrs $\times 10^{-7}$ M$_\odot$ yr^{-1} $\approx 10^{-5}$ M$_\odot$,

(not 0.05 M$_\odot$ as quoted in the literature, which is larger than He buffer mass!)

Size of the H-deficient knot? 80 yrs $\times 150$ km s^{-1} ≈ 0.01 pc

V605 Aql (2)

Evolutionary history *from direct observational evidences:*

- Born-again giant within a few years, $\tau_{\rm born-again} \approx 2$ yrs
- Surface H-poor & C-rich (^{12}C !)
- Lifetime as giant ? likely $\tau_{\rm giant} \approx 2$ yrs
- Re-contraction time scale $\tau_{\rm contr} \approx 10 \times \tau_{\rm born-again}$
- Now hot, luminous [WC] central star

Very Late TP starting on the upper part of the white-dwarf cooling track, star is now in first re-contraction episode

According to *Miller Bertolami & Althaus 2007*:

$\tau_{\rm born-again} \simeq 5 \ldots 10$ yrs for $M \simeq 0.53 \ldots 0.58\ {\rm M}_\odot$

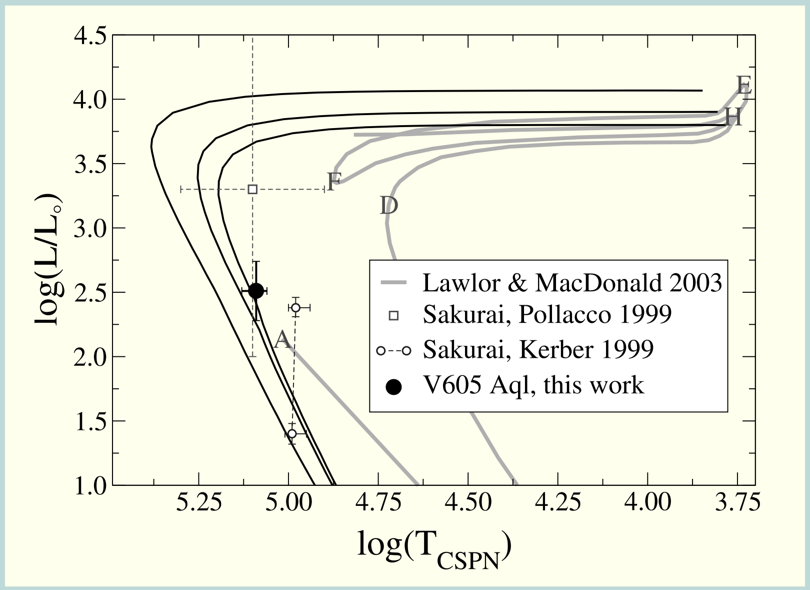
V605 Aql (3)

Analysis of the hydrogen-rich PN A 58,
supposed to contain records of the pre-flash evolution:

Lechner & Kimeswenger 2004

low-luminosity, high-gravity central star (pre-white dwarf),

$M \simeq 0.6$ M$_\odot$, $T_{\mathrm{eff}} \simeq 120\,000$ K, $L \simeq 300$ L$_\odot$ (3.1 kpc),



V605 Aql (4)

Is photo-ionisation modelling of A 58 trustworthy ?

- For H^+, He^+, & He^{+2} $\tau_{\rm rec} > \tau_{\rm born-again}$, $\tau_{\rm ion} \simeq \tau_{\rm born-again}$
  For many heavier ions $\tau_{\rm rec} > \tau_{\rm born-again}$, $\tau_{\rm ion} \gtrsim \tau_{\rm born-again}$
- During luminous re-contraction phase, $\tau_{\rm ion} < \tau_{\rm contr}$

$\Longrightarrow$ *Pre-flash ionisation certainly destroyed by now !*

- *Nebular line emission should rather correspond to the observed central star parameters*
- *which, however, are not those of a pre-white dwarf !*

Time-dependent calculations including star & nebula are needed !

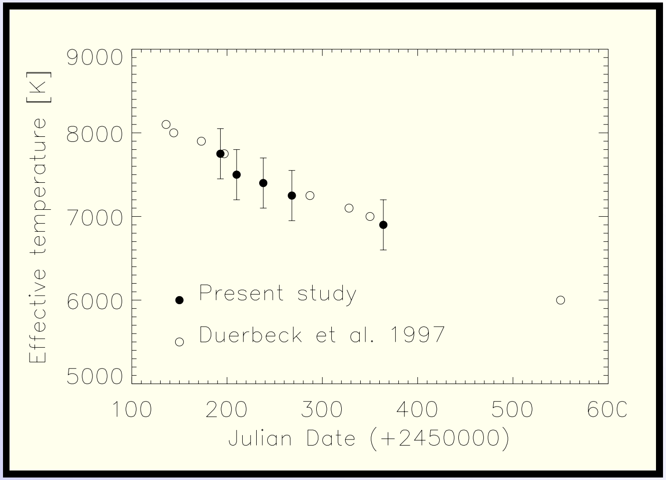
V4334 Sgr (Sakurai's Object, SO) (1)

- Extremely rapid cooling : *Dürbeck 1997, Asplund et al. 1999*

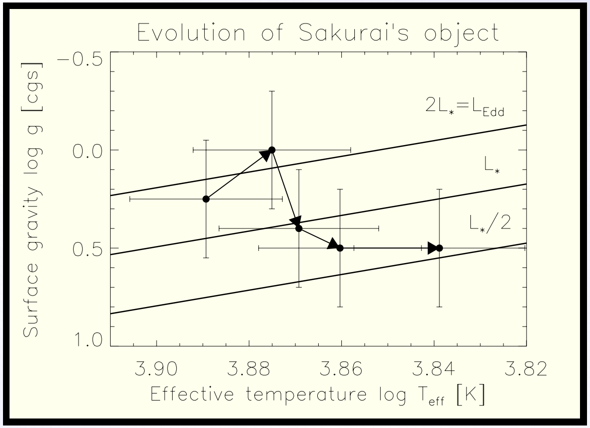
  1996/97: 1460 K/yr

- Further depletion of Hydrogen : *Asplund et al. 1999*

  1996/97: $H/He = 0.04 \Longrightarrow H/He = 0.004$



Cooling $\simeq 3 \times$ faster than for FG Sge, but slower than for V605 Aql



Evolution close to Eddington limit, $\log L/M \simeq 4.4$

V4334 Sgr (2)

Problem with the photospheric abundances :

Asplund et al. 1999

Inconsistency : assumed for the models $\mathrm{C/He} = 0.10$

spectroscop. determined $\mathrm{C/He} \simeq 0.02$

$\Longrightarrow$ Opacity problem ?

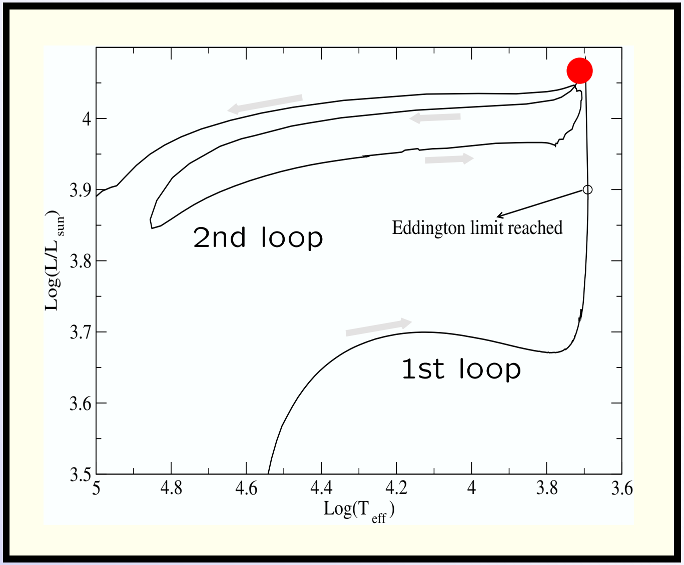
With $\mathrm{C/He} \simeq 0.02$:	$Y \simeq 0.85,\ X_\mathrm{C} \simeq 0.05,\ X_\mathrm{O} \simeq 0.03$
VLTP prediction:	$Y \simeq 0.32,\ X_\mathrm{C} \simeq 0.38,\ X_\mathrm{O} \simeq 0.22$
Typical PG 1159 composition	$Y \simeq 0.36,\ X_\mathrm{C} \simeq 0.40,\ X_\mathrm{O} \simeq 0.16$

There is something wrong with the VLTP simulations,
or the model atmospheres !

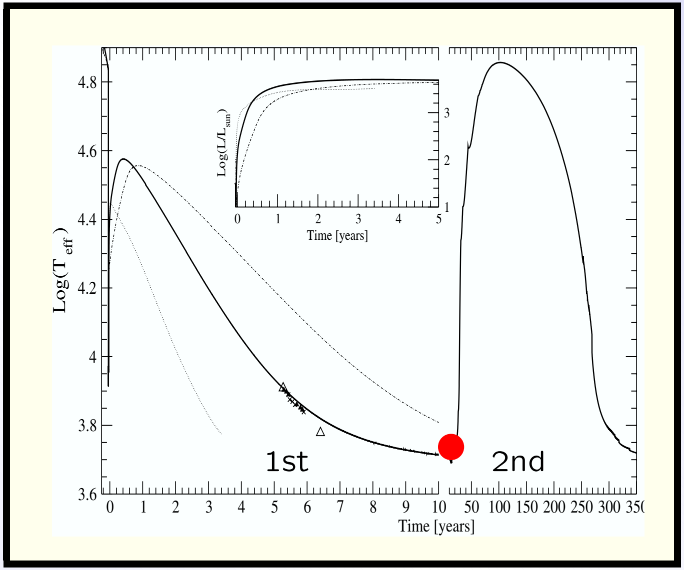
V4334 Sgr (3)

Predictions of VLTP simulations (1) :

0.584 $M_\odot$ *Miller Bertolami et al. 2006, Miller Bertolami & Althaus 2007*



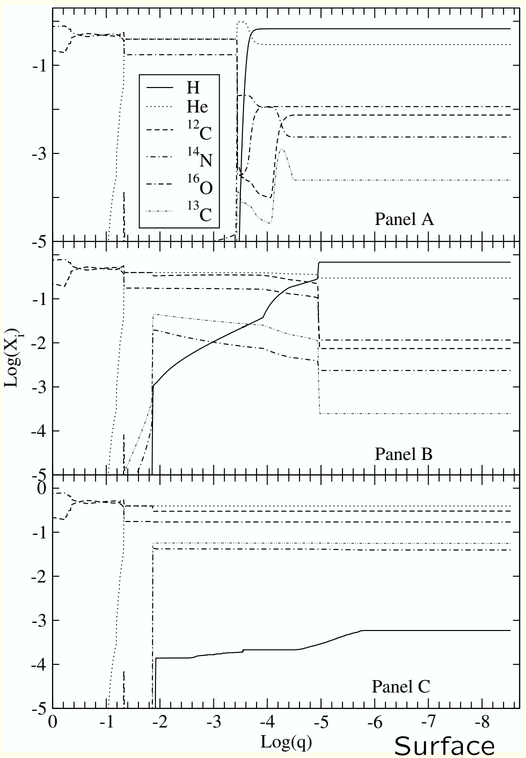
● Today



V4334 Sgr (4)

Predictions of VLTP simulations (2) :

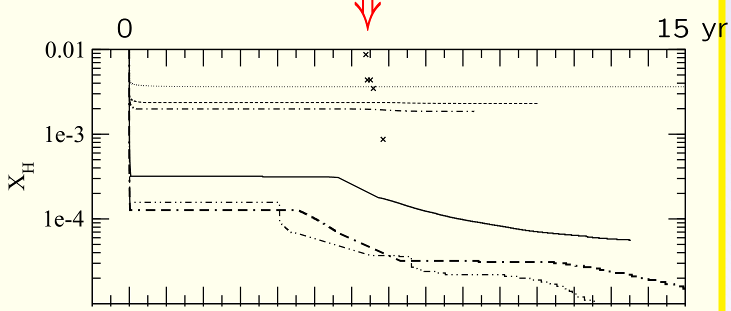
0.584 $M_\odot$ *Miller Bertolami & Althaus 2007*



A: Before, **B**: maximum, **C**: after

proton burning

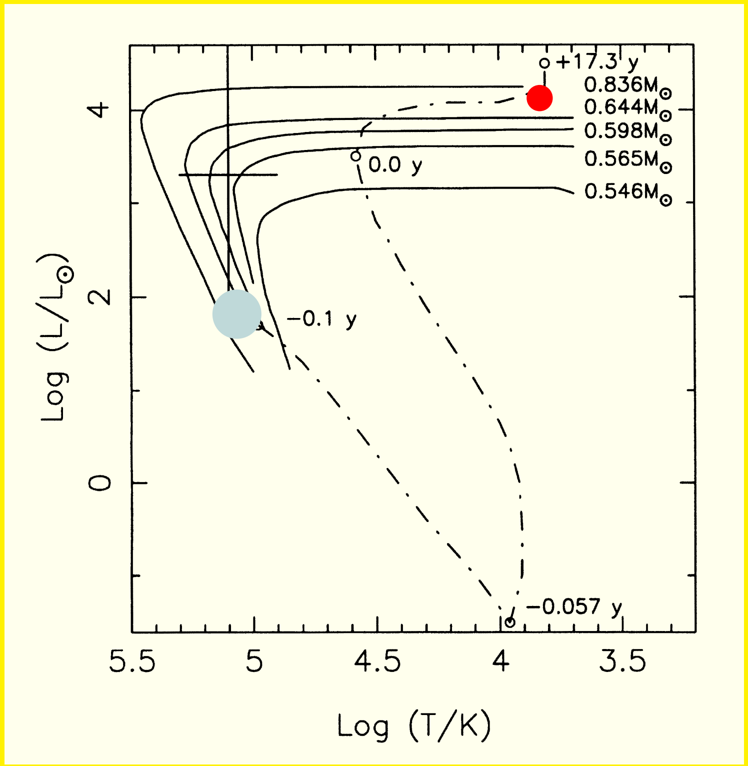
- H-envelope virtually completely mixed & burnt
- Positive radial H-abundance gradient
- Further H-dilution by surface convection (V4334 Sgr ?)



V4334 Sgr (5)

Photo-ionisation modelling of the PN :

Pollacco 1999, Kerber et al. 1999



Pre-flash Today

For all ions: $\tau_{\rm rec} \gg \tau_{\rm born-again}$

For species with
low ionisation energy:

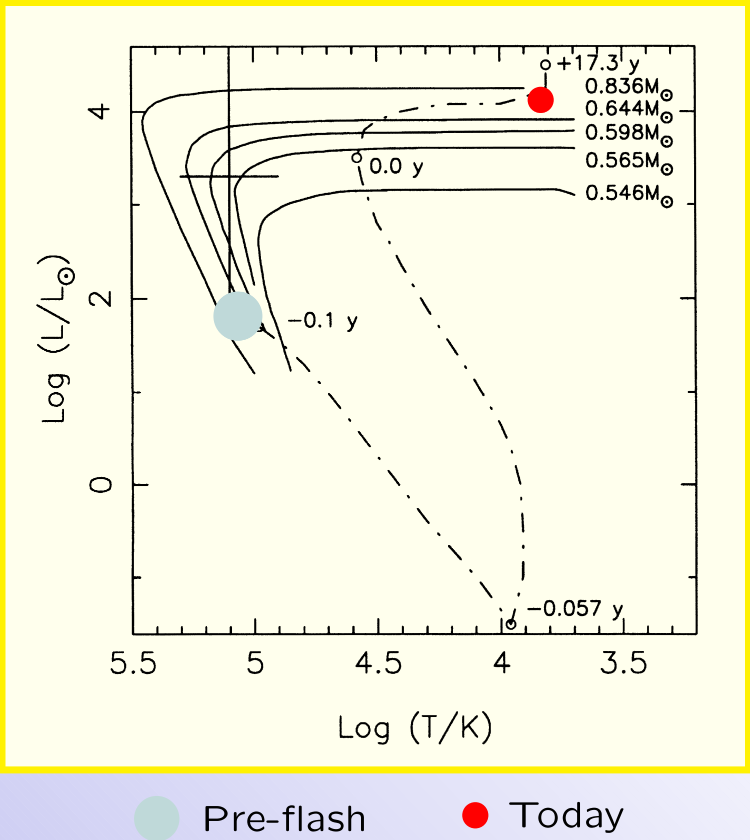
$\tau_{\rm ion} \gtrsim \tau_{\rm born-again}$

Again:

- *Use of standard photo-ionisation codes questionable !*
- *Derived stellar pre-flash parameters may not be correct !*

V4334 Sgr (6)

Central ionised matter :



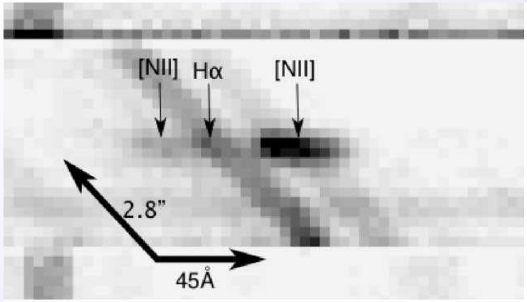
- Strong variation of the H-poor stellar wind expected :

  fast, hot & ionised $\longrightarrow$ *slow, cool & neutral*

- Central, H-poor expanding shell with

  $V_{\rm exp} \approx 500$ km s^{-1} & $D \simeq 1.5''$,

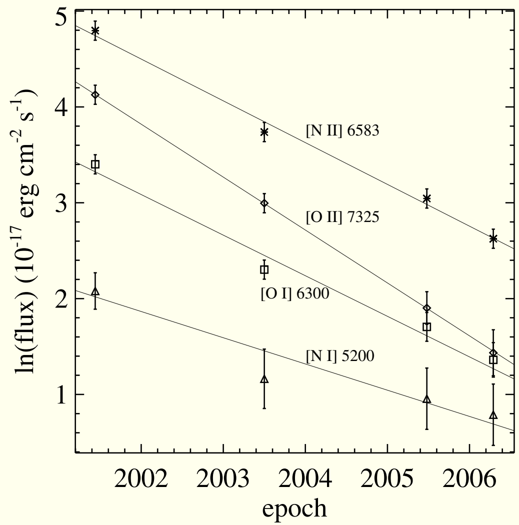
  created for ≈ 10 yrs by the stellar wind *Kerber et al. 2002*



V4334 Sgr (7)

Re-heating of the star (1) : *van Hoof et al. 2007*

Spectroscopy of the central knot/shell –



Post-shock cooling (?) – or just adiabatic expans. cooling of knot/shell (?)

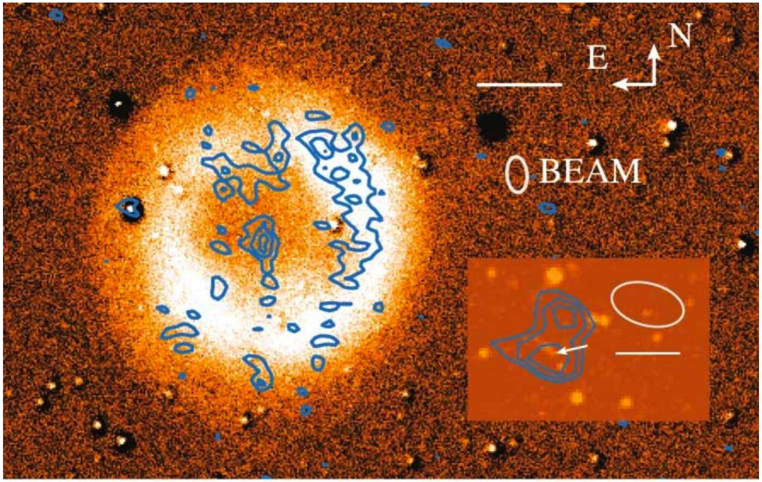


Fig. 1. Continuum-subtracted O^{2+} image showing the extended planetary nebula. Radio (8.6 GH contours are shown superposed at 30, 50, and 70 μJy per beam. A natural weighted map (beam 4.2 × 2.4 arc sec indicated by the oval) is shown. Scale bar, 10 arc sec. (Inset) An HST I-band (F814W image taken 29 August 2001. Sakurai's object (fainter of the two components, 0.2 arc sec apart) indicated by an arrow. The superposed radio data show a uniform weighted map (beam of 2.2 1.3 arc sec, indicated by the oval) with contours at 25, 35, and 45 μJy per beam. The old planetai nebula is 41 arc sec in diameter; its brighter inner ring is 29 arc sec across. Scale bar, 2 arc sec

During the same time, increasing radio flux, probably due to ionisation of C I *Hajduk et al. 2005*

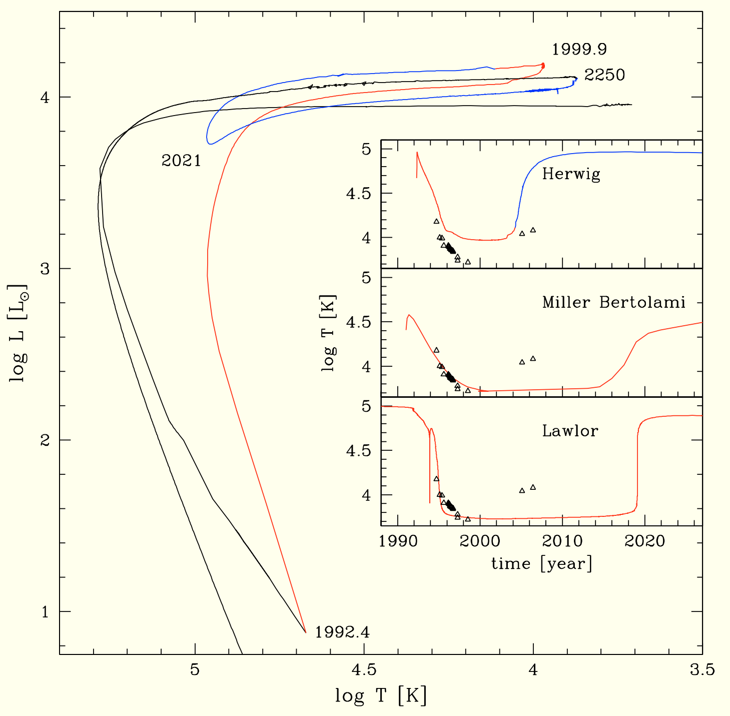
Stellar temperature ⇒ 12 000 K
with ≃1000 K/yr

V4334 Sgr (8)

Re-heating of the star (2) :

van Hoof et al. 2007

Comparison with existing VLTP calculations –



all models have problems

either with $T_{\rm eff}$, or with the re-heating/re-contraction time scale

Fine-tuned mass-loss rates may lead to correct giant lifetimes

Summary

- FG Sge, V605 Aql, Sakurai –

  most important objects to test the theory of late stellar evolution & nucleosynthesis

- FG Sge, V605 Aql, Sakurai –

  Analysis & interpretation of observational data hampered by severe difficulties

  - Determination of hydrogen in cool H-deficient atmospheres where helium is not visible !
  - Carbon problem of cool H-deficient atmospheres ?
  - Thermal & ionisation equilibrium of nebular structures ?
  - ...

- FG Sge, V605 Aql, Sakurai –

  More observational efforts & better theoretical interpretations badly needed !