Observations of born-again stars

Royal Observatory of Belgium

Peter van Hoof (Brussels)

Stefan Kimeswenger (Antofagasta)
Griet Van de Steene (Brussels)
Adam Avison (Manchester)
Albert Zijlstra (Manchester)
Lizette Guzman Ramirez (Leiden)
Falk Herwig (Victoria)
Marcin Hajduk (Torun)

Outline

Royal Observatory of Belgium

Introduction

The sample of born-again stars

Individual objects:

- FG Sge
- V605 Aql
- A30 & A78
- V4334 Sgr

Summary

Problems / Controversies

Introduction

Royal Observatory of Belgium

During the AGB evolution, intermediate mass stars will have both a hydrogen- and helium-burning shell.

Usually the hydrogen shell is active, but at semi-regular intervals the helium shell will ignite and briefly take over energy production (when sufficient helium has accumulated above the layer). These shell flashes are usually called thermal pulses.

For most stars the final thermal pulse will happen when they are still on the AGB, but around 10-20% of these stars (according to theory) will have one final thermal pulse after they leave the AGB.

When the final thermal pulse happens while the hydrogen burning layer is still active (i.e., while the star is on the horizontal track), we call such an object a Late Thermal Pulse (LTP) object.

When the hydrogen burning layer is inactive (i.e., when the star is on the cooling track) we call such an object a Very Late Thermal Pulse (VLTP) object.

Introduction

Royal Observatory of Belgium

LTP's and VLTP's are profoundly different. The reason is the hydrogen burning layer.

When a VLTP ignites, it triggers convection that will mix the remaining hydrogen-rich atmosphere into the helium burning shell.

This will cause violent burning (the Hydrogen Ingestion Flash or HIF) splitting the convection region. The HIF region will be characterized by i-process nuclear burning, leading to a very different chemical signature (talk by Falk Herwig). The star will experience a double loop in the HR diagram.

None of this happens in an LTP as the hydrogen burning layer prevents the convection from reaching the H-rich outer layer. The star will experience a single loop and the evolution will be roughly a factor 10 slower.

The Sample

Royal Observatory of Belgium

The sample of well-studied (V)LTP objects is very short:

- FG Sge (LTP)
- V4334 Sgr (Sakurai's object) (VLTP)
- V605 Aql (A58) (VLTP) → Stefan Kimeswenger
- A30 (VLTP)
- A78 (VLTP)

Less studied / possible objects:

- IRAS 15154–5258 (VLTP) → Stefan Kimeswenger
- HuBi 1 (VLTP) → Marcelo Miller Bertolami
- NSV 11749 (VLTP)
- IRAS 18333–2357 (VLTP, in M22, possibly merger?)

The Sample

Royal Observatory of Belgium

Possible objects (continued):

- SAO 244567 (Hen 3–1357, Stingray) (LTP or close binary)
- J1810–3305 (circumstantial evidence, needs confirmation)

Rejected objects:

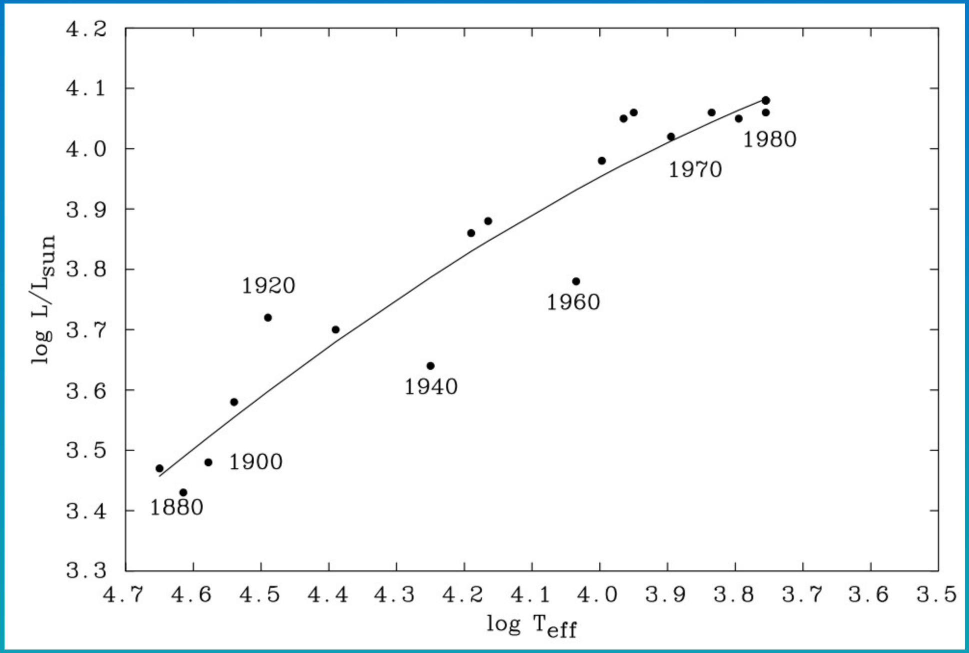
- CK Vul
- R CrB stars

Related objects:

- [WR] stars
- PG 1159 stars

FG Sge

A LTP that exploded in the 19th century. Has been cooling and increasing in luminosity for most of the 20th century.



(Jeffery & Schönberner 2006)

In 1992 it ejected a shell and formed a lot of dust. Since then it had a series of episodes where the star dimmed significantly.

Royal Observatory
of Belgium

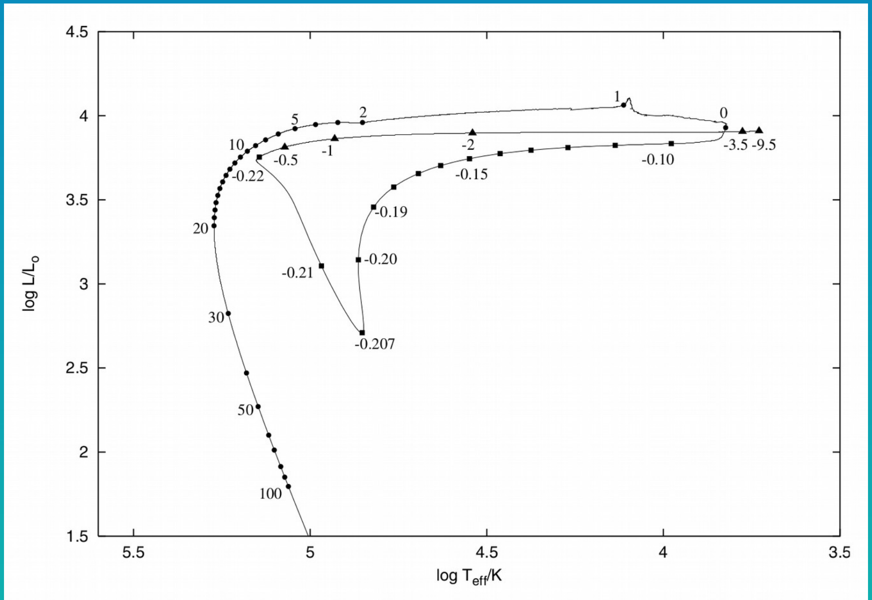
FG Sge

Before 1992 the star was hydrogen-rich, but since then the star has become hydrogen-poor while other abundances stayed the same (Jeffery & Schönberner, 2006).

After 1992 the infrared SED stayed roughly the same and is dominated by dust grains at near-sublimation temperatures (Gehrz+, 2005).

The central star now seems to be at the minimum temperature of the loop (Jeffery & Schönberner, 2006).

This object agrees quite well with the evolution as it was under-stood before V4334 Sgr…



V605 Aql

Royal Observatory of Belgium

The object was discovered in 1919. In 1921 a spectrum was taken that showed a cool star (~5000 K), very similar to V4334 Sgr in its early phase (Clayton & de Marco, 1997).

Soon after that dust formation started and the object was lost to contemporary instrumentation.

The spectrum now shows a hot [WR]-type central star. It is often referred to as “Sakurai’s older twin” and is widely believed to show what V4334 Sgr is supposed to evolve into.

Noteworthy is Seitter (1987):

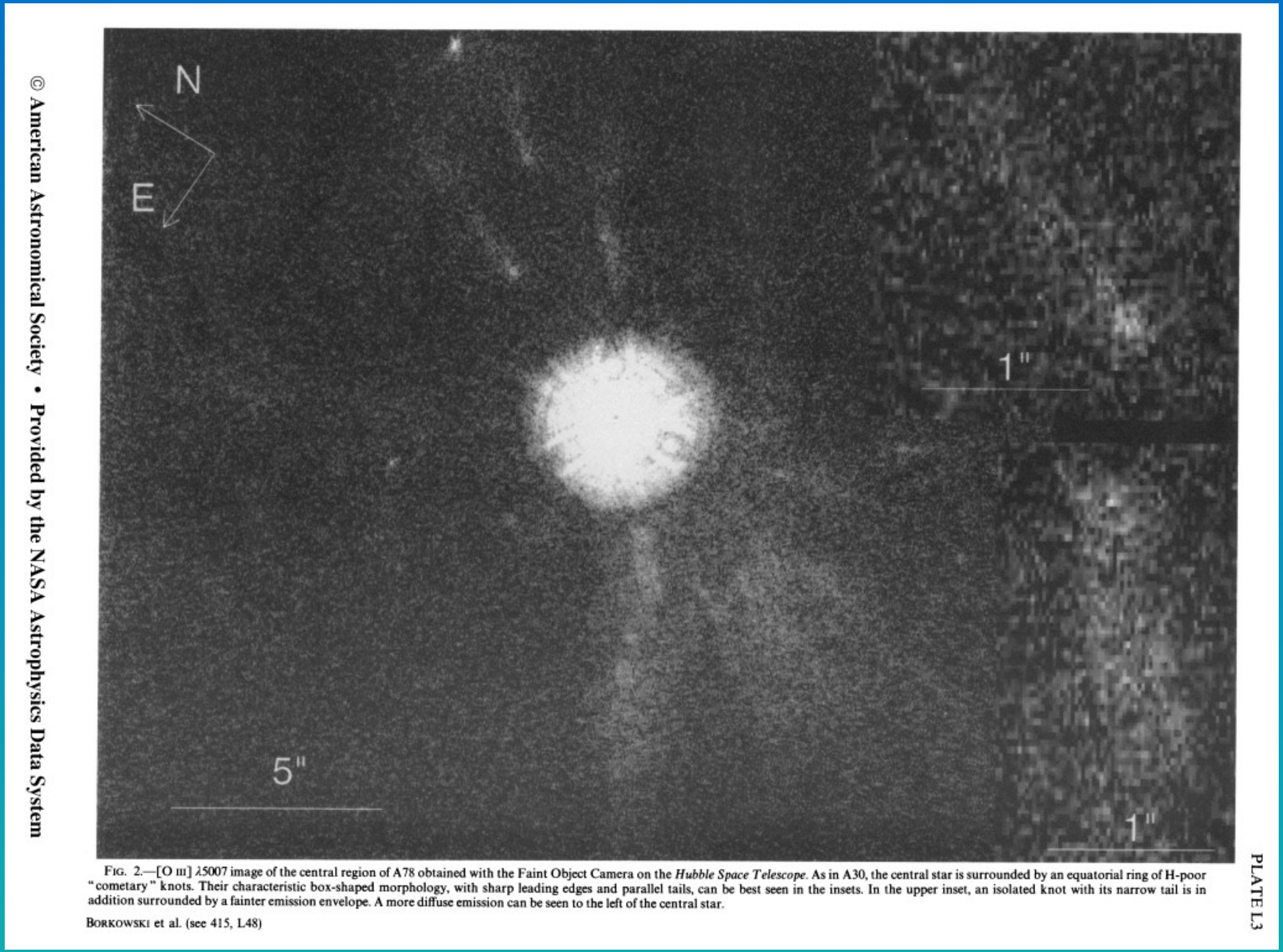
300 $L_\odot$. It places the object in the H-R diagram in a position which central stars of 0.6 $M_\odot$ reach thousands of years after a late final helium shell flash (Iben et al. 1981). This is more than two orders of magnitude longer than the time which V 605 Aql has actually taken to reach the place computed with the above assumptions. Even a higher mass star would still need much longer than a few tens of years. Observationally, V 605 Aql

A30 & A78

Royal Observatory of Belgium

- These are oldest known VLTP objects. They exploded ~1000 yr ago (Fang+ 2014).
- The disk has fragmented into cometary knots in these objects. Despite their high age, they are cold, dusty and molecular at their center (Wesson+ 2003; Tafoya+ 2017).
- Stochastic heating required to explain dust spectrum (Borkowski+ 1994; Kimeswenger+ 1998) → very small grains present.
- Both objects also show knots in the polar direction. Dense knots are heated by photoionization while tenuous gas is heated by PE effect (Borkowski+ 1993).
- Wesson+ (2003) found C/O < 1 in one of the hydrogen-deficient knots of A30.
- Both objects have been detected in X-rays, believed to be from shocks between the very fast wind and the shell and knots (Chu+ 1995; Guerrero+ 2012; Toalá+ 2015).

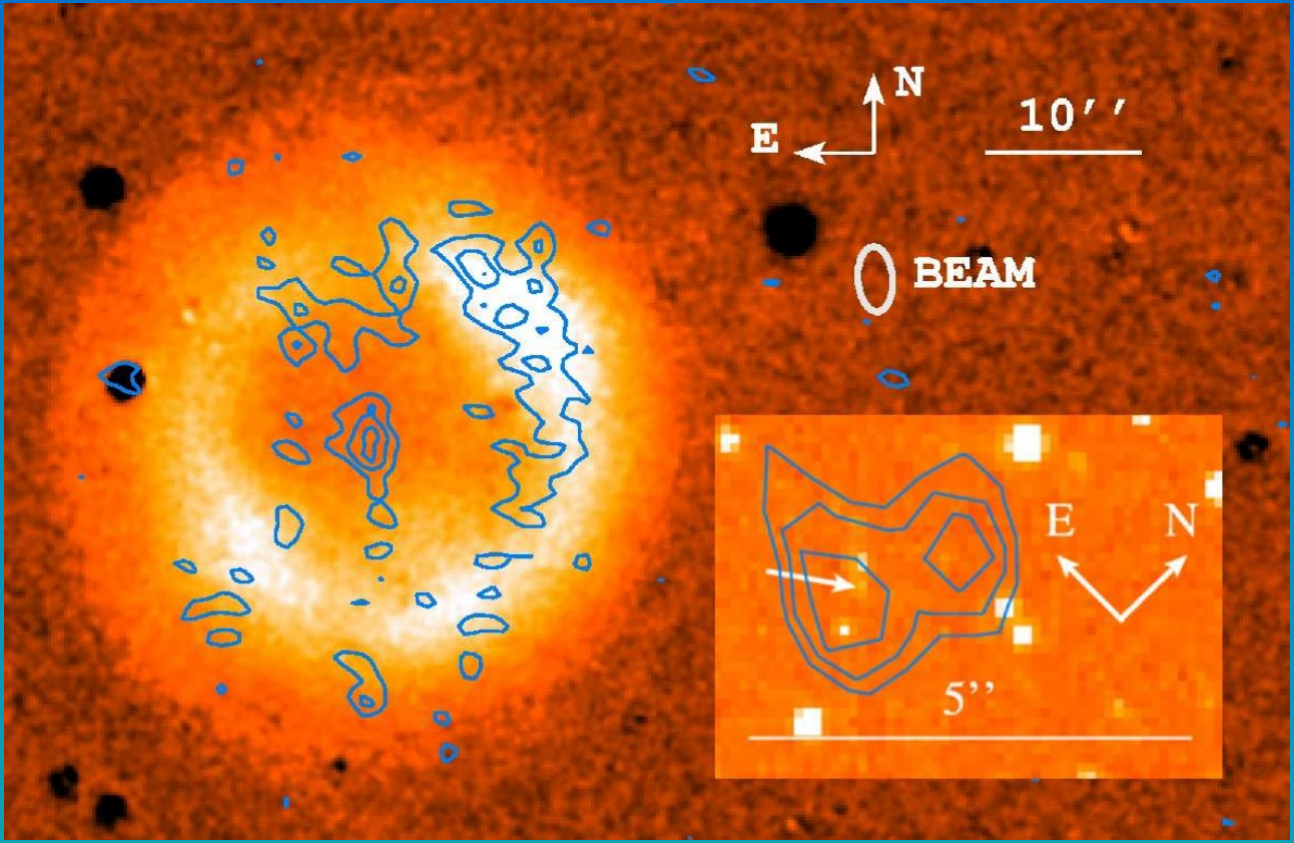
A78



An HST [O III] 5007 image of A78 (Borkowski+ 1993).

V4334 Sgr

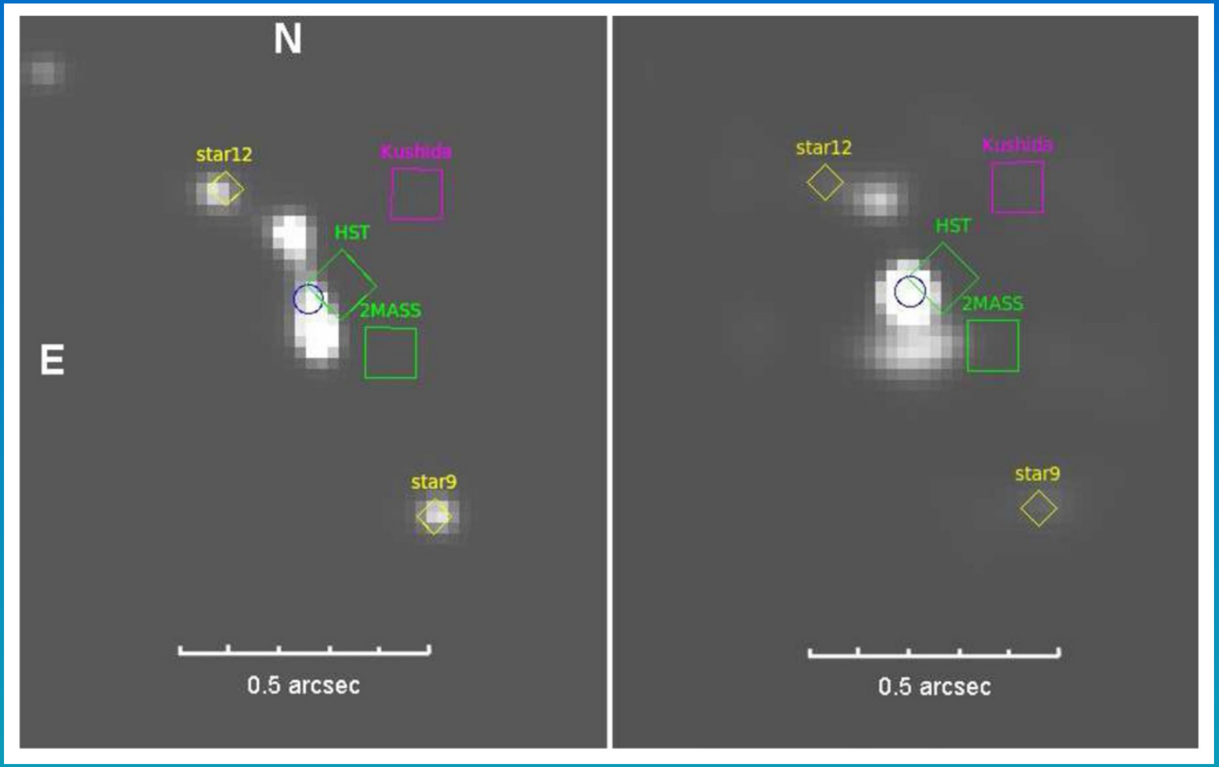
Royal Observatory of Belgium



[O III] image of the old PN with the radio contours from the 2004 VLA observations superimposed (Hajduk+ 2005).

Note that the old PN is round, while the new ejecta are bipolar!

Ks imaging



Deconvolved Ks images taken in 2010 (left) and 2013 (right) by Hinkle & Joyce (2014, hereafter HJ14).

The expansion of the bipolar structure can clearly be seen, the central star also seems to be brightening in the NIR.

Image credit: Hinkle & Joyce (2014).

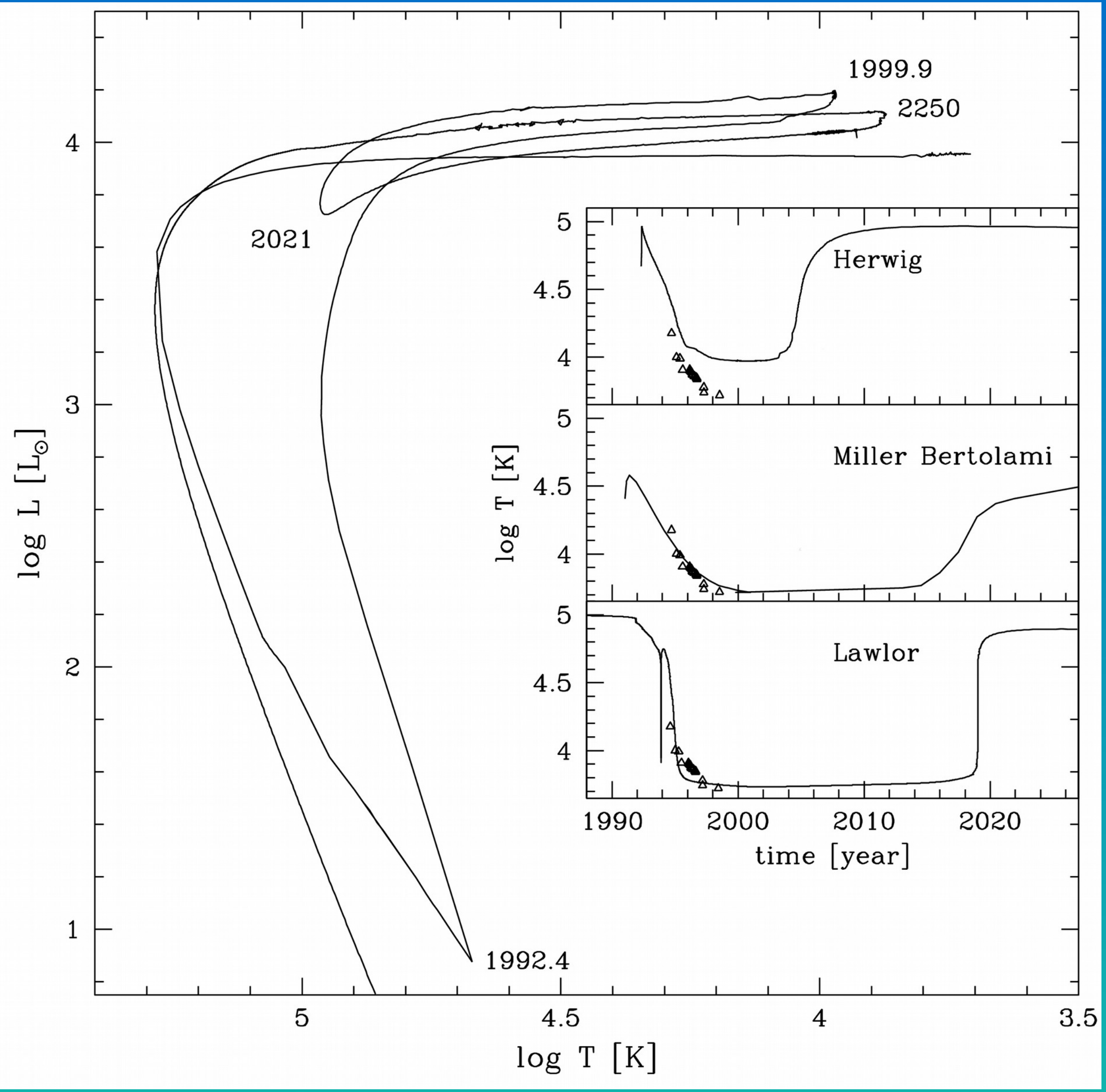
Evolutionary Models

Royal Observatory of Belgium

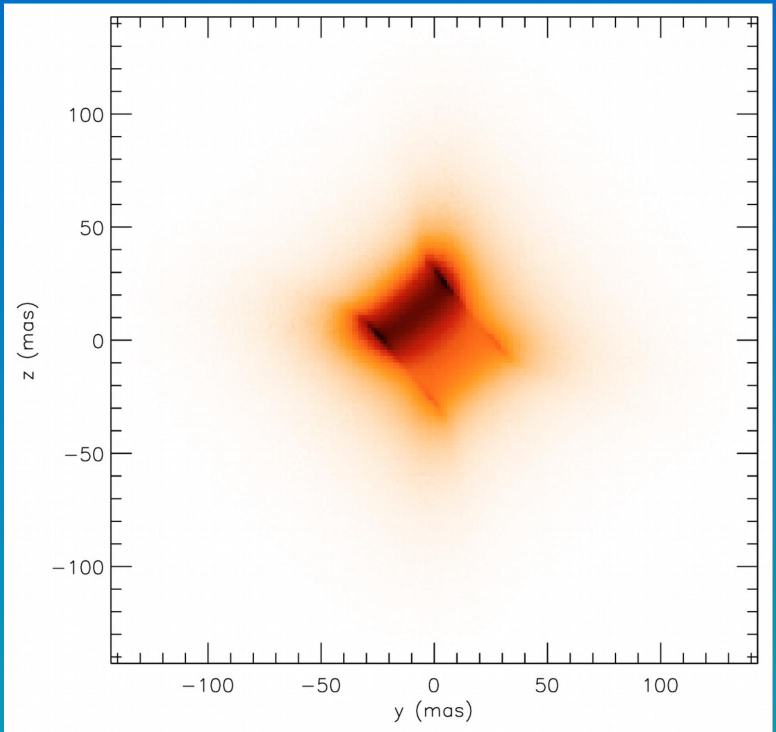
- Sakurai's object baffled the scientific community with its very fast evolution, much faster than pre-discovery models predicted.
- Three evolutionary models have been proposed to explain the fast evolution, all focusing on the hydrogen ingestion flash in the helium burning shell.
- Herwig (2001, ApJ, 554, L71) and Lawlor & MacDonald (2003, ApJ, 583, 913) assume that hydrogen burning takes place close to the stellar surface due to the HIF. This is investigated further by Herwig using full 3D hydro models.
- Lawlor & MacDonald (2003) were the first to predict the double-loop evolution in the HR diagram, later confirmed by Herwig's model in Hajduk et al. (2005, Science, 308, 231).
- Miller Bertolami et al. (2006, A&A, 449, 313) claim that they can reproduce very fast evolution by using very small time steps, but without changing the mixing physics.

Evolutionary Models

Royal Observatory of Belgium



VLTI observations



Chesneau+ (2009) observed Sakurai's object using VLTI. They detected the presence of a thick and dense dust disk with dimensions 30x40 mas. This equates to 105x140 AU assuming D= 3.5 kpc. Shown above is a model at 13 μm.

Image credit: Chesneau+ (2009).

Optical Observations

Royal Observatory of Belgium

We have been monitoring the evolution of the optical emission line spectrum since 2001. Its evolution is different from the radio flux.

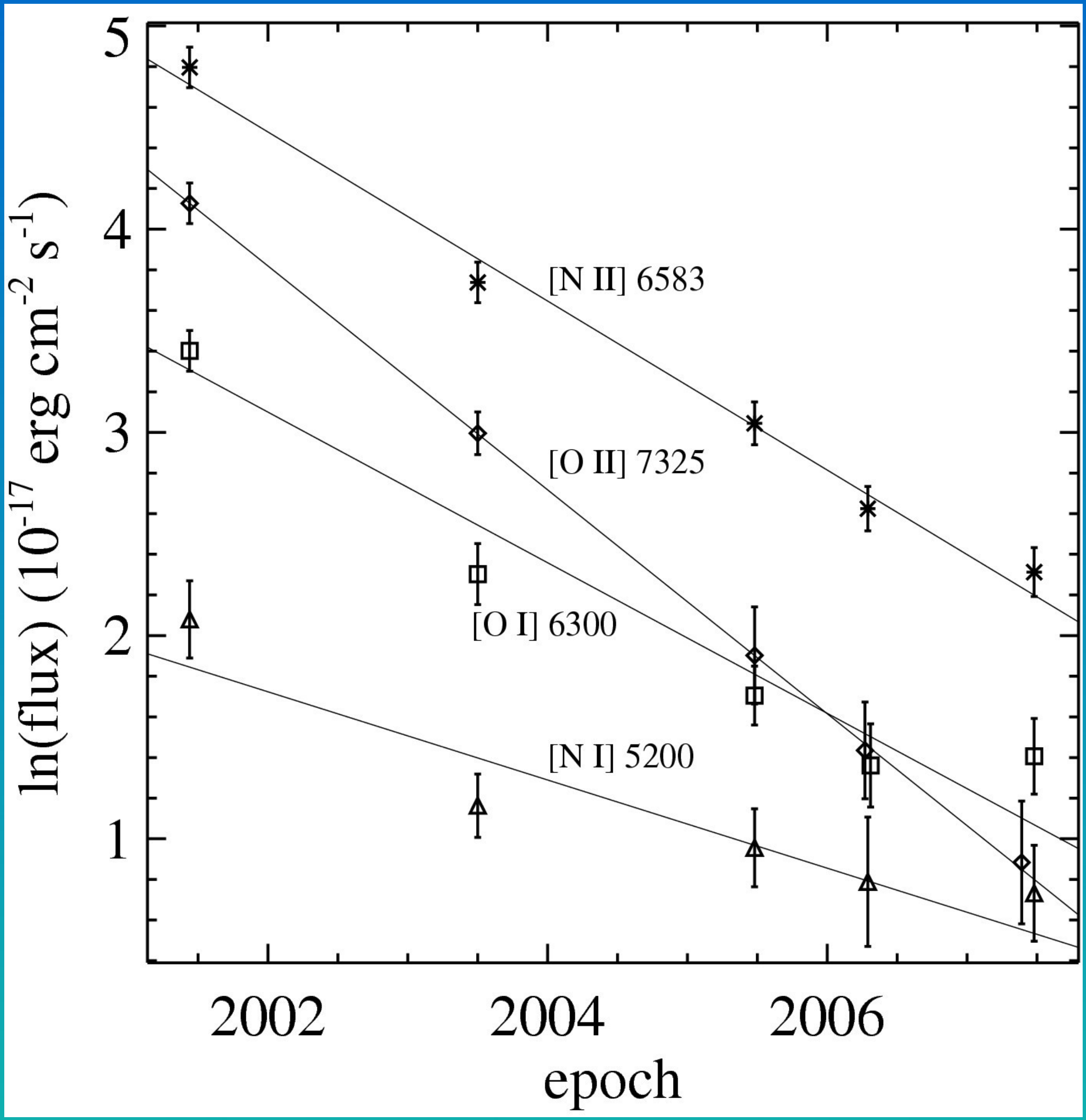
The optical lines initially showed an exponential decline in intensity, and also a decreasing level of excitation. This trend continued until 2007.

Between 2001 and 2007 the optical spectrum is consistent with a shock that occurred before 2001, and started cooling and recombining afterwards. The low T_e derived from the [N II] lines in 2001 (3200 – 5500 K) and the [C I] lines in 2003 (2300 – 4300 K) is consistent with this.

The earliest evidence for this shock is the detection of the He I 10830 recombination line in 1998 (Eyres+ 1999). This line was absent in 1997. The shock must have occurred around 1998 and must have stopped soon after, leaving cooling and recombining gas in its wake.

van Hoof et al., 2007, A&A 471, L9

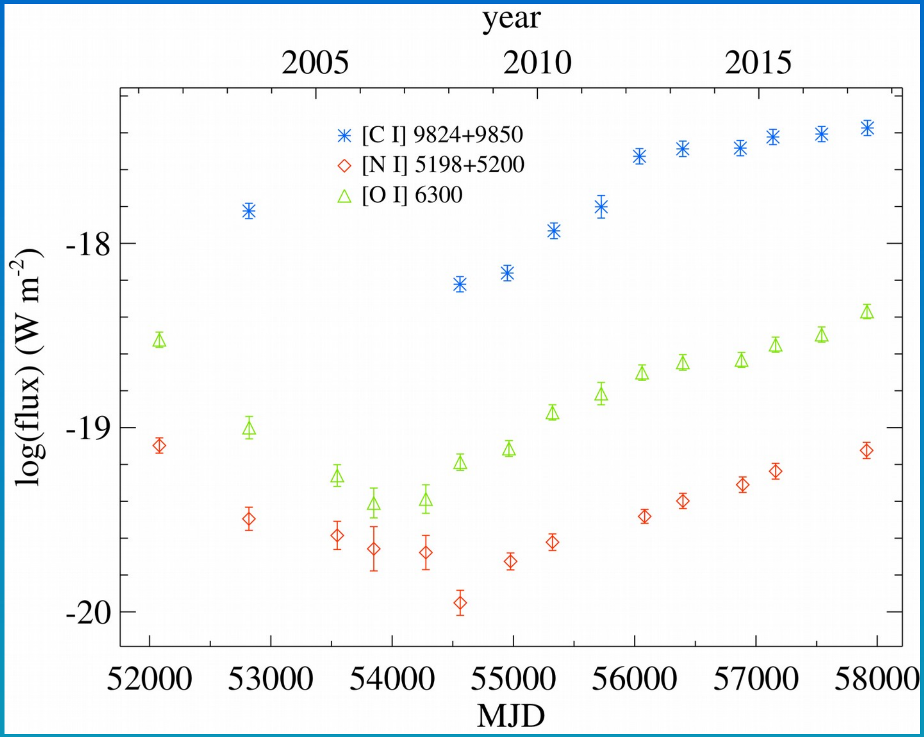
(figure has been extended with 2007 data)

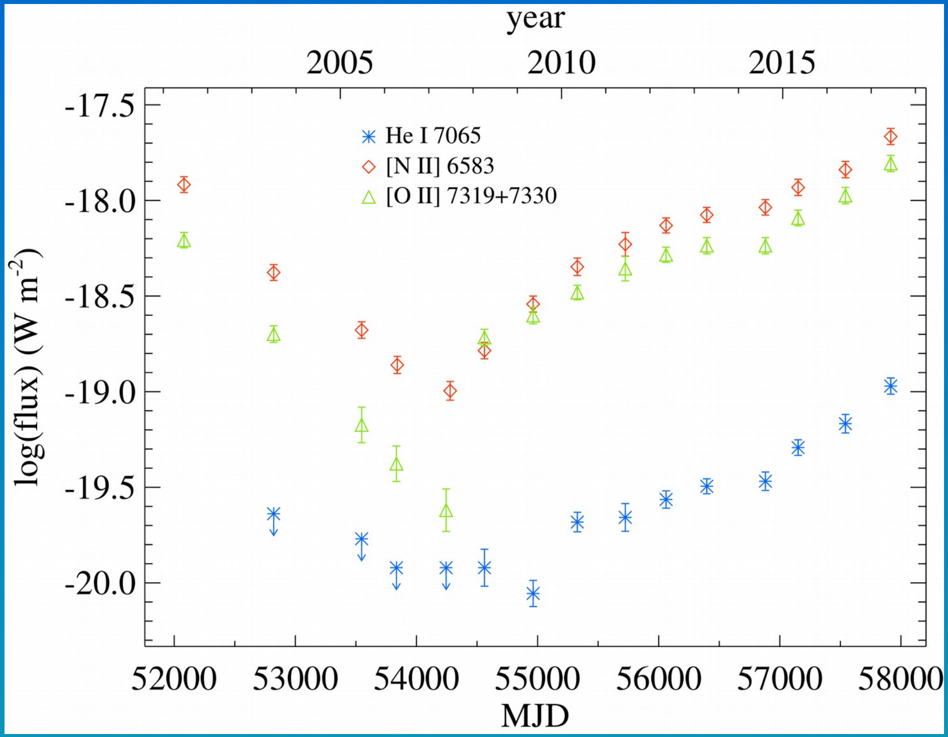


Royal Observatory of Belgium

Line flux evolution up to 2017

Royal Observatory of Belgium





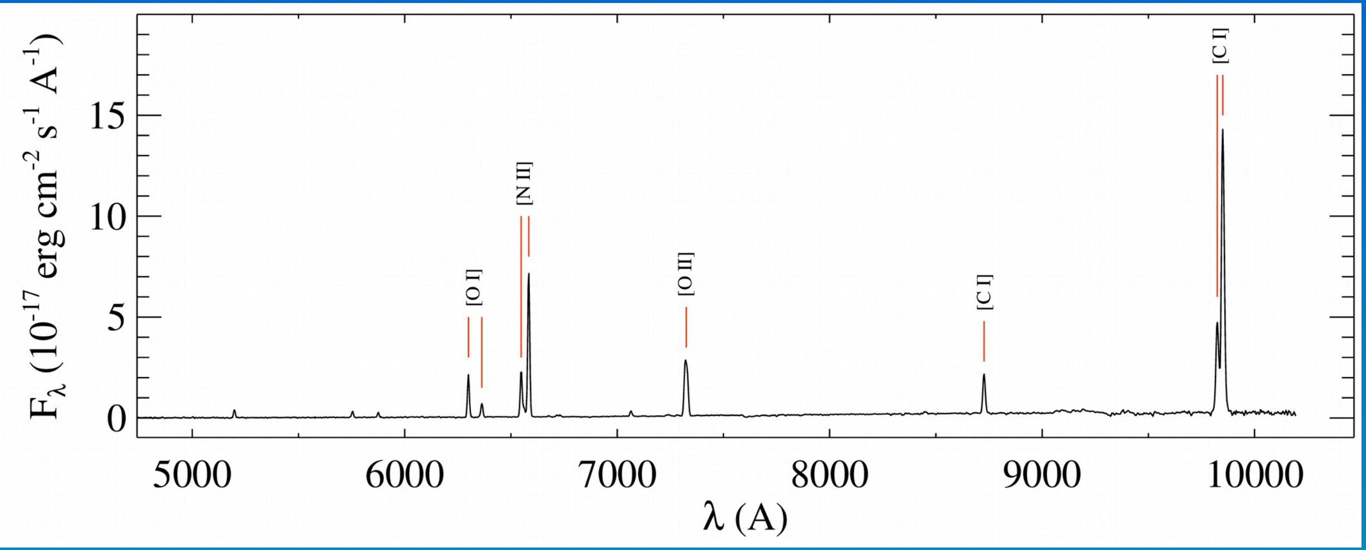
Line fluxes have been monotonically increasing since 2008! This confirms the trend for [C I] 9823/50 seen by Hinkle & Joyce (2014).

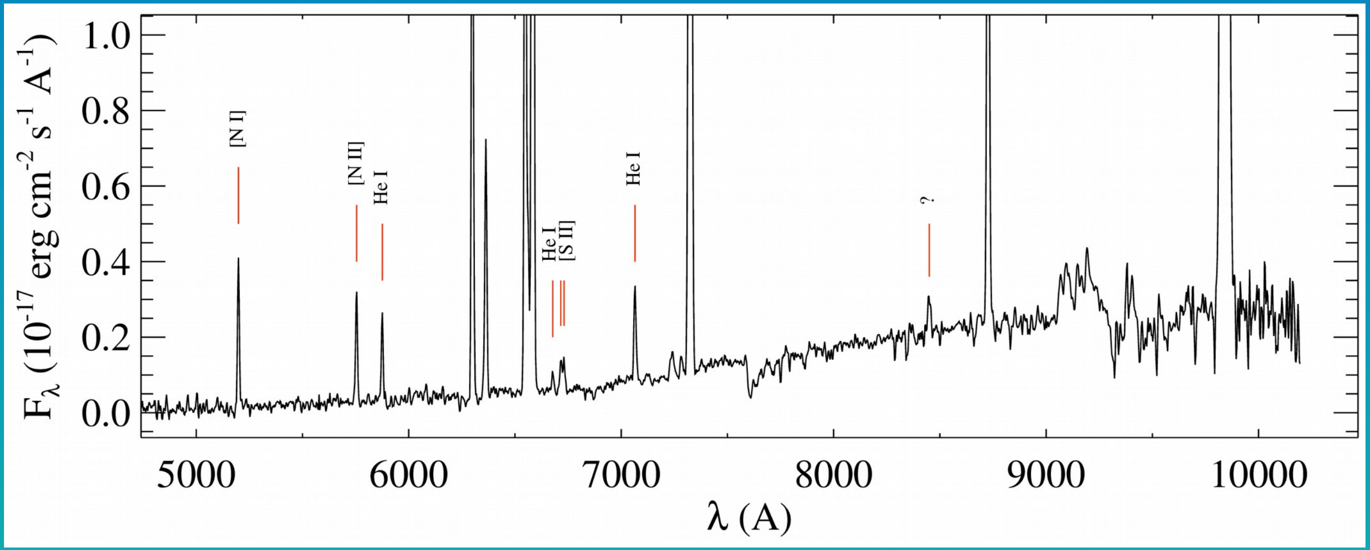
Three exceptions: [O I] started increasing in 2007, [N I] dropped in 2008 and He I dropped in 2009. However, these lines are weak and some suffer from telluric contamination, so this may not be real.

There is a strong discontinuous jump in the [O II] flux in 2008!

Optical spectrum 2013

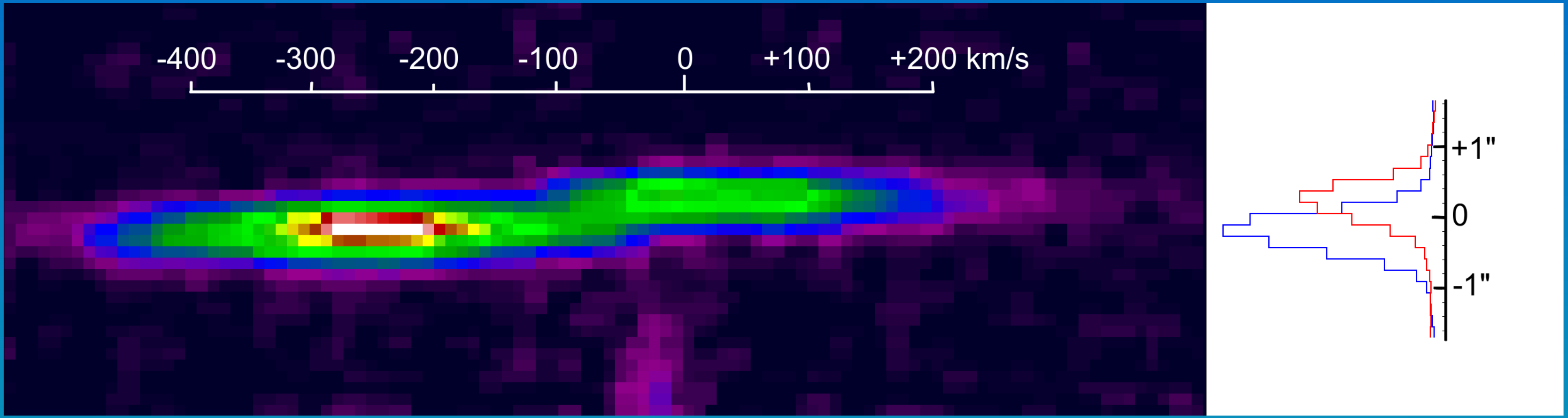
Royal Observatory of Belgium





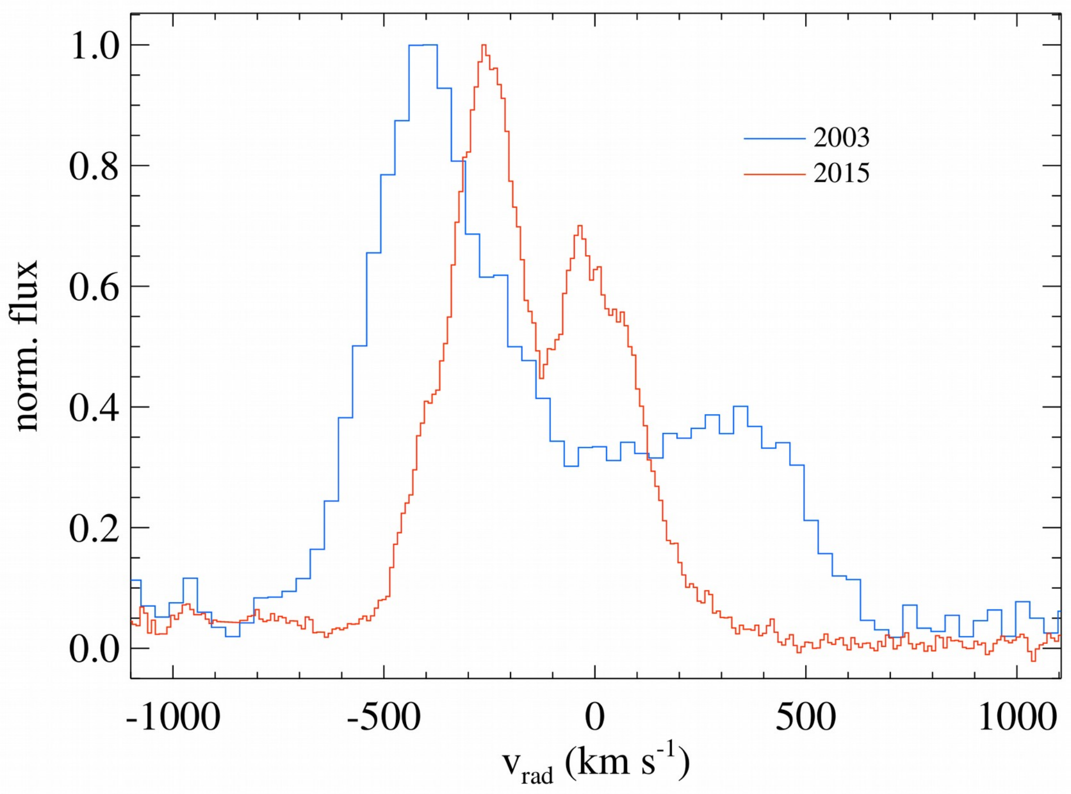
The nebular lines

Royal Observatory of Belgium



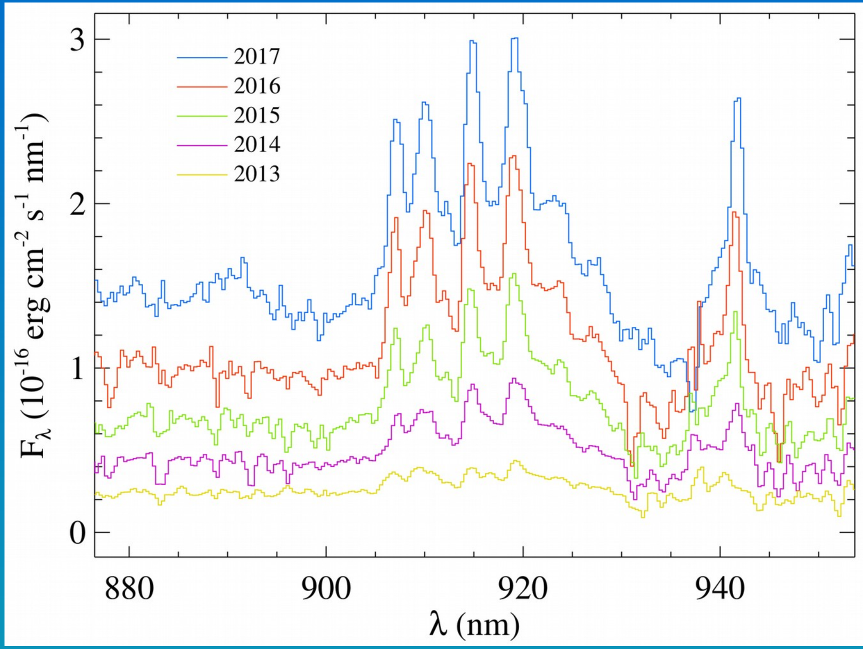
Looking at the XSHOOTER PV diagram of [N II] 6583 we can clearly see that the blue and red emission comes from different regions. The redshifted and blueshifted emission regions are +0.24” and -0.18” displaced wrt the continuum source. From this we conclude that the forbidden and recombination lines come from the bipolar lobes seen by HJ14.

The nebular lines



Comparing the [N II] 6583 line profile in 2003 (FORS2) and 2015 (Xshooter), we can see that the line has become narrower and also seems shifted. The systemic velocity is 0 km s^{-1}. We conclude that the outflow is decelerating, possibly due to mass loading.

A new line complex



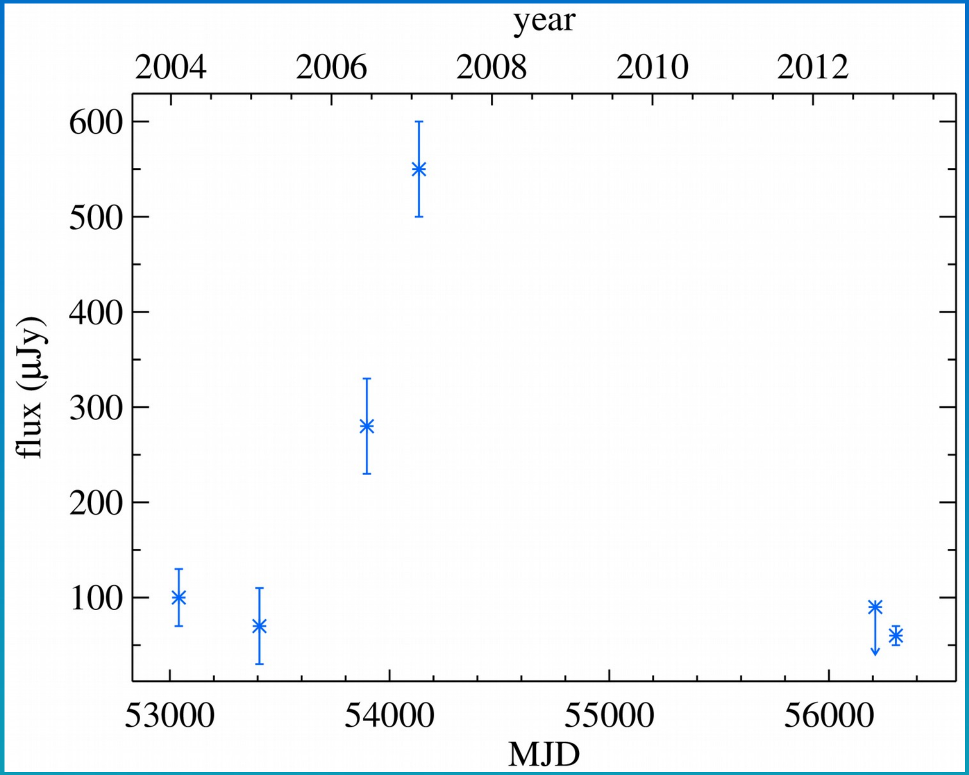
Since 2013 a complex of new lines has been emerging in the red. Many of these lines are still unidentified.

We tentatively identify some of these as electronic transitions in CN (the 1,0 and 0,0 lines of A $^2\Pi_1 \rightarrow$ X $^2\Sigma^+$ – the 0,0 lines would be the unidentified lines reported by HJ14). We also identified the Na I doublet at 589.0 and 589.6 nm.

The continuum is also rising, this was already reported by HJ14.

8 GHz VLA Observations

Royal Observatory of Belgium



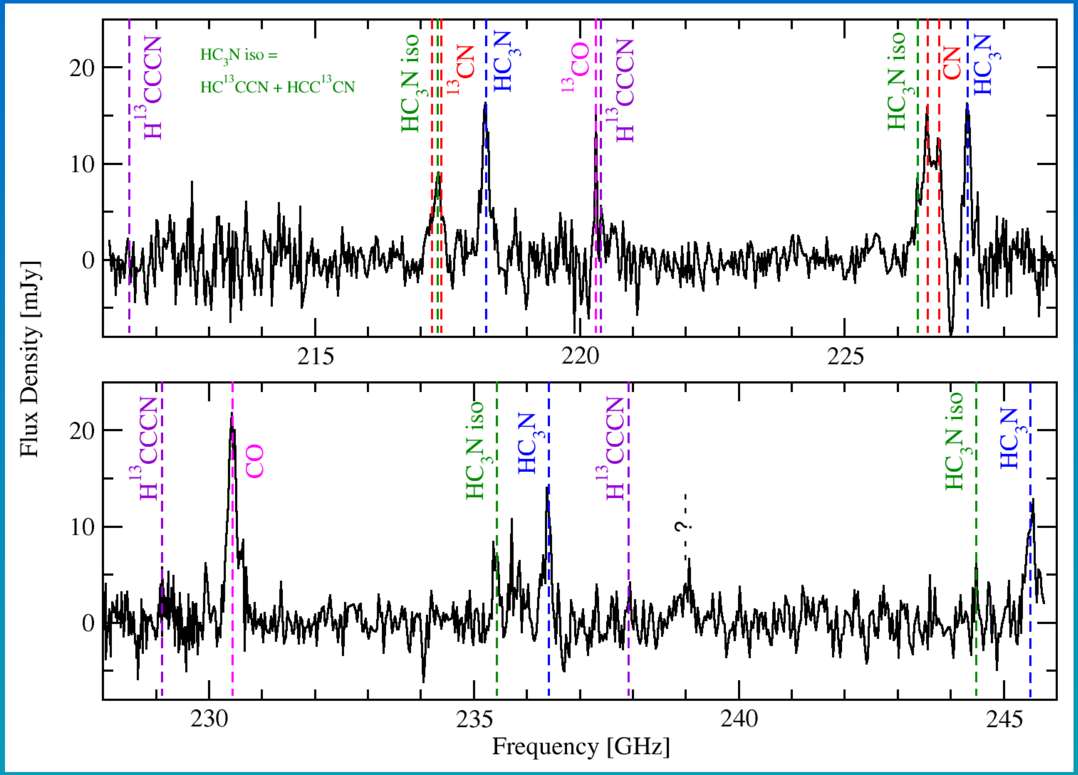
Between 2004 and 2007 the radio flux was increasing.

At the time we interpreted that as evidence for the onset of photoionization.

The most recent data show that the source has faded. The only plausible explanation is that the flux rise was due to a shock.

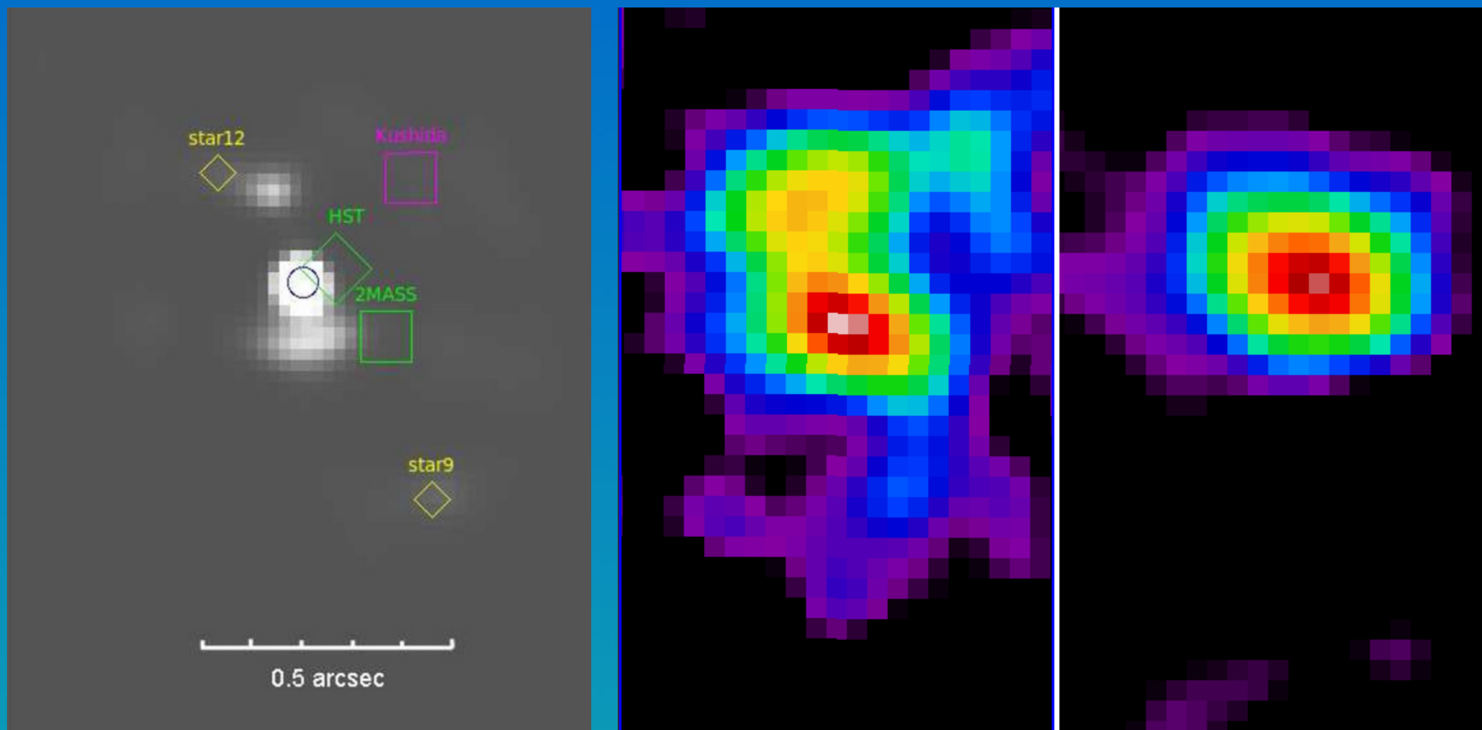
Royal Observatory of Belgium

ALMA spectrum



We detect lines of CO, ^{13}CO, CN, likely ^{13}CN (blended), HC_3N, HC_3N iso, and possibly $H^{13}CCCN$. The absorption on the blue side of the CN is real and associated with CN. There is also an unidentified line at 239 GHz.

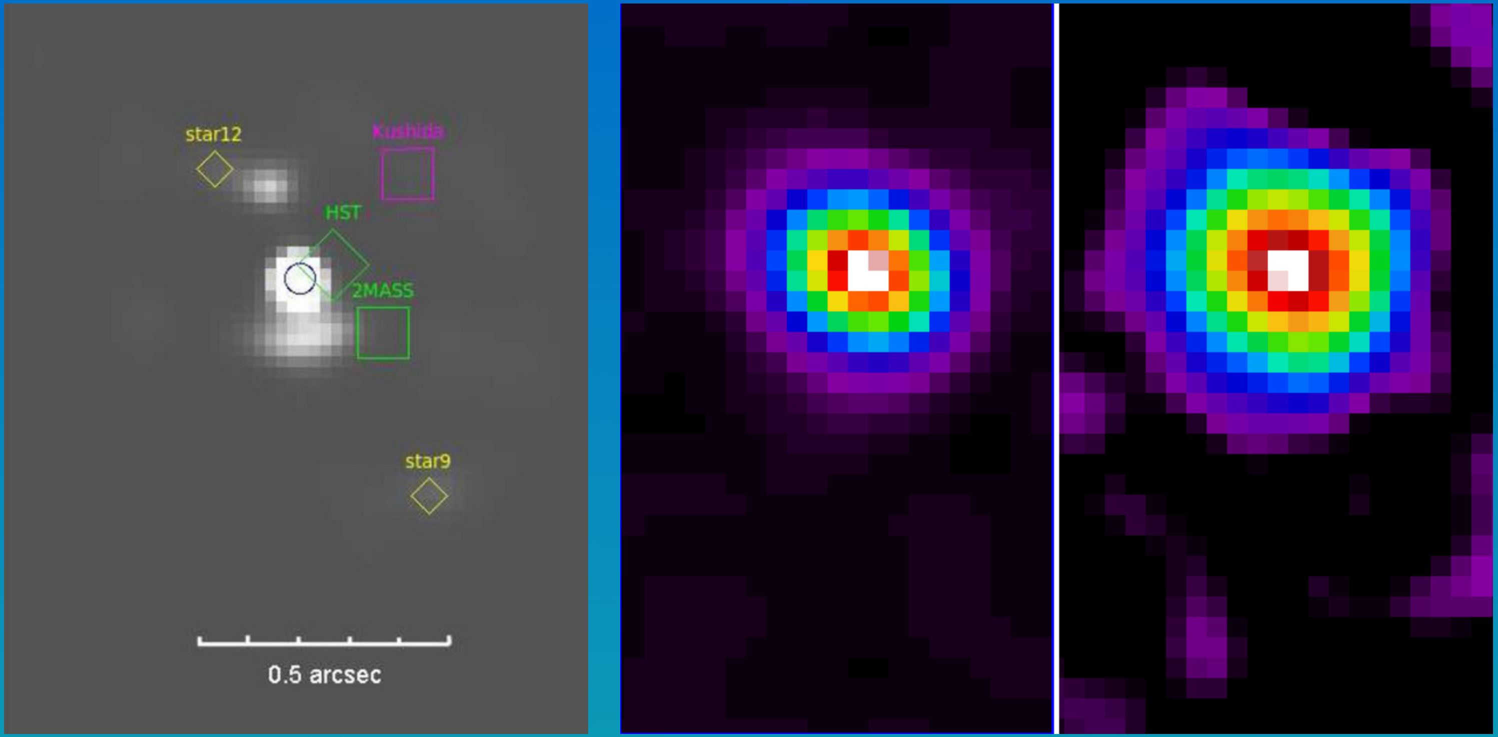
ALMA CN and CO



On the left we repeat the Ks image from 2013 by HJ14. In the middle we show the CN emission and on the right the CO emission detected by ALMA in 2015.

The CN emission is bipolar and coincides with the bipolar lobes. The CO emission is (nearly) point-like and coincides with the central star.

ALMA Continuum and HC_3N



On the left we repeat the Ks image from 2013 by HJ14. In the middle we show the continuum image and on the right the HC_3N emission detected by ALMA in 2015.

Both the continuum and HC_3N emission are nearly point-like and coincide with the central star. There is no continuum emission detected in the lobes!

Preliminary discussion

Royal Observatory of Belgium

V4334 Sgr underwent a VLTP a few years before its discovery in 1996. It ejected a new, hydrogen-deficient nebula in the process.

The geometry of the source was clarified by Chesneau+ (2009) who discovered the presence of a dense and thick dust disk with dimensions 30x40 mas using VLTI. The disk must have formed in the VLTP event and was already in place in 1997. It may be a keplerian disk. All the dust is in the disk.

HJ14 discovered the presence of bipolar lobes in the Ks band. These appear to be expanding. The total extent of these lobes along the major axis is ~ 0.4 arcsec.

Emission lines were first discovered in 1998 (He I 10830) and 2001 (optical). The optical emission spectrum has been monitored since, showing an exponential decline in flux and the level of excitation also dropped. We see this as evidence for a brief shock that occurred around 1998.

Preliminary discussion

Royal Observatory of Belgium

A plausible explanation is that this is the fastest material ejected in the VLTP hitting slower ejecta from the same event.

Between 2005 and 2007 the 8 GHz radio emission showed a marked increase. The radio flux has returned to pre-2005 levels since. We see no counterpart for this behavior in the optical data. A shock in an obscured region?

The optical line fluxes started to increase again since 2008. The sudden jump in the [O II] flux in 2008 could point to a second shock as the cause of the change in behavior. The shock breaks out of the obscured region?

Our working hypothesis is that the wind is now interacting with the lobes. The nebular lines are now formed there. This is confirmed by Xshooter spectra.

The optical spectrum shows new lines which have been emerging since 2013. Some have tentatively been identified as electronic transitions of CN and Na I.

Preliminary discussion

Royal Observatory of Belgium

The optical CN lines, as well as the other lines that are emerging with them, are formed close to the central star (Xshooter, not shown), possibly in the disk.

If the optical CN lines are pumped by UV radiation from the central star, this is an indication that the reheating has started. Alternatively this could be a C-shock where the outflow is collimated into jets.

In ALMA spectra we detect the presence of CO, CN, HC_3N, and ^{13}C isotopologues. The CO and HC_3N (+isotopologues) emission is unresolved, so most likely comes from the disk.

The ALMA CN and ^{13}CN emission is resolved and matches the bipolar lobes. Maybe CN is formed via shock-induced dissociation of HCN in the lobes?

We are witnessing the very early stages of the hydrodynamic shaping of a bipolar nebula!

Problems / Controversies

Royal Observatory of Belgium

- There are far fewer (V)LTP objects than predicted (even if we count in [WR] and PG1159 stars). Likely this requires more observational effort (IR searches?). Theory effort also needed?
- The vast majority of known objects are VLTP rather than LTP. Observational bias? Theory effort needed? (still low number statistics though).
- Several VLTP show a round(ish) old PN, but strongly bipolar inner ejecta. How does the hydro work here? Do you need a binary to create the bipolar ejecta? Alternate theories:
  - Infall from old PN (Noam Soker)
  - Rapidly rotating WD (Ken Hinkle)
  - GOSH? (Falk Herwig)
- C/O < 1 and very high Ne found by Wesson in A30 & A58 → ONe WD → evolved from SAGB star. Needs independent review.