Herschel observations of planetary nebulae in the MESS program

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and the MESS consortium

The MESS GT key programme

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- MESS = Mass loss of Evolved StarS
- Herschel guaranteed time key programme, PI Martin Groenewegen.
- Aim 1: study the time dependence of the mass loss process via a search for shells and multiple shells.
- Aim 2: study the dust and gas chemistry as a function of progenitor mass.
- Aim 3: study the properties and asymmetries of a representative sample of evolved objects.
- Covers many phases of stellar evolution: AGB & post-AGB stars, planetary nebulae, massive stars (RSG, WR, LBV), supernovae.
- We obtain both photometry and spectroscopy using Herschel PACS and SPIRE (not all sources are done in all modes).
- I will also discuss results from the DDT Must-Do 7 (MD7) proposal led by J. Cernicharo and a follow-up OT2 proposal (P.I. P. van Hoof).

NGC 6720: General Properties

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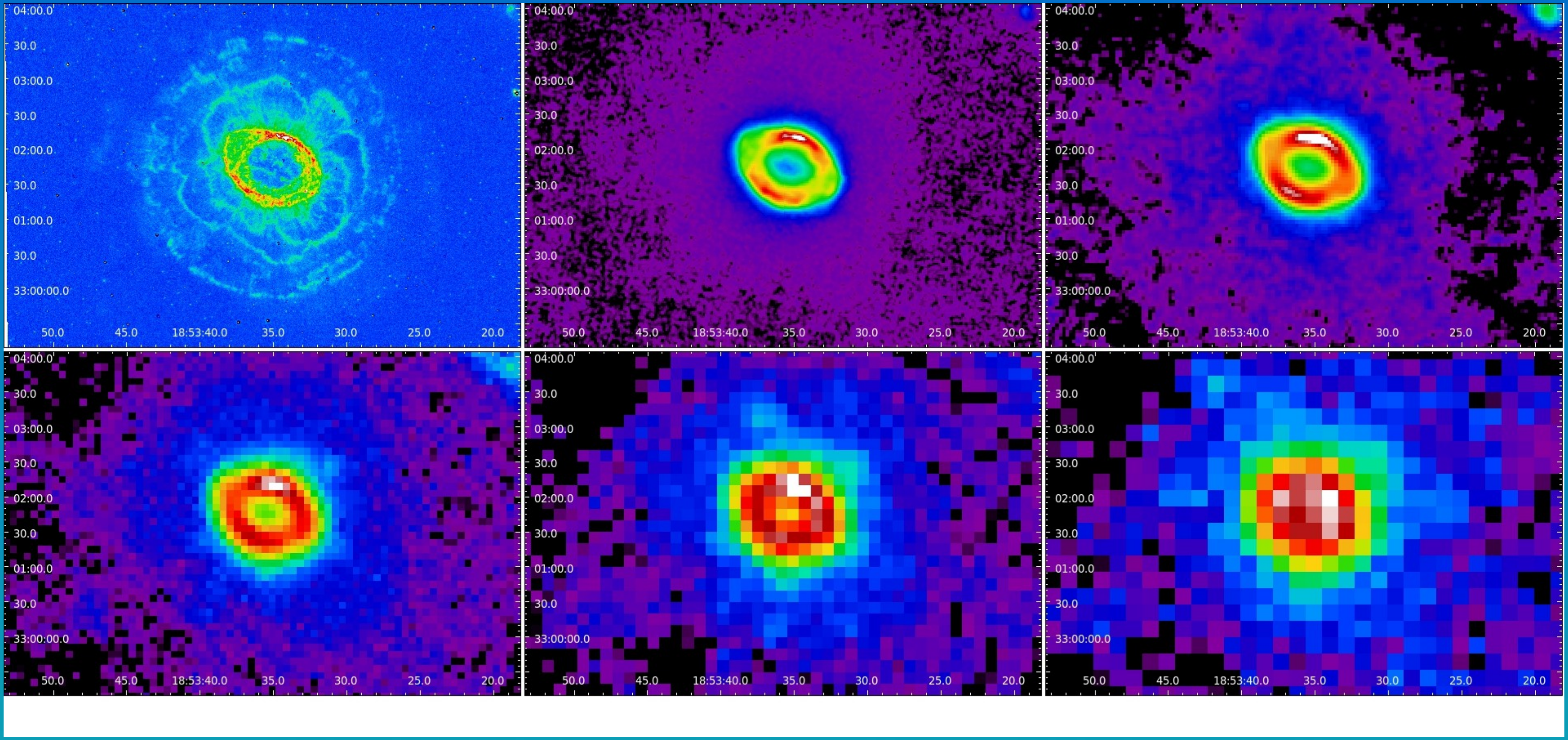
- NGC 6720 = M57 = Ring Nebula
- Evolved, oxygen-rich bipolar nebula seen nearly pole-on
- Ionization bounded, but optically thin in polar direction, detected in molecules (H_2, CO, ...)
- Central star is on cooling track and outer nebula is recombining; re-ionization of the recombined material due to expansion has just started (O'Dell et al. 2007)
- T_e = 10 – 12 kK
- n_e = 400 – 800 cm^{-3}
- $T_{Z\text{-HeII}}$ = 125 kK, L = 200 $L_\odot$, M_c = 0.61-0.62 $M_\odot$

NGC 6720



Top row – left: H_2 2.12 µm (Calar Alto), middle: PACS 70 µm, right: PACS 160 µm. Bottom row – left: SPIRE 250 µm, middle: SPIRE 350 µm, right: SPIRE 500 µm image.

NGC 6720: H_2 formation on dust grains

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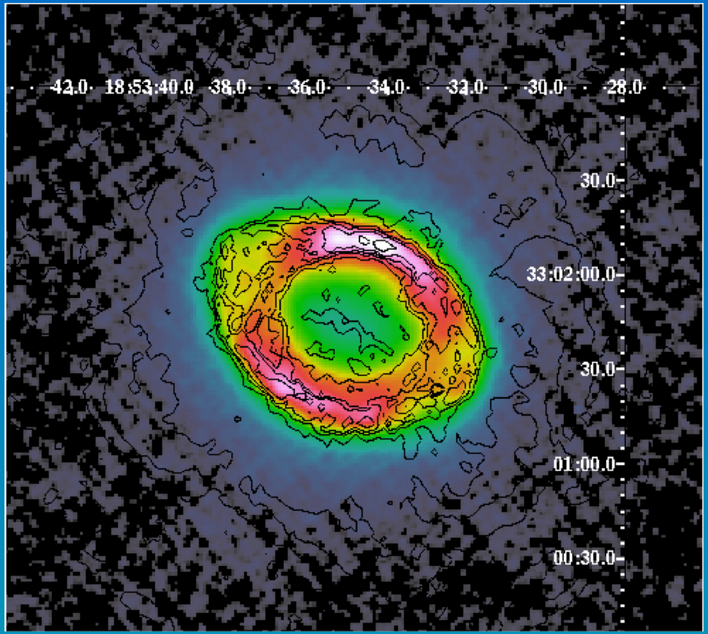
- NGC 6720 is very similar to NGC 7293 (the Helix nebula). It seems they are on the same evolutionary path.
- A static photoionization model cannot explain the H_2 emission in the Helix nebula, but a hydrodynamic model can (Henney et al. 2007, ApJ, 671, L137).
- This model indicates that the erosion of the knots by the radiation field of the central star is substantial: between 10^{-10} and 10^{-9} Msol/yr despite the low luminosity of the central star (120 Lsol).
- Considering the fact that the central star luminosity was much higher in the past and the knots must have been closer to the central star, survival of the knots from the AGB phase (as was e.g. proposed by Matsuura et al. 2009, ApJ, 700, 1067) to the current time seems problematic. More detailed modeling is warranted though to reach a more definitive conclusion.

NGC 6720: H_2 formation on dust grains



Overlay of the H_2 2.12 µm emission (contours) on the PACS 70 µm image of NGC 6720 showing the dust emission. The detailed match between the H_2 and dust emission appears to be the first observational evidence that H_2 forms on oxygen-rich dust grains.

- We have developed a photoionization model of the nebula with the Cloudy code, which we used to investigate possible formation scenarios for H_2.
- We conclude that the most plausible scenario is that the H_2 resides in high density knots which were formed after the recombination of the gas started when the central star luminosity dropped steeply around 1000-2000 years ago.
- The models show that H_2 formation in the knots is expected to be substantial since then, and may well still be ongoing at this moment.
- van Hoof et al. 2010, A&A, 518, L137

NGC 650

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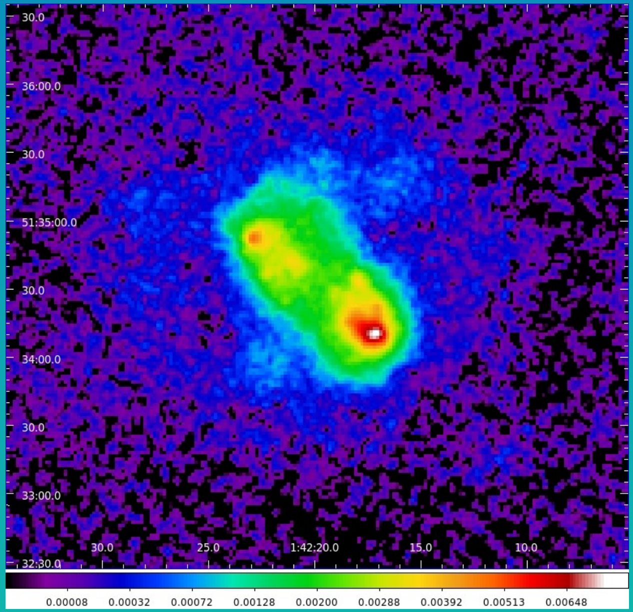
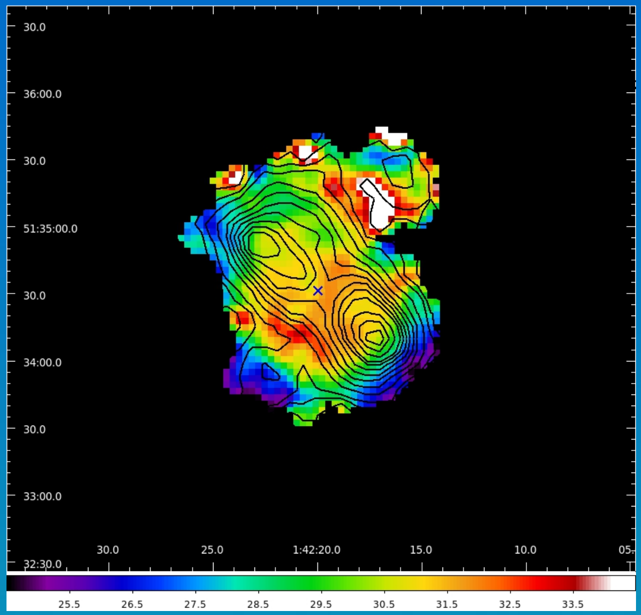
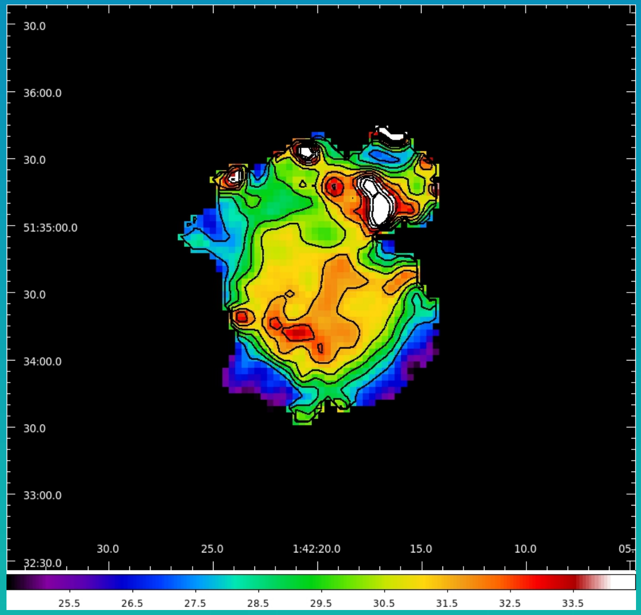


- The top panel shows the optical image of NGC 650 (NOT), the lower the PACS 70 µm map.
- The nebula is bipolar. We can clearly see the edge-on EDE. The knots towards the SE and NW are detected, though faint. The bipolar lobes themselves are not detected by PACS.
- The torus is very clumpy and shows H_2 emission inside these clumps. This nebula is very unusual in that it shows internal extinction despite its highly evolved status.
- This object appears to be an example of a nebula with a very clumpy PDR where the clumps are embedded in the ionized gas.

NGC 650





- Here we show the temperature map constructed from the PACS 70/160 µm ratio image. It is clear that the hottest grains are in the low density regions in the hole of the torus, the colder grains have a more or less spherical distribution. The extinction in the torus is evident.
- Using a Cloudy model we derived that the grains in this nebula are large (0.15 µm), while excess emission around 25 µm could indicate the additional presence of very small grains (possibly PAHs) in the dense clumps.
- Fitting a modified blackbody to the photometry we derived $T_{dust} = 29.9 \pm 1.1$ K and $\beta = 2.12 \pm 0.12$.

NGC 650

- The temperature map shows evidence for two radiation components heating the grains: direct stellar radiation which is readily absorbed in the torus and diffuse radiation (mainly Lyα photons) which propagate everywhere and produce more or less circular isothermal contours.

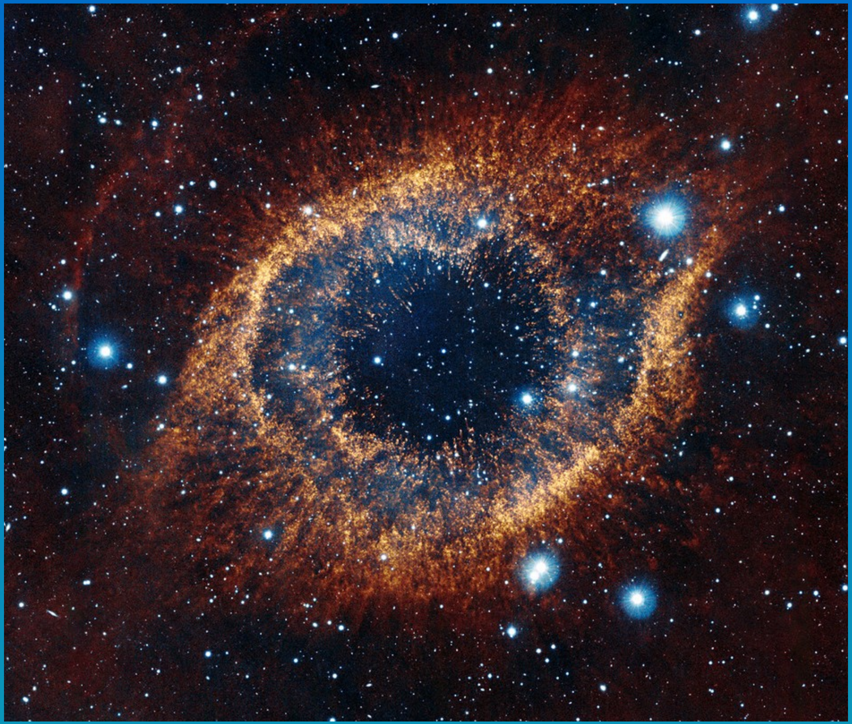
  Based on the Cloudy photoionization model we could also reach the following conclusions.

- The central star was shown to be hotter than hitherto thought, though it turned out to be difficult to determine an accurate value. The most plausible values are between 170 and 190 kK. Most likely the central star progenitor was fairly massive with a mass of at least 3 $M_\odot$, possibly as high as 7 $M_\odot$.

- We could confirm that the nebula is carbon rich with C/O = 2.1. The abundances are typical for a type IIa PN, also indicative of a fairly massive central star.

- van Hoof et al., 2013, A&A, 560, A7.

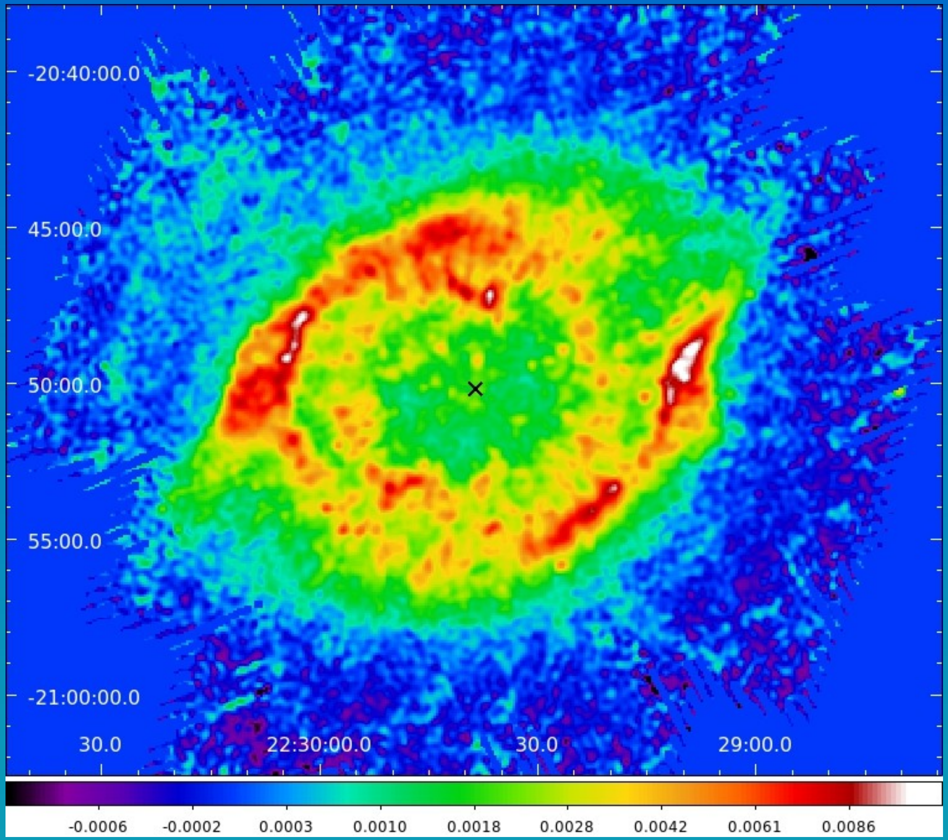
NGC 7293



- NGC 7293 is one of the most famous planetary nebulae and also the closest to Earth (216 pc)
- It is well known for its thousands of cometary knots that are clearly seen in the HST images.
- The central star is on the cooling track (T_{eff} = 120 kK, L = 76 L_{sol}) and is probably oxygen-rich (C/O = 0.87 ± 0.12; Henry+ 1999).

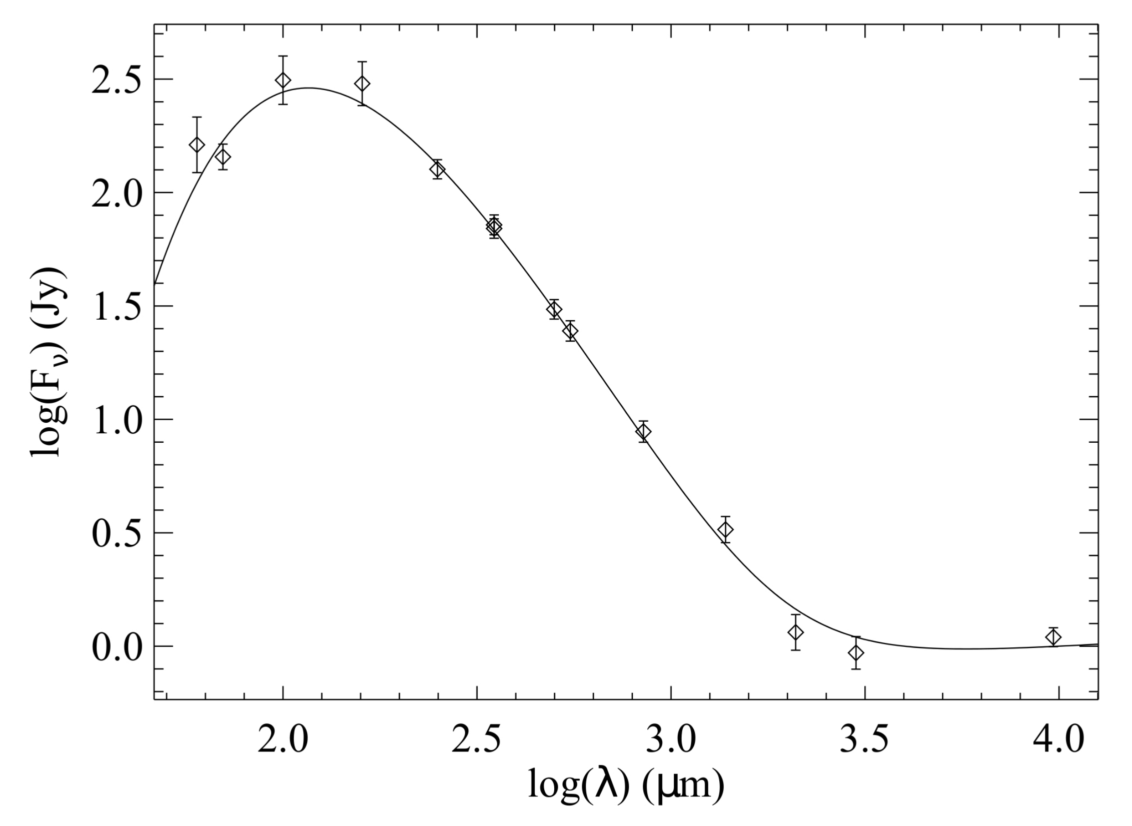
- The image above is the VISTA image of the Helix nebula in the Y, J, and K bands clearly showing the very clumpy nature of the nebular material.
- The nebula is very large (roughly 15 arcmin in diameter) making it ideal for detailed studies.
- The cometary knots are very dense (~ 10^6 cm^{-3}) and contain molecules like H_2 and CO.

NGC 7293



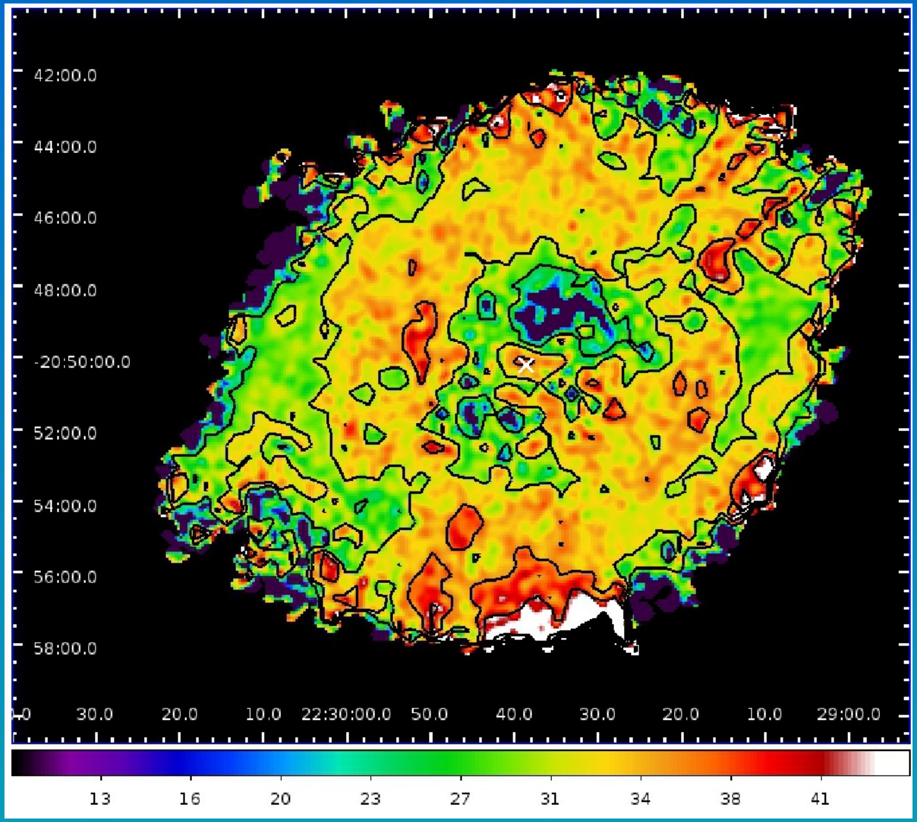
- The SPIRE 250 µm image based on the DDT MD7 data. The data clearly show the clumpy inner and outer ring, where the outer ring is much brighter. The extensions towards the NW and SE are also clearly visible and have the highest surface brightness of the whole nebula.
- Published in Van de Steene et al. (2015, A&A 574, A134).

NGC 7293



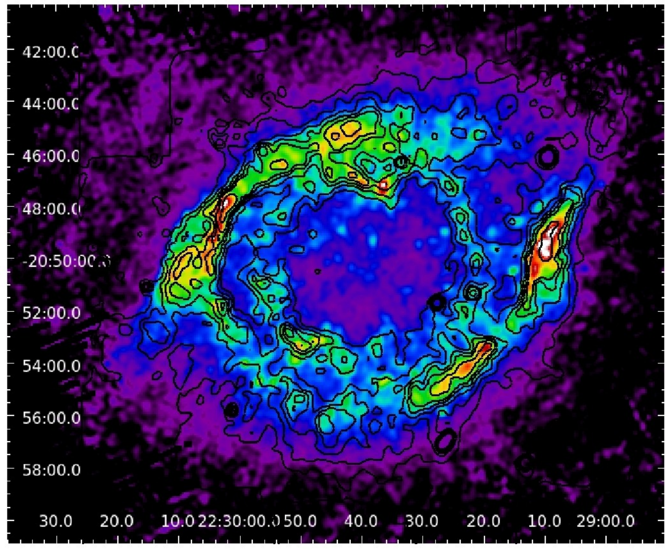
- We fitted a modified blackbody to the photometry of NGC 7293, including a component for the radio free-free emission. The data points are IRAS, PACS, SPIRE, and Planck fluxes and a 31 GHz point from Casassus+ (2004).
- The fit yielded T_{dust} = 30.8 ± 1.4 K and β = 0.99 ± 0.09.
- The low β could indicate the presence of layered amorphous grains.

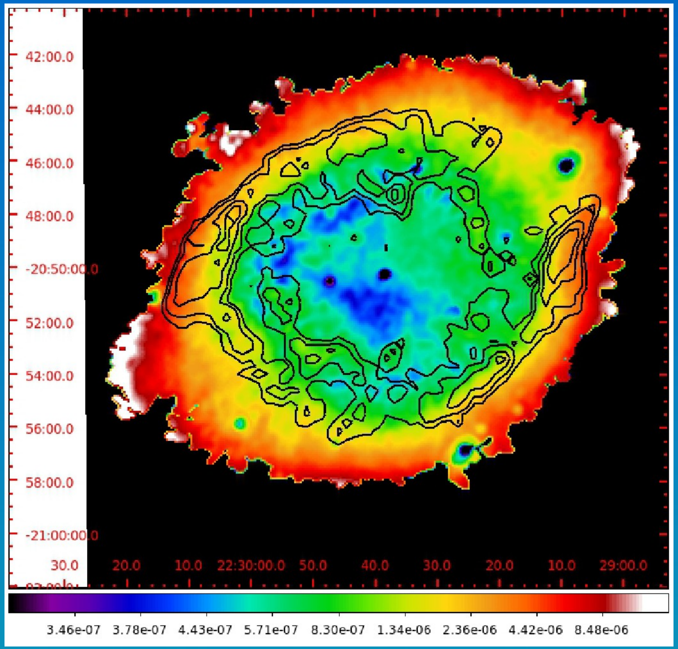
NGC 7293



- The dust temperature map constructed from the PACS 70 μm and SPIRE 250 μm maps, assuming grains with $\beta = 1$.
- There clearly is a ring of warmer dust that encompasses both the inner and outer ring.
- The extensions towards the NW and SE are colder, likely due to a combination of greater distance and optical depth effects.

NGC 7293





- The image on the left shows the H_2 emission as contours overlaid on the SPIRE 250 µm image. It emphasizes the detailed match between the H_2 and dust emission, as was already seen in NGC 6720.
- On the right we see the ratio of the H_2 and Hβ emission with the SPIRE 250 µm image overlaid as contours. The density structure has virtually disappeared and we see the rapid decrease of the ionizing radiation field outwards beyond the inner ring..

NGC 7293

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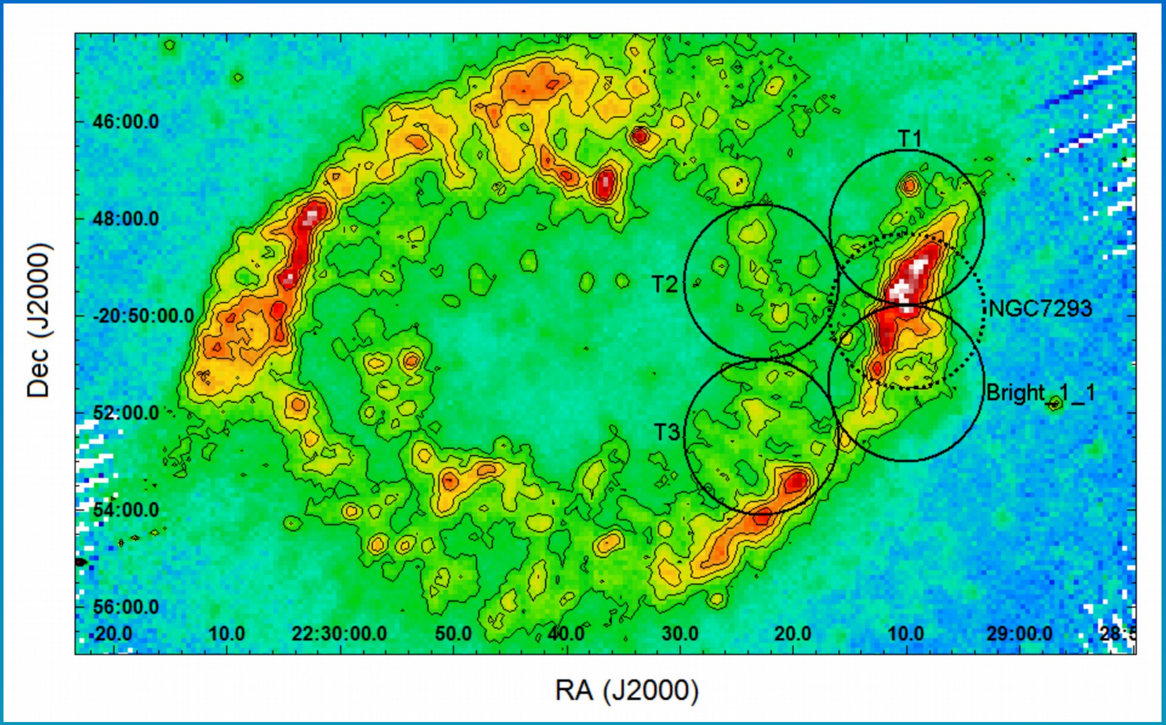
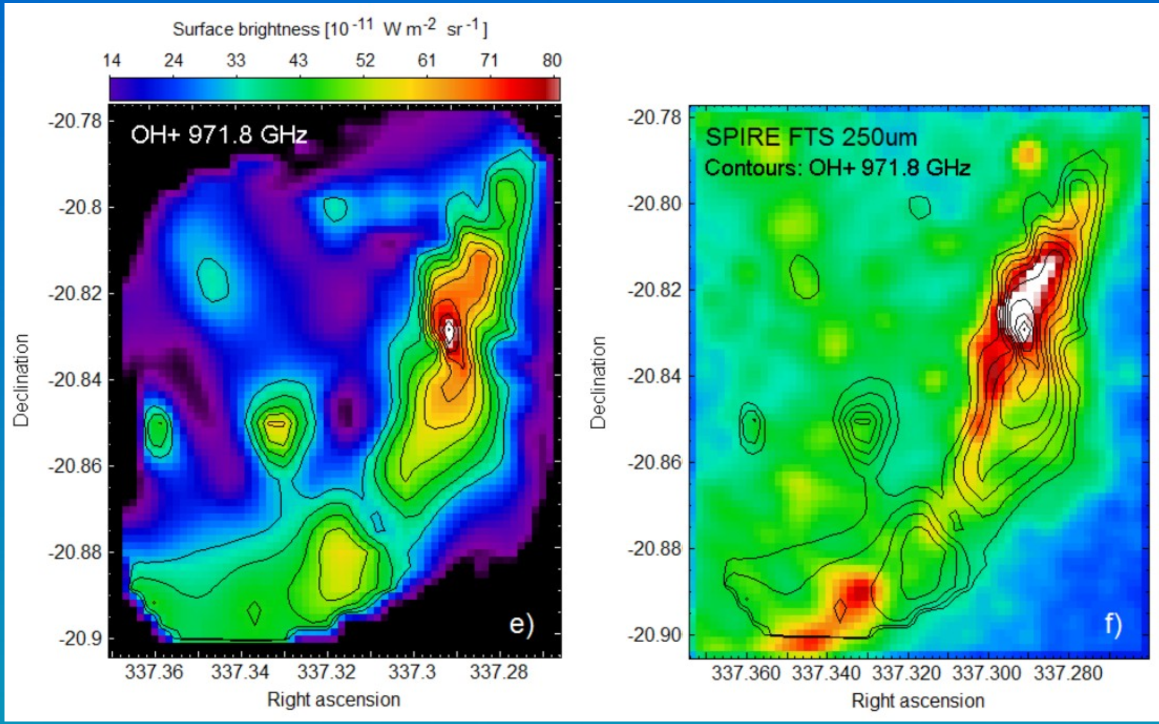


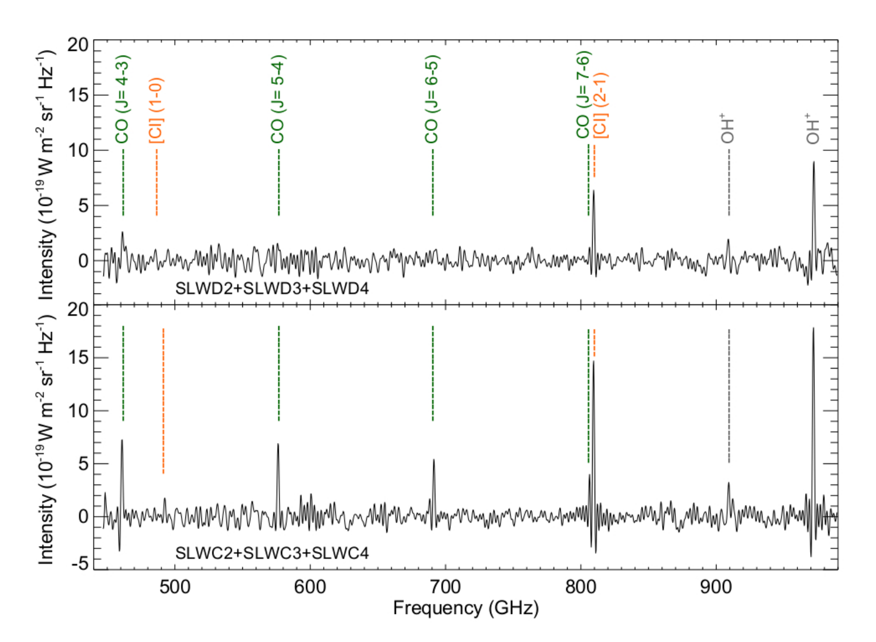
- We obtained SPIRE spectroscopy of the Helix nebula as part of the DDT MD7 proposal (solid circles) as well as a OT2 proposal (dotted circle). They cover the inner as well as the outer ring. The apertures are shown on top of the SPIRE 250 μm image.
- We have pooled these data and the following slides will show the results from the joint analysis.

NGC 7293



- We have obtained the first detection of OH^+ emission in a planetary nebula!
- The left panel shows the map of the OH^+ 971.8 GHz emission in the western arm. The right panel shows the OH^+ emission as contours overlaid on the SPIRE 250 μm image. The OH^+ emission is mainly concentrated on the NW extension of the nebula and the outer ring.
- Shocks don't seem important to create the molecular ion. Formation mechanisms are still being discussed. A possible scenario is advection flows off the molecular knots taking H_2 towards the ionized gas.

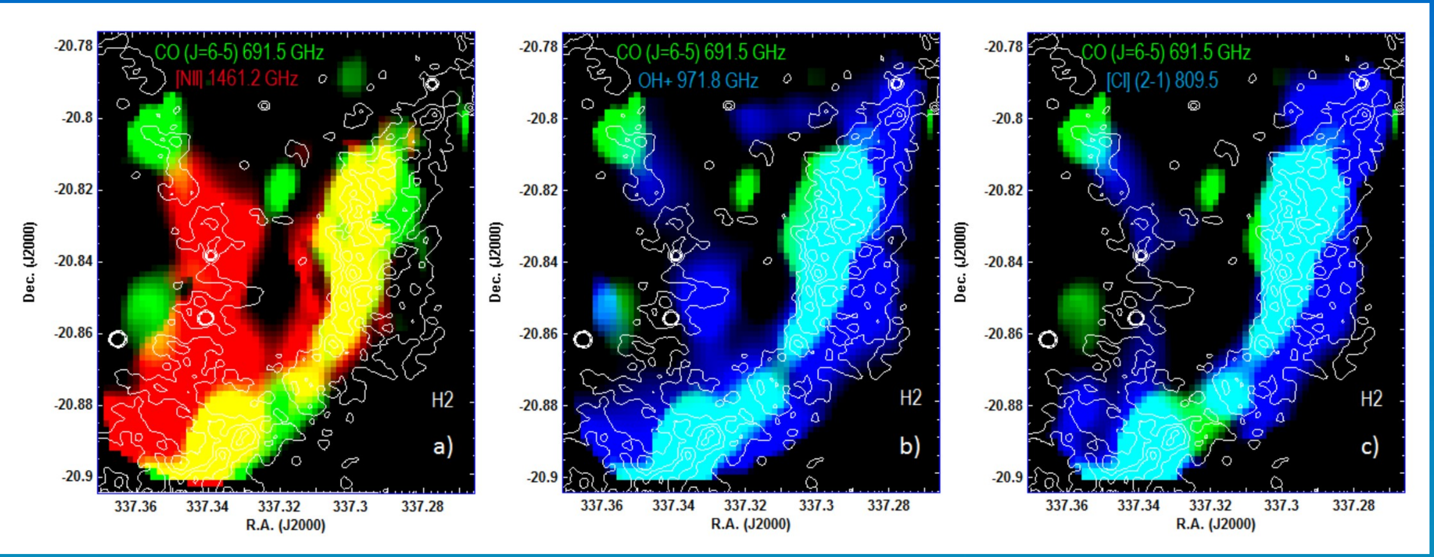
NGC 7293



- The top and bottom panel show the co-added spectra from the inner and outer arm, respectively. The SSW spectrum is not shown.
- The OH^+ line at 971.8 GHz is the strongest molecular line in the spectrum, even stronger than CO! We additionally see [C I] and [N II] emission.

- We also detected OH^+ emission in NGC 6853, another PN from the OT2 proposal.
- The OT1 proposal HerPlaNS (P.I. T. Ueta) is a program to do photometry and spatially resolved spectroscopy of planetary nebulae. They also detected OH^+ emission in 3 PNe, bringing the total to 5 known PNe with OH^+ emission.
- Published in Etxaluze et al. (2014, A&A 566, A78) and Aleman et al. (2014, A&A 566, A79).

NGC 7293



- Here we compare the spatial distribution of the emission in various lines.
- It is clear that the OH^+ and the [C I] emission have a very similar distribution. Regions that emit CO also emit OH^+ (with some minor differences) but the CO emission is more narrowly confined. The CO is cold (20 – 40 K).
- The [N II] emission has a very different distribution than the other lines shown. The [N II] emission is much stronger in the inner ring.

The very fast evolution of the VLTP object V4334 Sgr

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Outline

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Introduction

Imaging in the NIR and MIR

Optical and radio observations of Sakurai's object.

ALMA spectra of Sakurai's object.

Preliminary discussion of the data.

Introduction

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V4334 Sgr (aka Sakurai's object) is the central star of an old PN that underwent a very late thermal pulse (VLTP) a few years before its discovery in 1996.

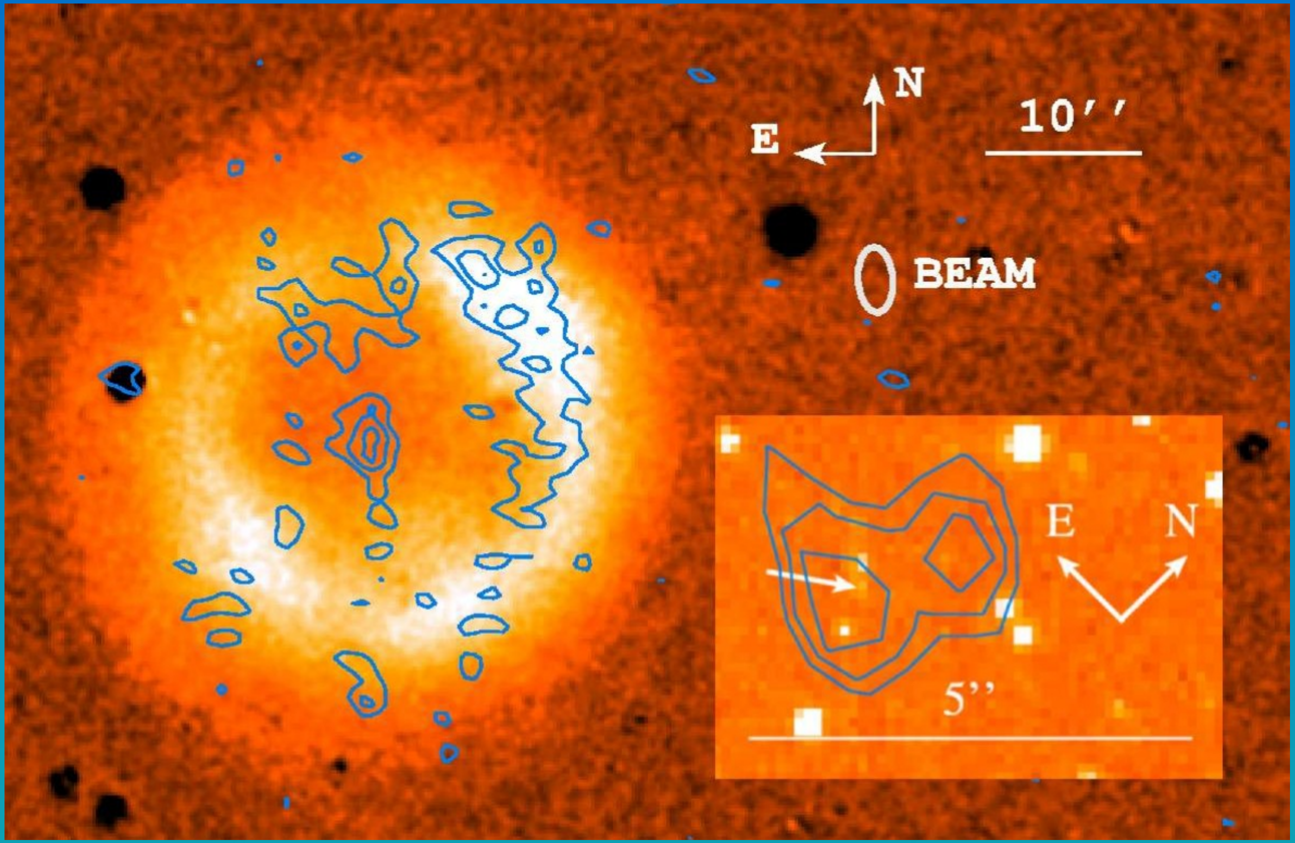
During the VLTP it ingested its remaining hydrogen-rich envelope into the helium-burning shell and ejected the processed material shortly afterwards to form a new, hydrogen-deficient nebula inside the old PN.

The star brightened considerably and become very cool (born-again AGB star) with a spectrum resembling a carbon-star.

After a few years, dust formation started in the new ejecta and the central star became highly obscured, similar to R CrB stars.

Emission lines were discovered. First He I 10830 in 1998 (Eyres+ 1999), later in 2001 also optical forbidden lines from neutral and singly ionized nitrogen, oxygen, and sulfur (Kerber+ 2002).

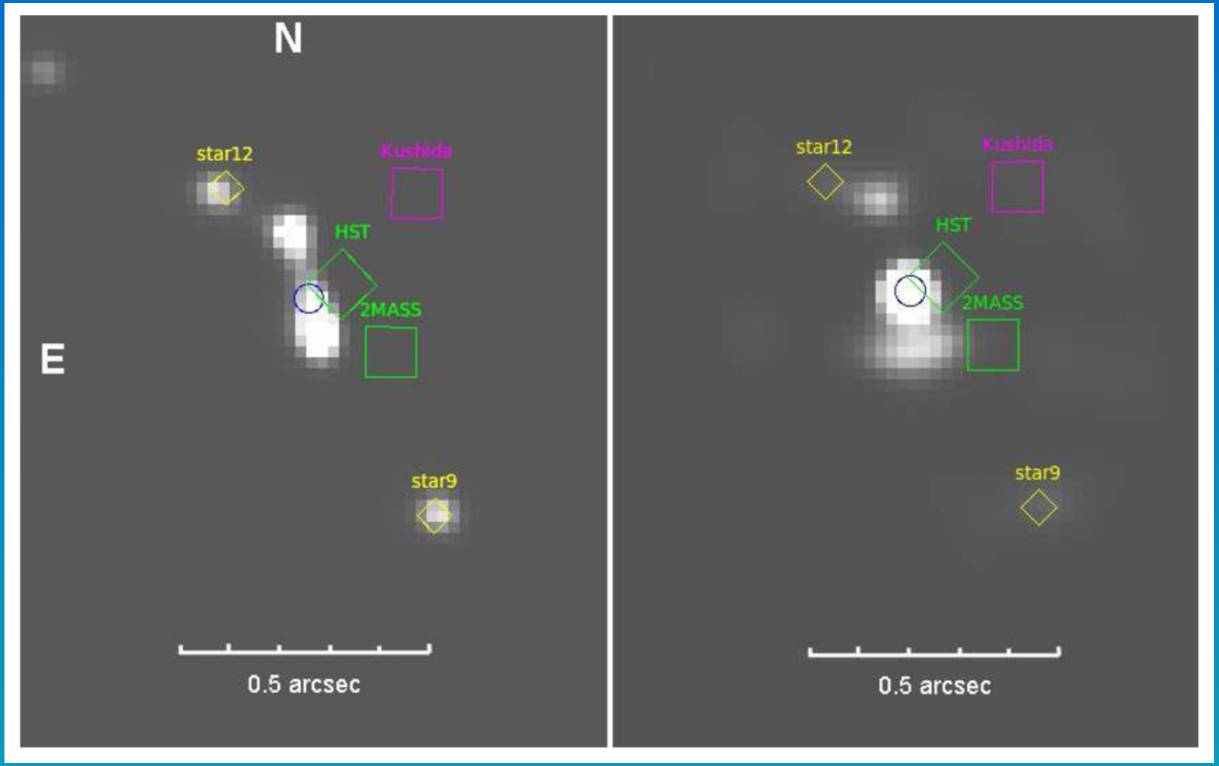
Introduction



[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).

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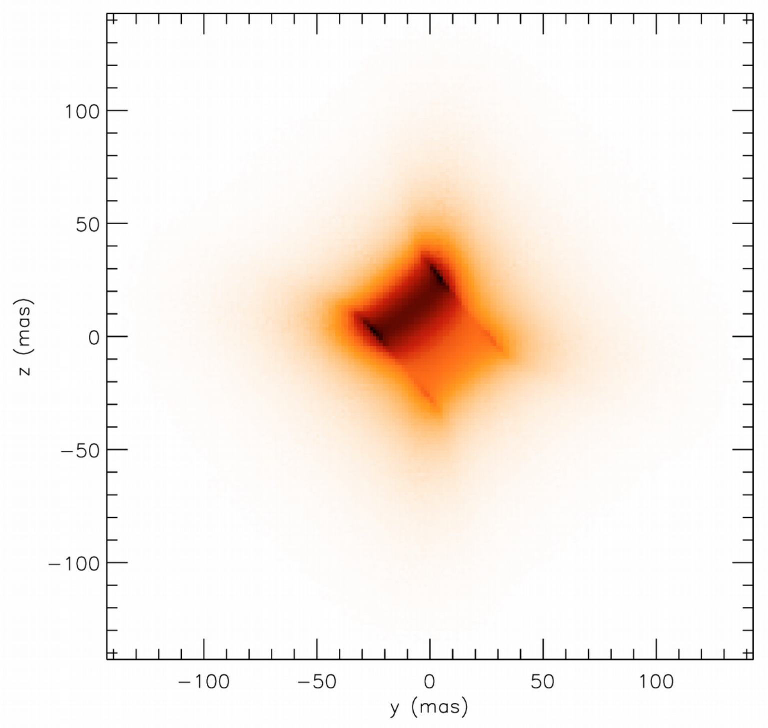
VLTI observations



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

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

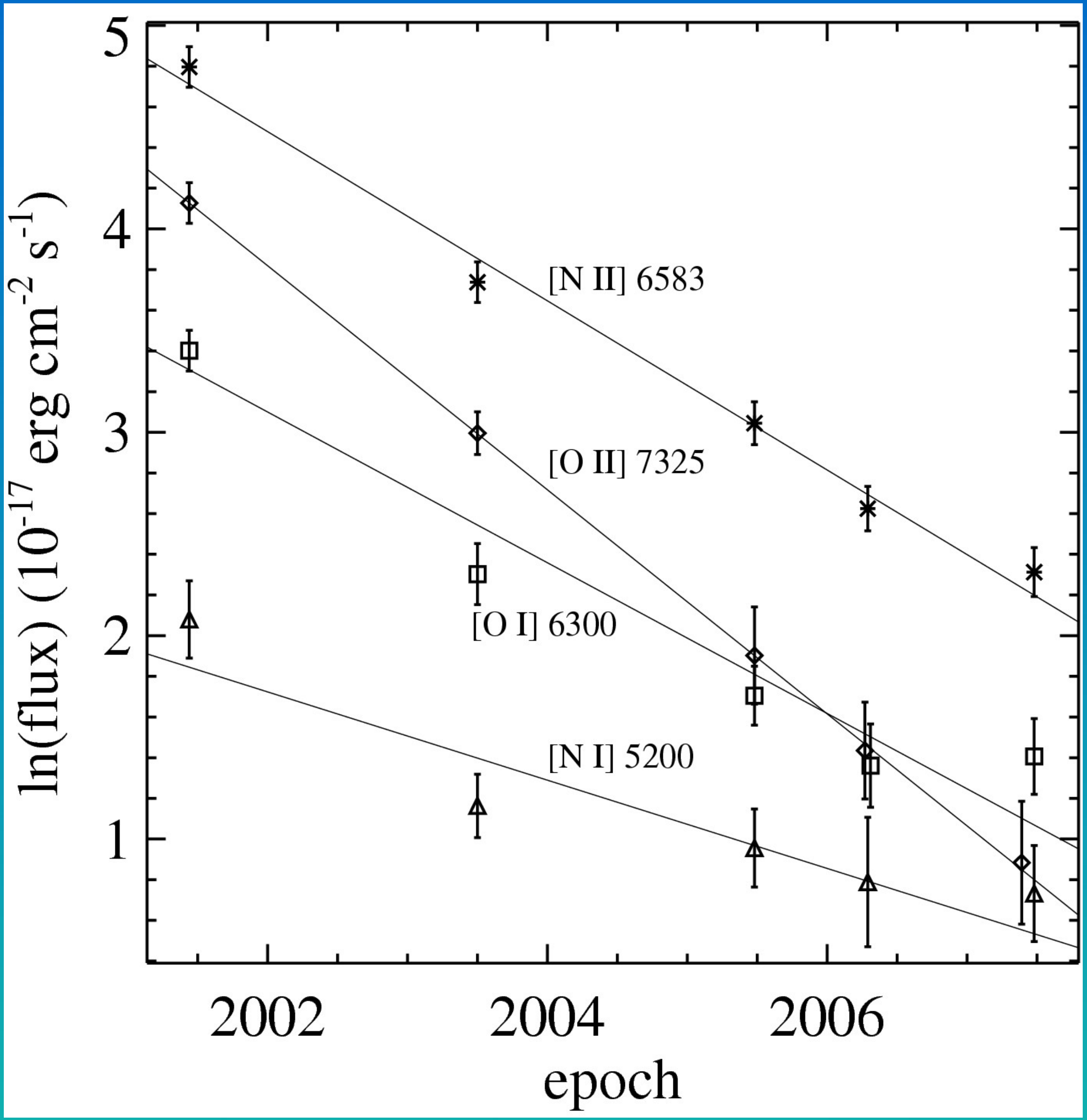
The optical lines initially showed an exponential decline in intensity, and also a decreasing level of excitation. This trend continued until 2007.

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)



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Line flux evolution up to 2017

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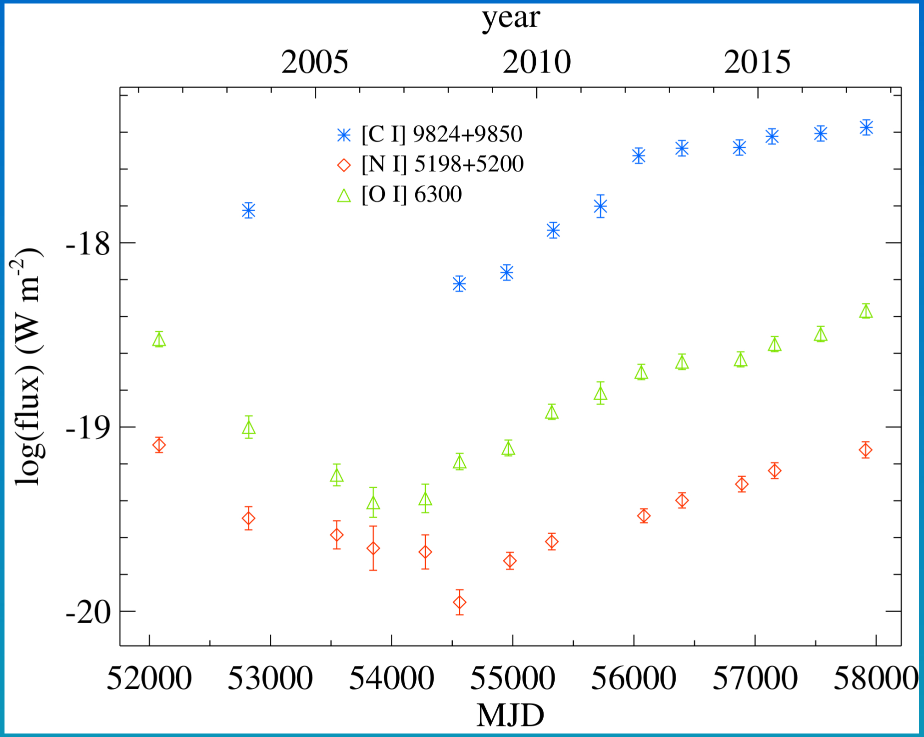
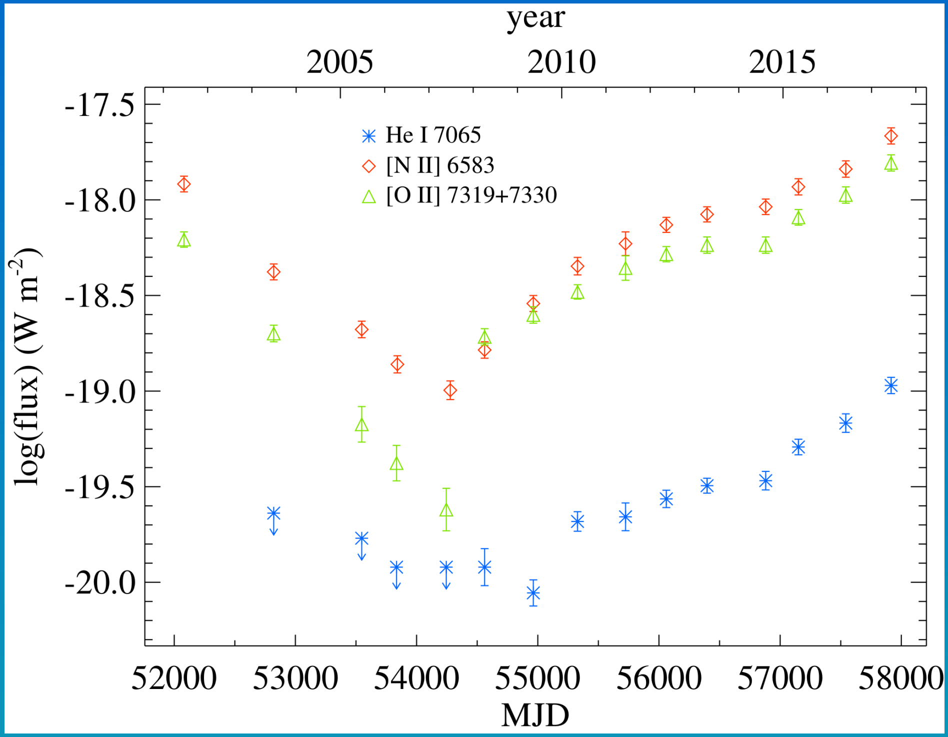


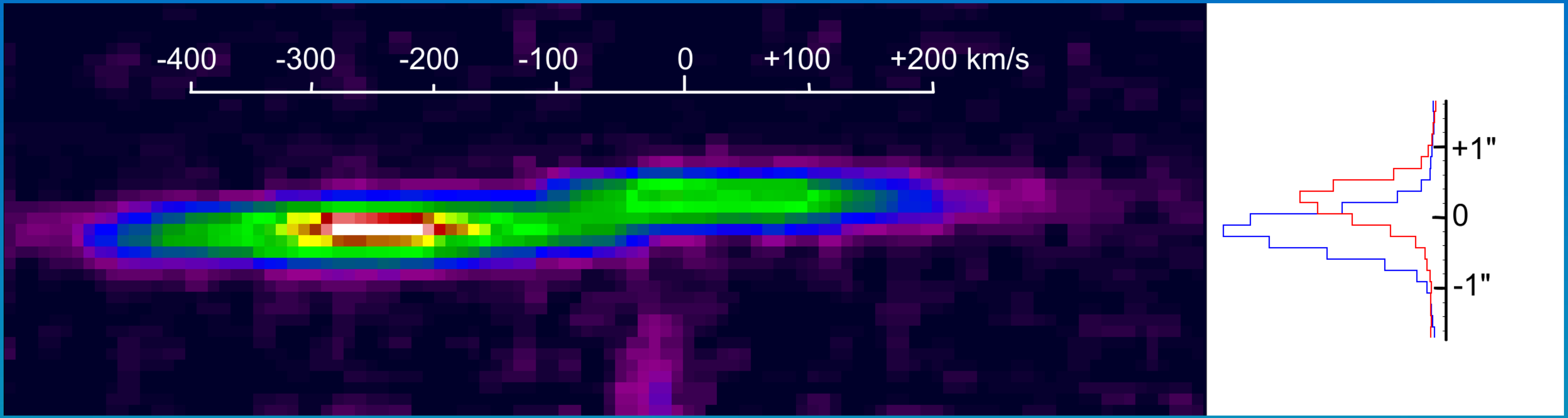


Line fluxes have been monotonically increasing since 2008! This confirms the trend for [C I] 9823/50 seen by Hinkle & Joyce (2014).

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.

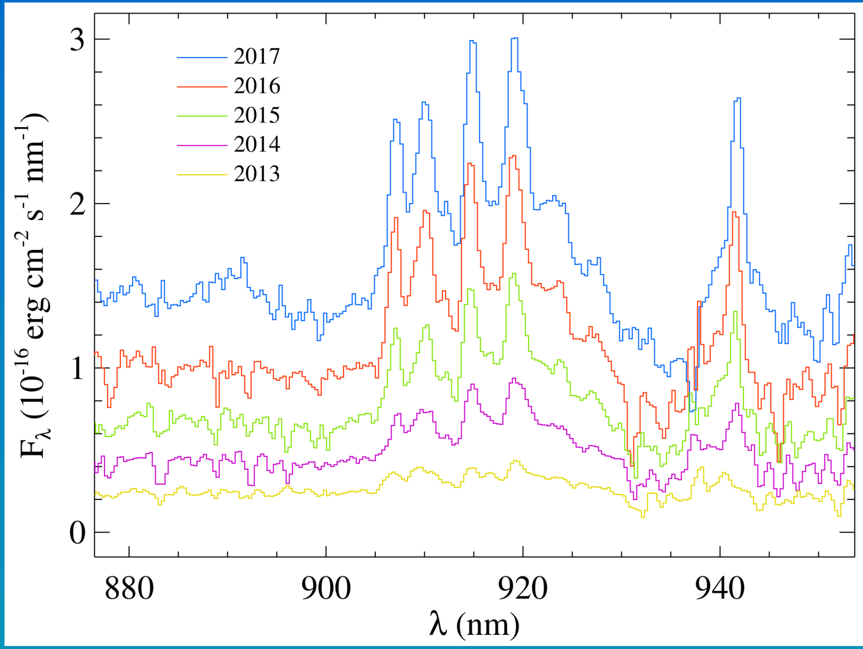
There is a strong discontinuous jump in the [O II] flux in 2008!

The nebular lines



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.

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

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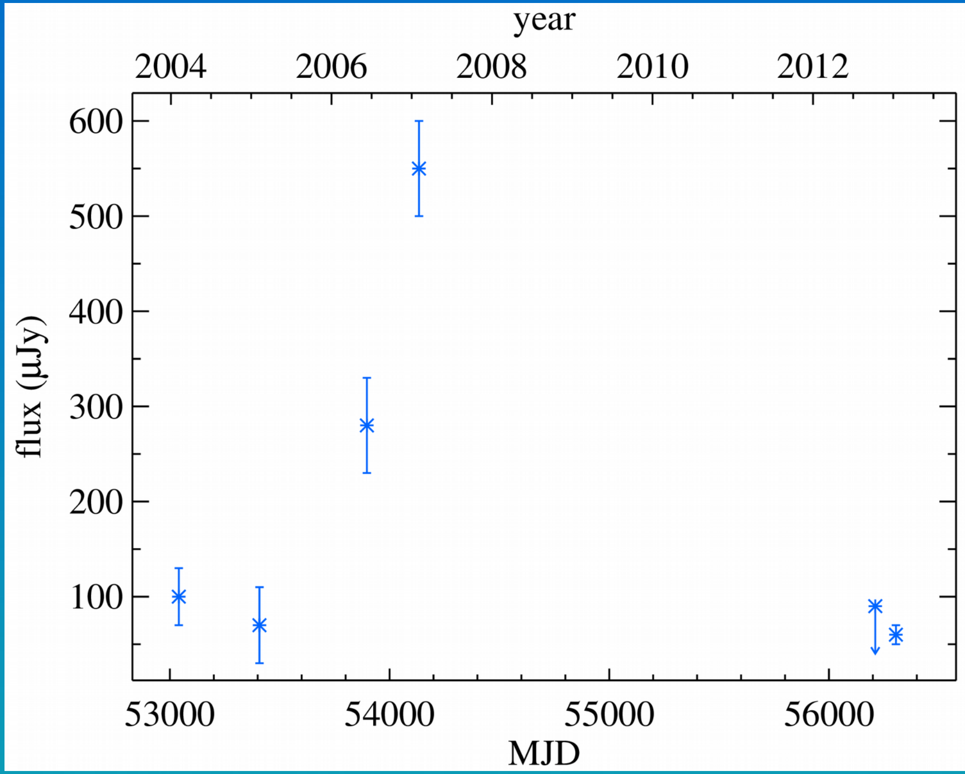
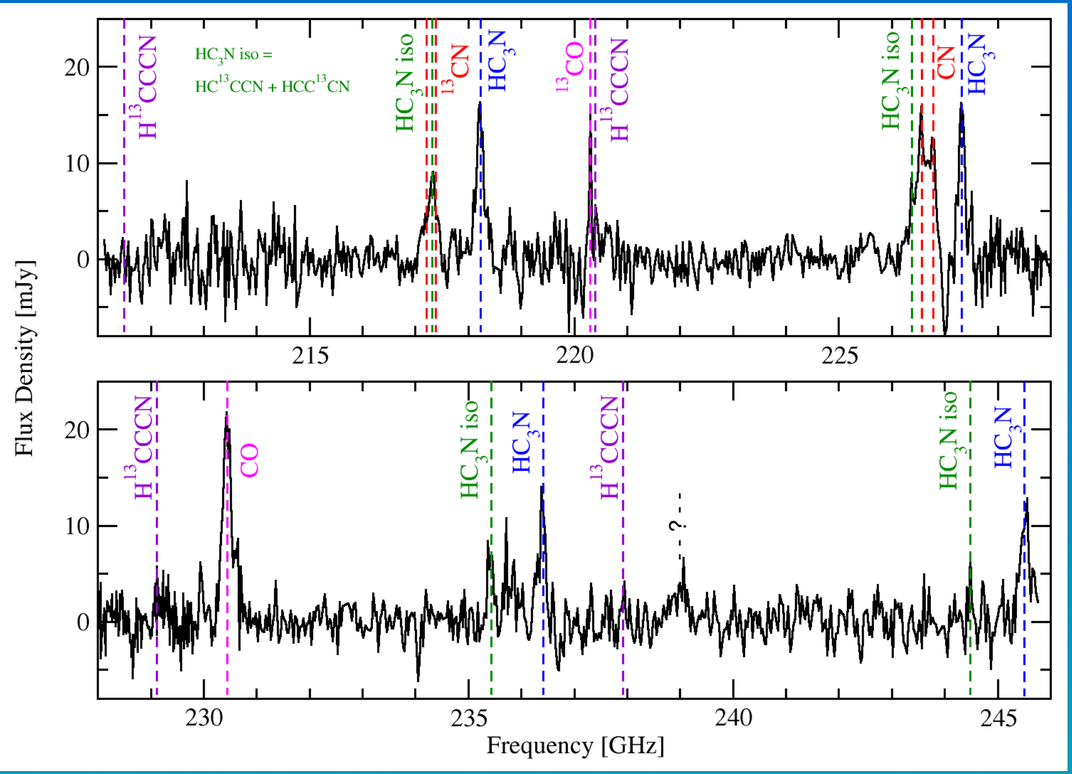


- Between 2004 and 2007 the radio flux was increasing.
- At the time we interpreted that as evidence for the onset of photoionization.
- The most recent data show that the source has faded. The only plausible explanation is that the flux rise was due to a shock.

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

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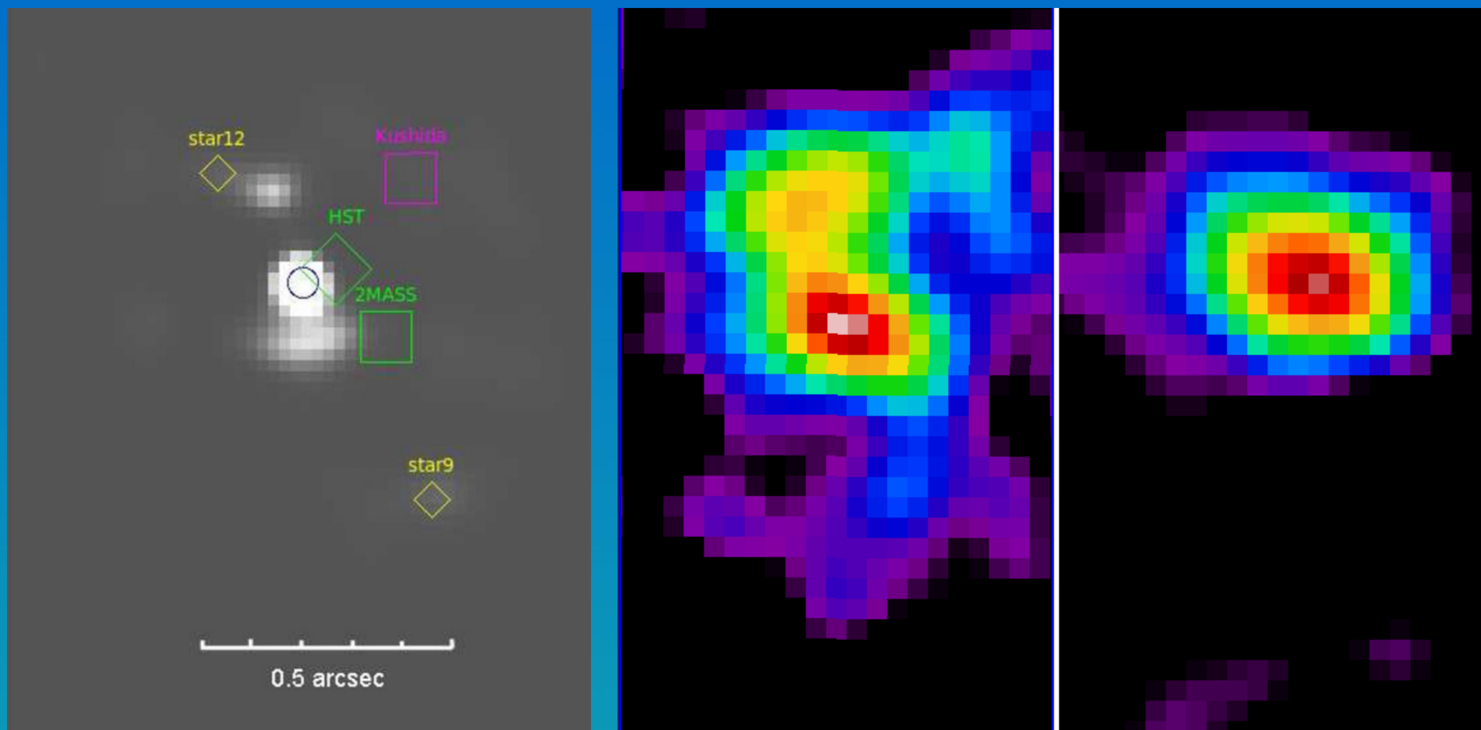

On the left we repeat the Ks image from 2013 by HJ14. In the middle we show the CN emission and on the right the CO emission detected by ALMA in 2015.

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

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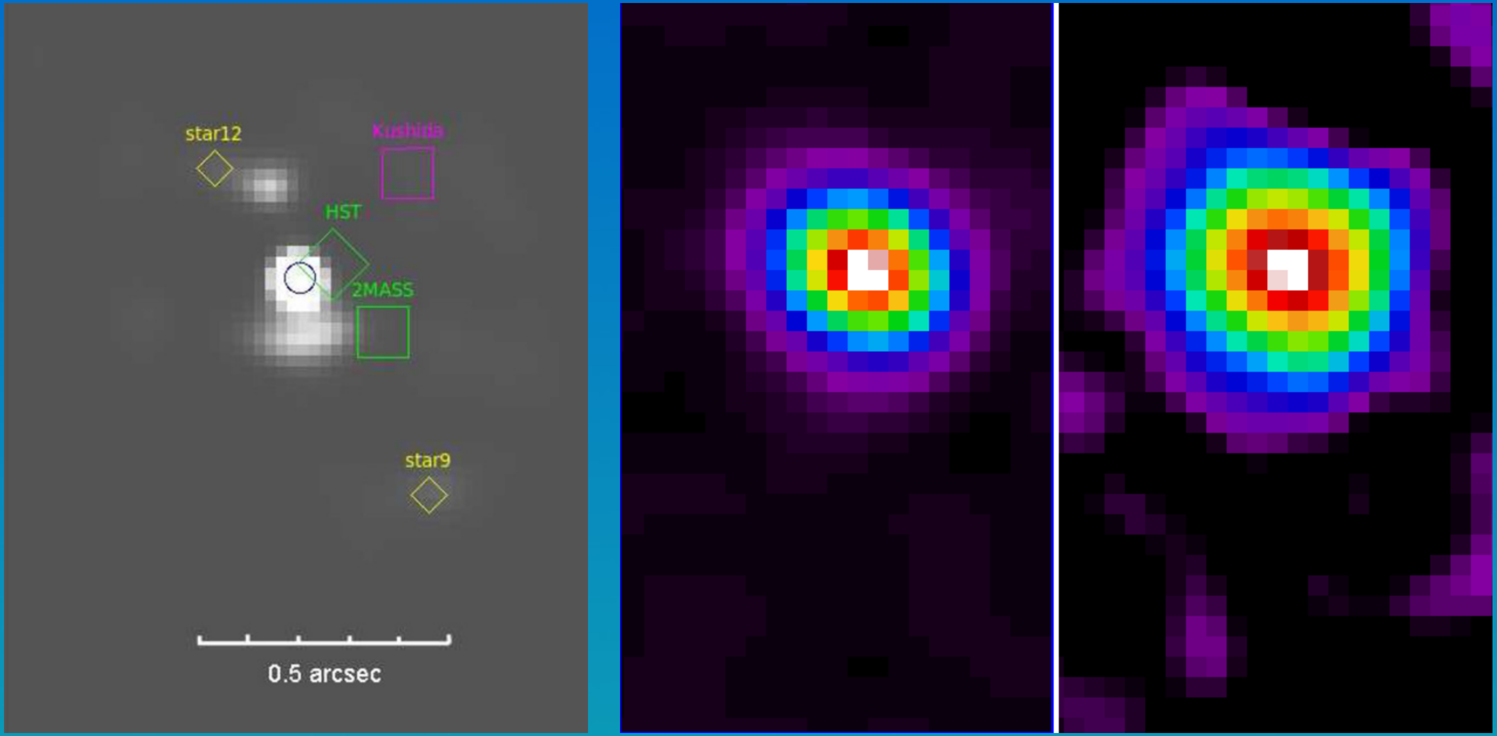

On the left we repeat the Ks image from 2013 by HJ14. In the middle we show the continuum image and on the right the HC_3N emission detected by ALMA in 2015.

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!

Cloudy modeling

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Unfortunately we have no Cloudy models to show!

We need to extend the chemistry in Cloudy to include HC_3N and other relevant molecules.

A new branch has been created to update the chemistry network to the UDfA RATE12 release.

This network needs further testing. Running the full network will not work as it leads to unstable solutions. This likely is a result from the fact that we seek a steady-state solution.

In all likelihood we will run a subset of species from the network to avoid the problems. This subset still needs to be decided.

This branch will not be ready to be included in the C17 release.

We do hope to include it in the subsequent major release.

Preliminary discussion

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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

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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

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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!