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).

PNe imaged in our sample

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- NGC 650: PACS, SPIRE (van Hoof et al., A&A, in press, arXiv:1308.2477)
- NGC 3587: PACS, SPIRE (too faint)
- NGC 6543: PACS (partially resolved), SPIRE (unresolved)
- NGC 6720: PACS, SPIRE (van Hoof et al., A&A, 518, L137)
- NGC 6853: PACS, SPIRE
- NGC 7027: PACS (partially resolved)
- NGC 7293: PACS+SPIRE (parallel mode), SPIRE (DDT MD7)
- IRAS 22036+5306: PACS (unresolved?)
- All targets are observed in scan map mode. With PACS we obtain images in the 70 and 160 μm bands (beam size: 5.2'' and 12'', resp.), with SPIRE we obtain all 3 bands: 250, 350, and 500 μm (beam size: 18.1'', 25.2'', and 36.6'', resp.).
- The analysis of these images is still ongoing! For NGC 6543, 7027 and IRAS 22036+5306 we will use deconvolution to improve the resolution.

PN spectroscopy in our sample

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- NGC 6302: PACS, SPIRE
- NGC 6537: PACS, SPIRE (Barlow GT2)
- NGC 6543: PACS (during PV phase)
- NGC 6853: PACS, SPIRE (van Hoof OT2)
- NGC 7027: PACS (during SDP), SPIRE
- NGC 7293: SPIRE (DDT MD7, van Hoof OT2)
- For all targets except NGC 6853 we obtain full spectral scans, covering the wavelength range 51-98 μm + 103-192 μm for PACS and 196-667 μm for SPIRE. For NGC 6853 we obtained line scans on selected CO lines with PACS and a full scan with SPIRE.
- As was the case with the images, the analysis of these spectra is still ongoing!

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: H_2 formation on dust grains

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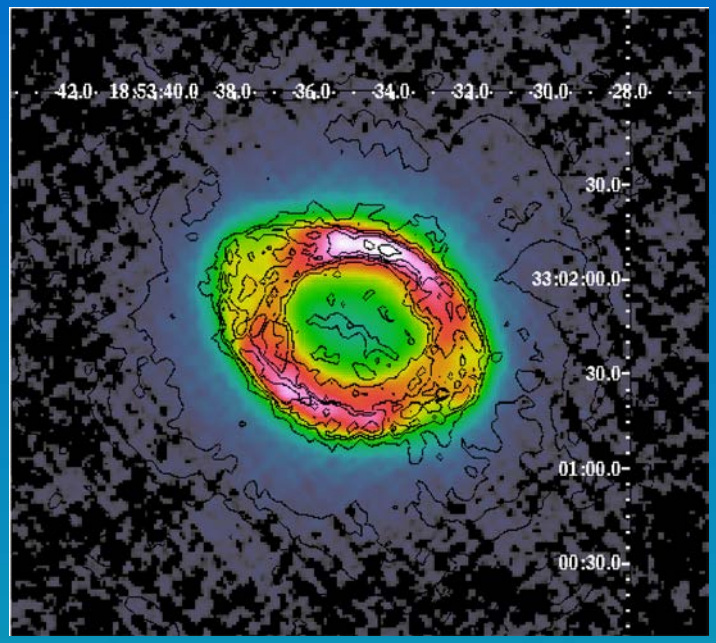
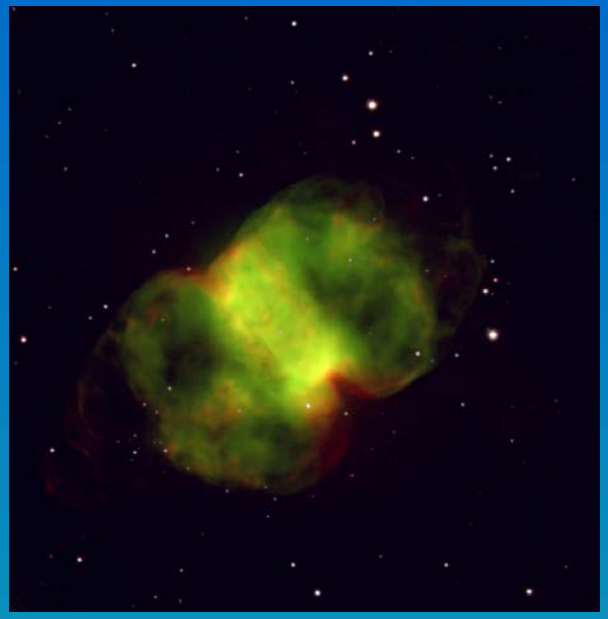
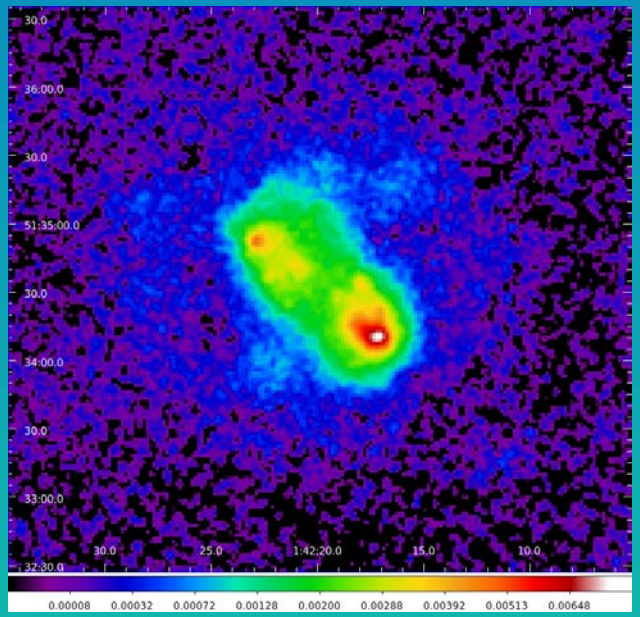


Overlay of the H_2 2.12 µm emission (contours) on the PACS 70 µm image of NGC 6720 showing the dust emission. The detailed match between the H_2 and dust emission appears to be the first observational evidence that H_2 forms on oxygen-rich dust grains.

- 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





- 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 another example of a nebula with a very clumpy PDR where the clumps are embedded in the ionized gas.

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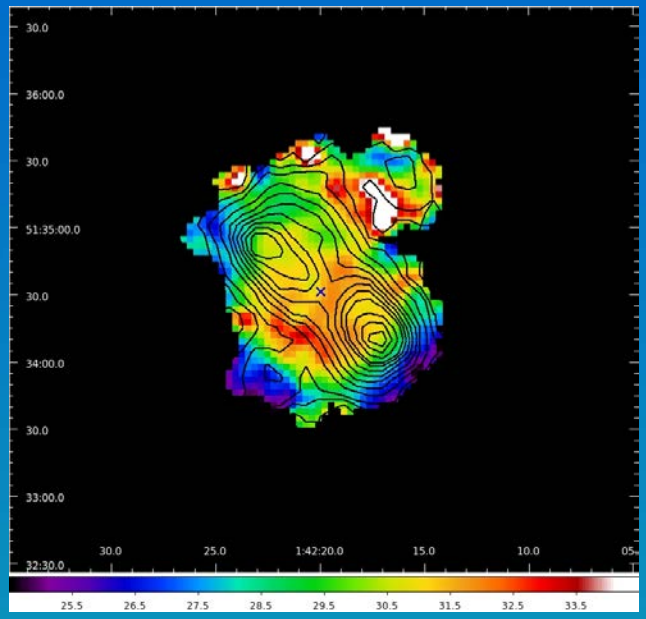
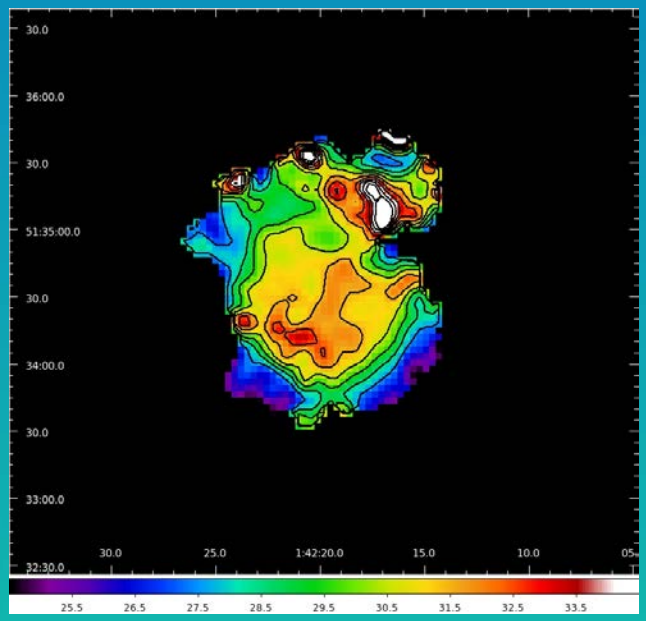
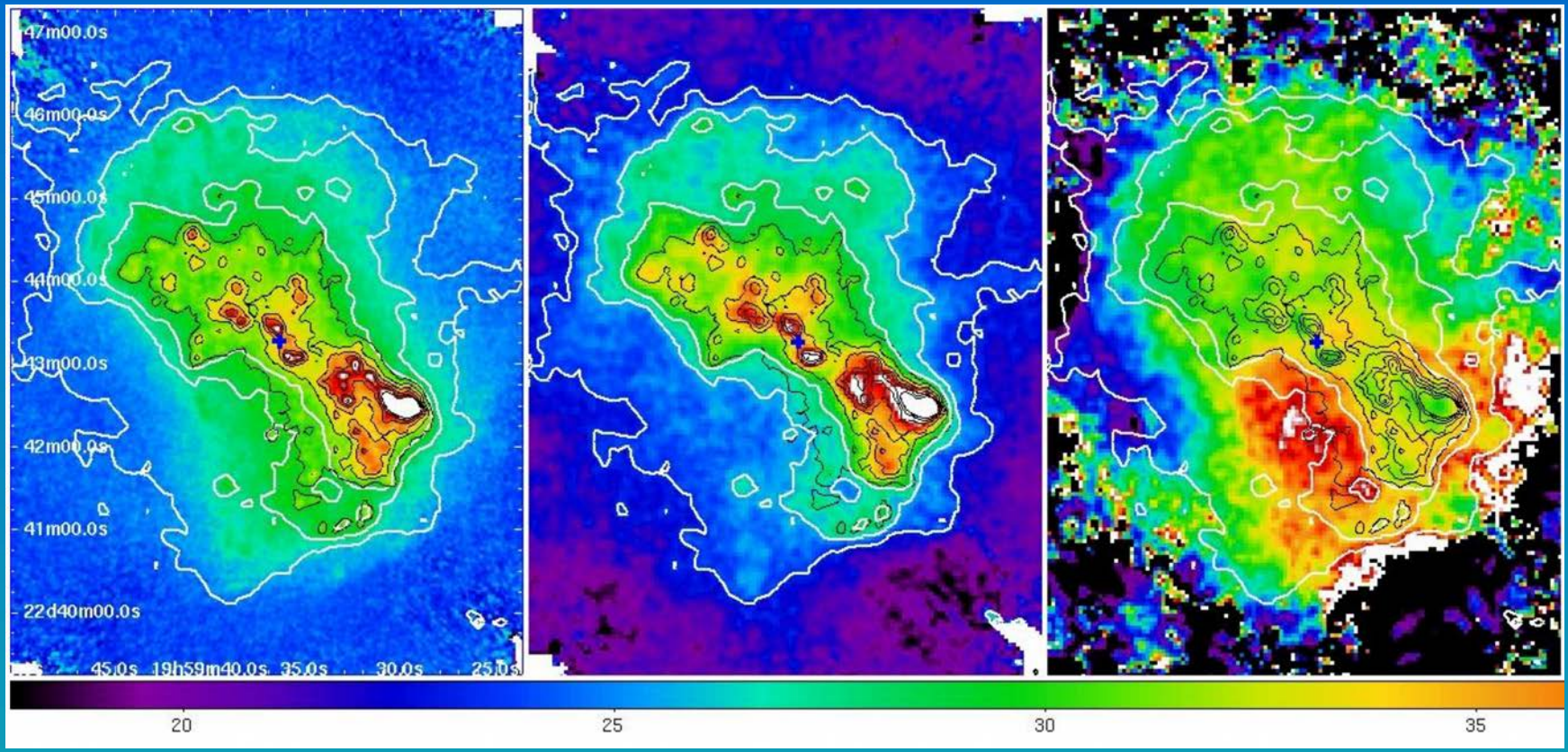
NGC 650





- 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 ± 1.1 K and β = 2.12 ± 0.12.
- van Hoof et al., 2013, arXiv:1308.2477.

NGC 6853



- Left: PACS 70 μm, middle: PACS 160 μm, right: temperature map derived from the PACS 70 / 160 μm ratio image after convolution.
- The high-density regions have colder dust. The hot patch towards the south appears to be real and has no counterpart in the north.

NGC 7027

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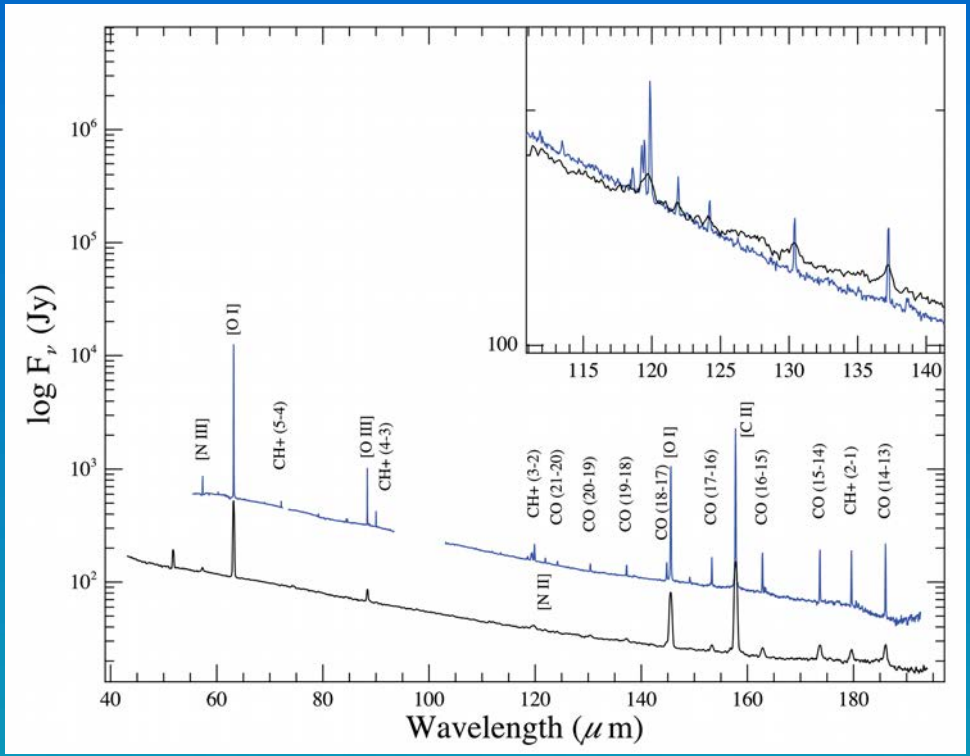

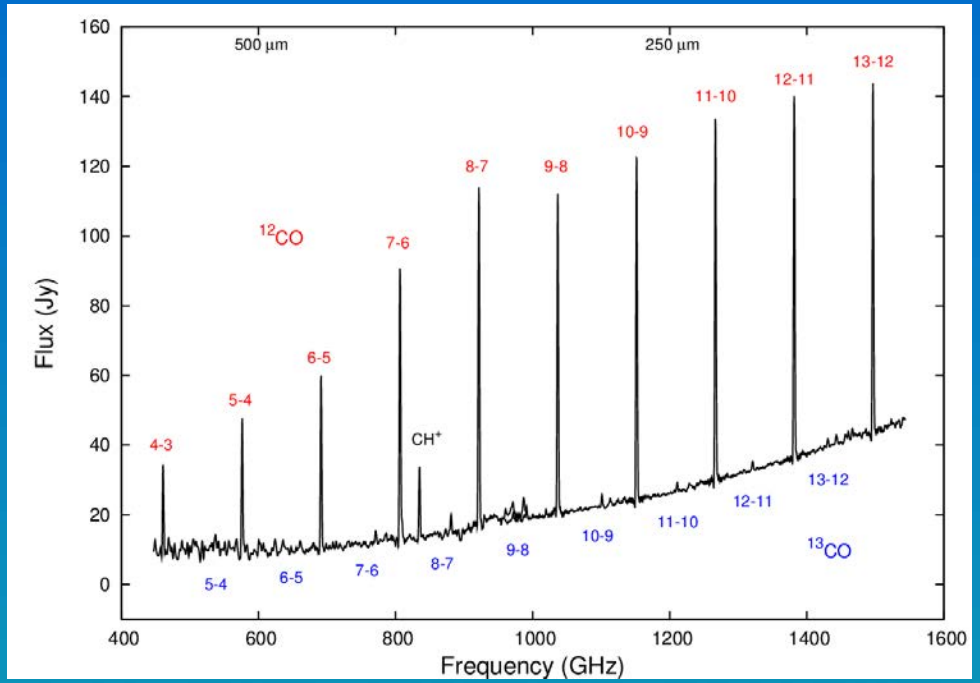

- Left: the PACS spectrum, right: the SPIRE spectrum. Underneath the PACS spectrum we show the ISO-LWS spectrum for comparison.
- We see atomic lines from H I, [C I], [C II], [N II], [N III], [O I], [O III] and molecular lines from ^{12}CO, ^{13}CO, OH, H_2O, CH, CH^+, C_2H, HCN, HCO^+, and possibly CN.
- Oxygen-rich molecules can be formed because the harsh radiation field keeps CO partially dissociated throughout the nebula.

NGC 7027

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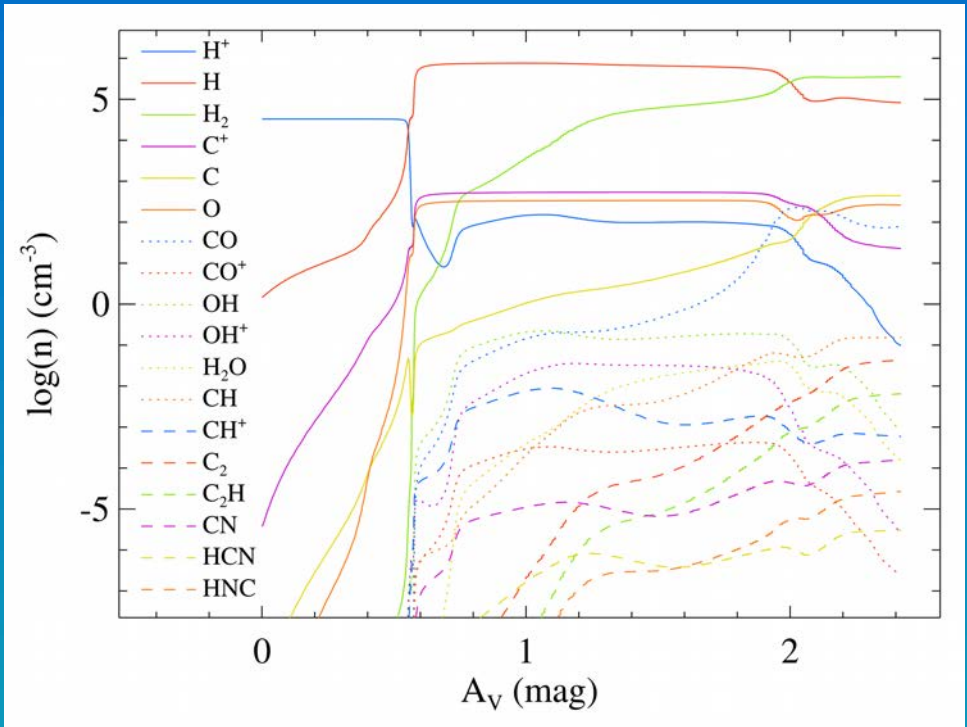

- We have created a preliminary model of the ionized region and the PDR of NGC 7027 using Cloudy.
- Here we show the abundance of the most important species as a function of depth.
- The region up to A_V = 0.57 is ionized. The PDR is at A_V > 0.57.
- The model shows that CO stays partially photodissociated up to the outer edge; n(O) > n(CO) nearly everywhere in the PDR!

- We could produce a decent fit assuming that the density was piece-wise constant in the ionized region and the PDR with a density jump at the ionization front. The model indicated n_H = 3.3 x 10^4 cm^{-3} in the ionized region and 7.9 x 10^5 cm^{-3} in the PDR. A constant pressure model could not reproduce the observations.

NGC 7293

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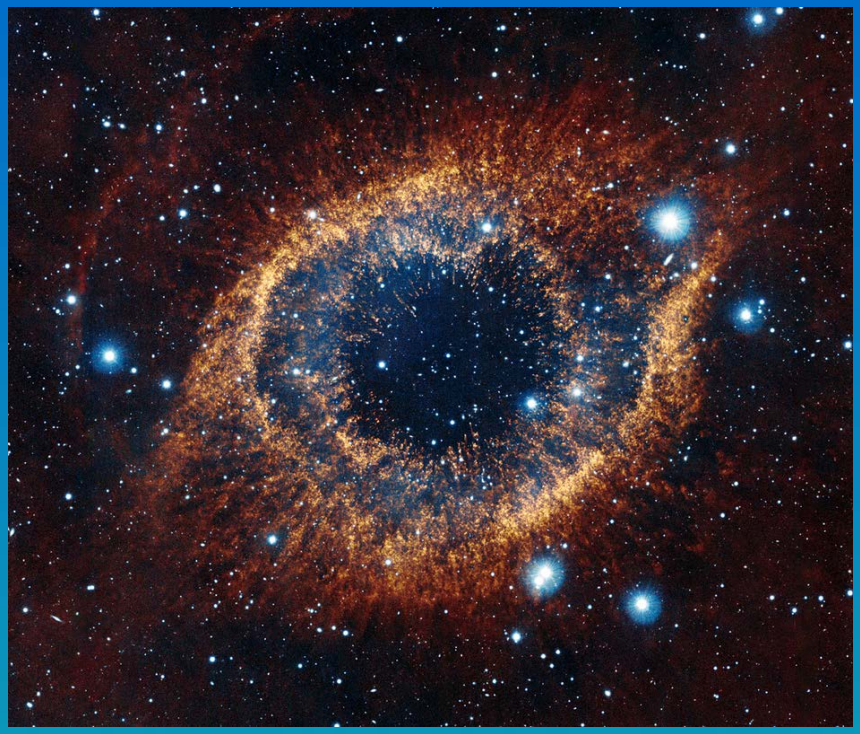

- NGC 7293 is one of the most famous planetary nebulae and also the closest to Earth (219 pc)
- It is well known for its thousands of cometary knots that are clearly seen in the HST images.
- The central star is on the cooling track (T_{eff} = 120 kK, L = 76 L_{sol}) and is probably oxygen-rich (C/O = 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.

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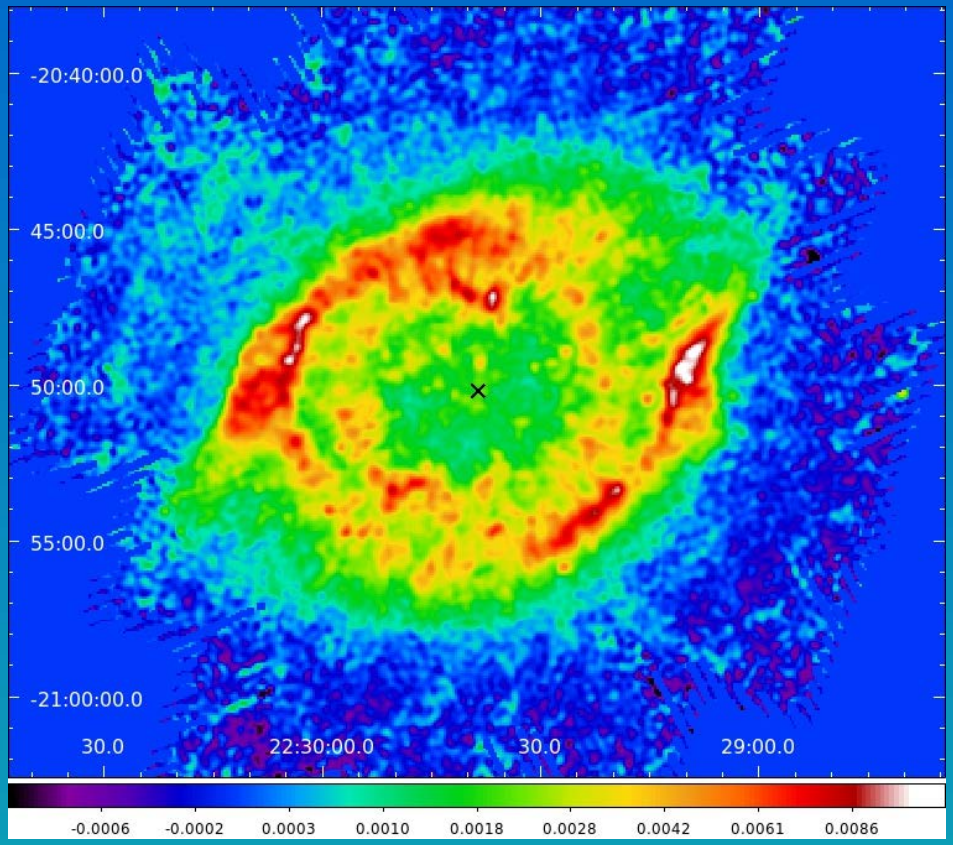
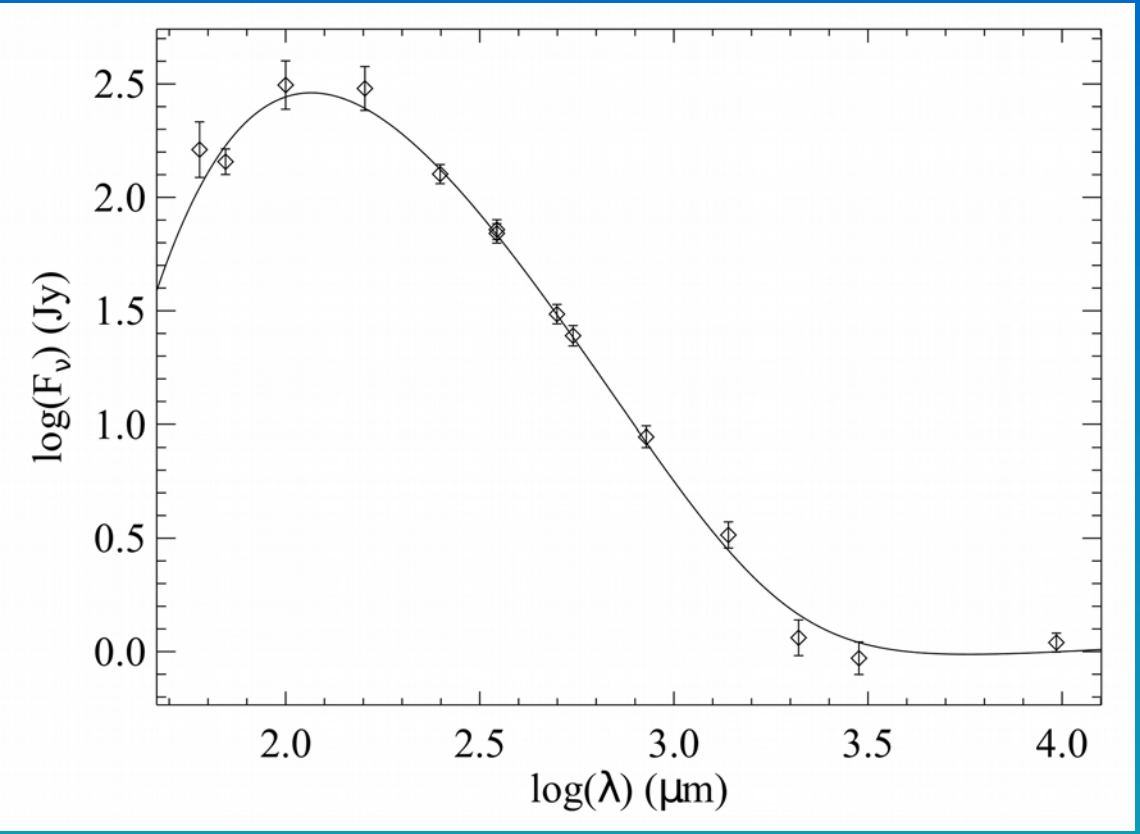
NGC 7293



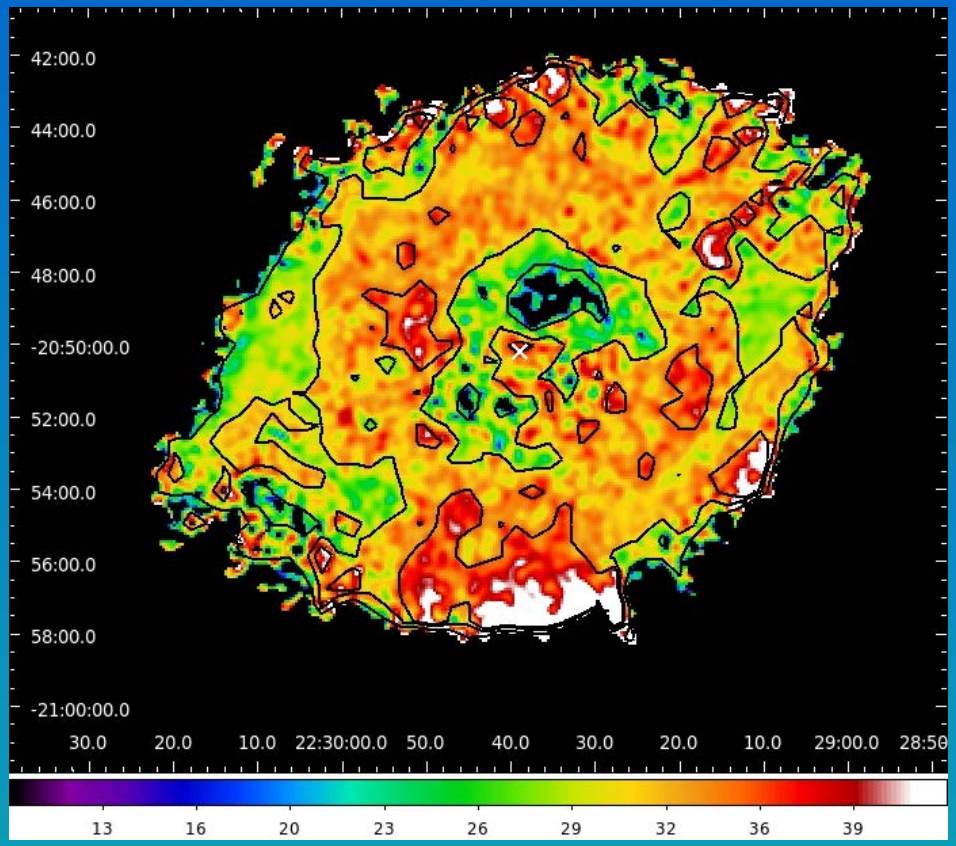
- The SPIRE 250 μm image based on the DDT MD7 data. The data clearly show the clumpy inner and outer ring, where the outer ring is much brighter. The extensions towards the NW and SE are also clearly visible and have the highest surface brightness of the whole nebula.
- See poster P82 in session B by Van de Steene et al. for details.

NGC 7293



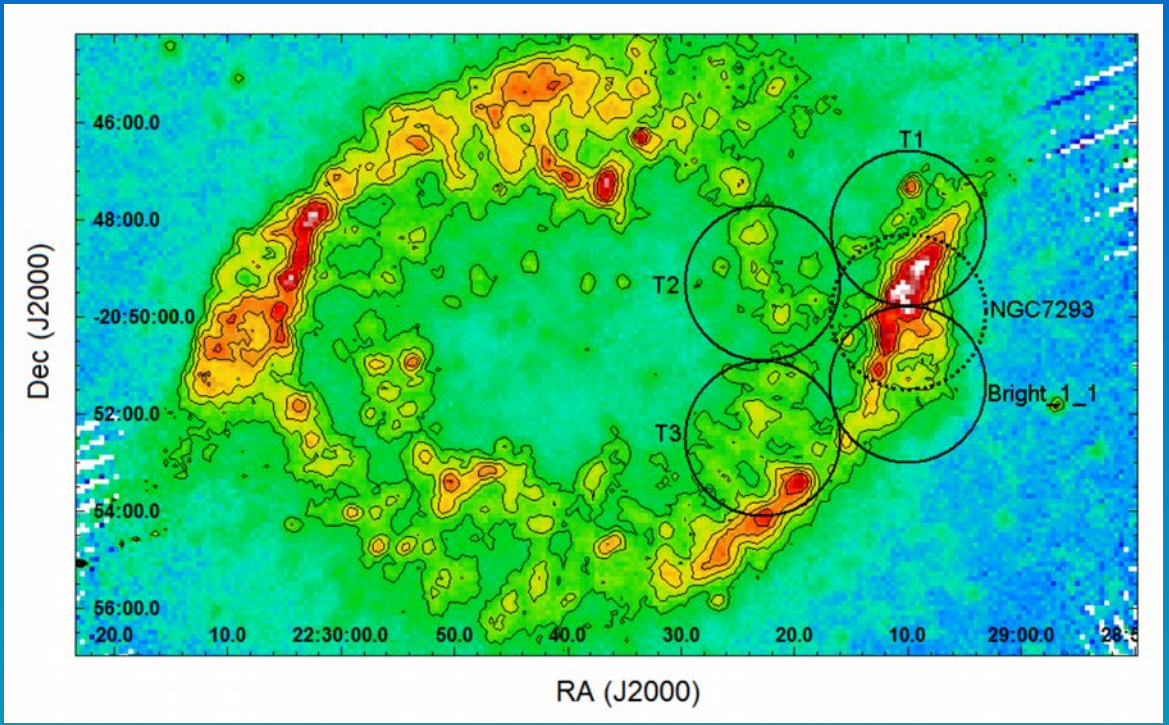
- We fitted a modified blackbody to the photometry of NGC 7293, including a component for the radio free-free emission. The data points are IRAS, PACS, SPIRE, and Planck fluxes and a 31 GHz point from Casassus+ (2004).
- The fit yielded T_{dust} = 30.8 ± 1.4 K and β = 0.99 ± 0.09.
- The low β could indicate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

NGC 7293



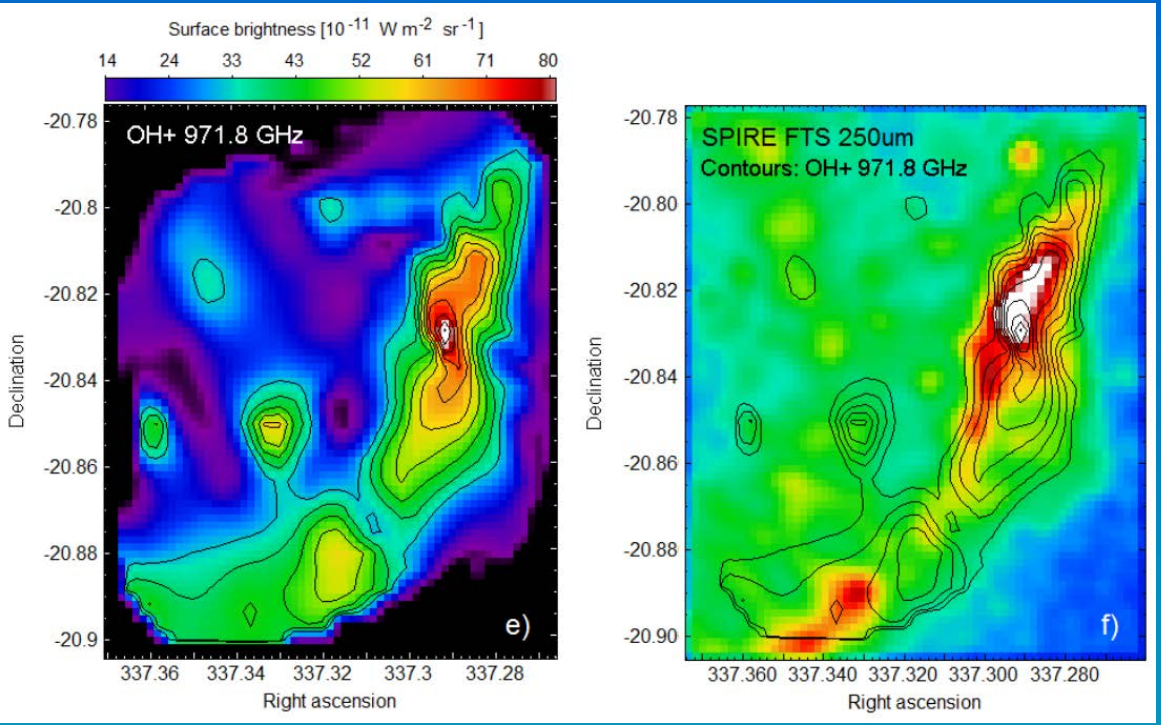
- The dust temperature map constructed from the PACS 70 μm and SPIRE 250 μm maps, assuming grains with β = 1.
- There clearly is a ring of warmer dust that encompasses both the inner and outer ring.
- The extensions towards the NW and SE are colder, likely due to a combination of greater distance and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

NGC 7293



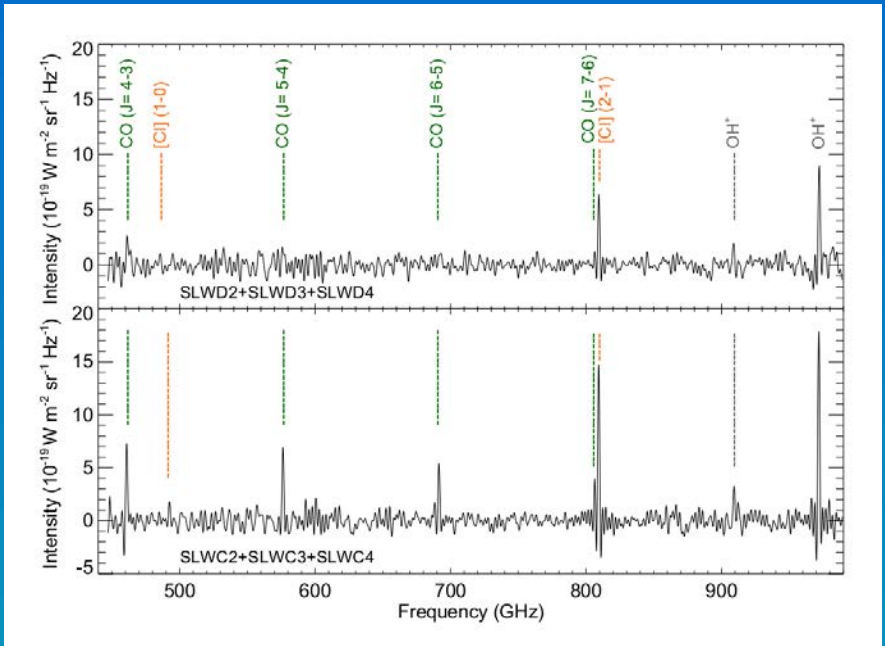
- We obtained SPIRE spectroscopy of the Helix nebula as part of the DDT MD7 proposal (solid circles) as well as a OT2 proposal (dotted circle). They cover the inner as well as the outer ring. The apertures are shown on top of the SPIRE 250 μm image.
- We have pooled these data and the following slides 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 and a tentative detection of the o-H_2O fundamental.

- 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. See poster P52 in session B by Ladjal et al. for an overview of HerPlaNS.
- We are now coordinating our efforts to simultaneously publish discovery papers by Etxaluze+ and Aleman+.

NGC 7293

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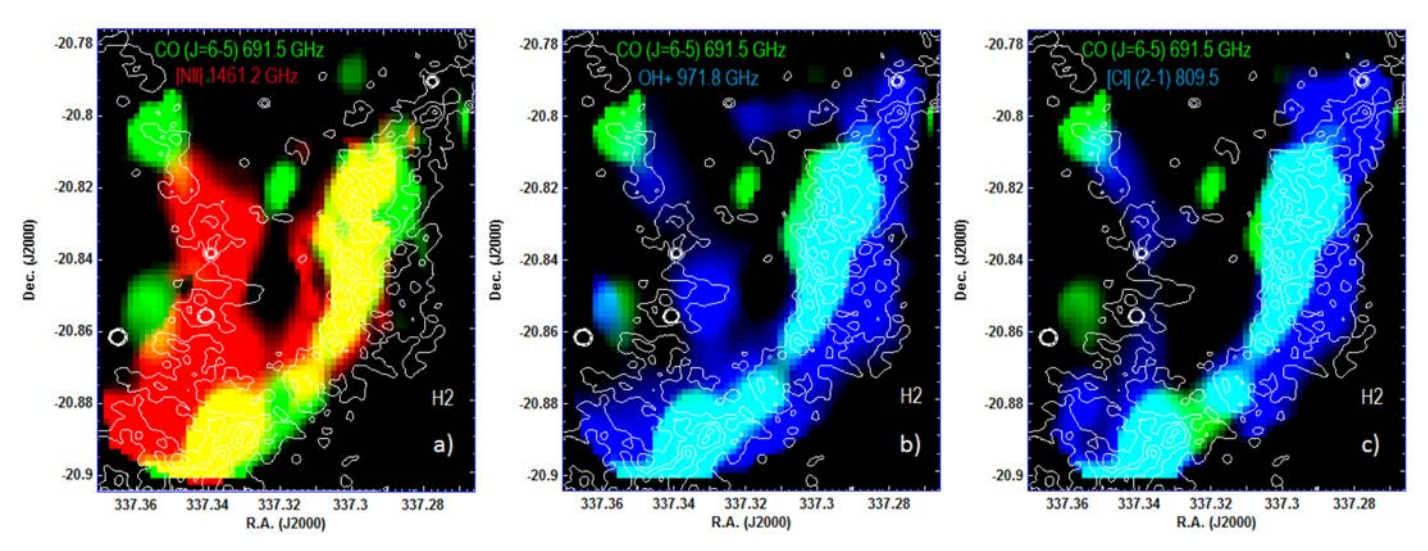

- Here we compare the spatial distribution of the emission in various lines.
- It is clear that the OH^+ and the [C I] emission have a very similar distribution. Regions that emit CO also emit OH^+ (with some minor differences) but the CO emission is more narrowly confined. The CO is cold (20 – 40 K).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

Summary

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- For most PNe we see a detailed match between the FIR dust emission and the H_2 emission, showing that the dust and H_2 are closely associated. In the case of NGC 6720 this close association provides the first observational evidence for H_2 formation on oxygen-rich dust grains in an astrophysical environment.
- We produced temperature maps from the PACS 70 / 160 µm or the PACS 70 µm / SPIRE 250 µm ratio images which show a rich structure. They indicate that internal extinction in the UV is an important factor in determining the dust temperature, despite the highly evolved status of the nebulae.
- Many molecules were detected in the spectrum of NGC 7027. A preliminary Cloudy photoionization / PDR model of NGC 7027 indicates that the PDR has higher density than the ionized region and the nebula is not in pressure equilibrium.
- Many of the PNe in our sample show molecular clumps that are embedded in ionized gas. All central stars produce photospheric X-rays, leading to mild XDR conditions. Photodissocitation is likely to be important in all sources, which is confirmed by the Cloudy model of NGC 7027.
- We report the first detection OH^+ emission in a planetary nebula. Shocks don't seem to be important in the formation. A possible formation scenario is in advection flows off the molecular knots inside the ionized gas.