SINFONI Observations of Comet-shaped Knots in the Planetary Nebula NGC 7293 (the Helix Nebula)

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One of the most interesting characteristics of the planetary nebula NGC 7293 (the Helix Nebula) is its comet-shaped knots. We have observed one of the knots using the SINFONI imaging spectrometer on the VLT with adaptive optics. The spectra are analysed to obtain the spatial variation of molecular hydrogen line intensities within the knot. The images clearly show the detailed structure, which resembles a tadpole in shape, suggesting that hydrodynamic flows around the knot core create a pressure gradient behind the core. The three-dimensional spectra reveal that the excitation temperature is uniform at approximately 1800 K within the knot. The SINFONI observations help to determine the H_2 excitation mechanism in planetary nebulae, as well as the importance of hydrodynamics in shaping the knots.

Cometary knots in the planetary nebula NGC 7293

The Helix Nebula (NGC 7293; Figure 1), located at 219 pc (Harris et al., 2007), is one of the closest planetary nebulae (PNe). The diameter of the entire nebula is approximately a quarter of the size of the full moon. This proximity enables a study of the detailed structure inside the nebula. The most interesting feature in the Helix Nebula is its knots, which have a typical size of 0.5–3 arcsec at their heads and are accompanied by tails up to 15 arcsec long (O'Dell and Handron 1996; Figure 1). All of the knots have bright tips facing the central star and the tails extend in the opposite direction away from the central star. The knots were first discovered by Walter Baade in about 1940, according to Vorontsov-Velyaminov (1968). The formation mechanism of these tails is not well understood: the two most likely explanations are mass injection from cores followed by hydrodynamic processes creating a tail, or photoionisation of an optically thick globule creating a shadow. Furthermore, ionised lines, hydrogen recombination lines, and molecular emission (H_2 and CO) have been detected from these knots. However, the excitation mechanisms of the molecular lines are not yet known. In particular, the H_2 line excitation mechanism of PNe in general is still a subject of dispute and UV excitation and shock excitation have both been proposed.

Planetary nebulae are the late stages of the stellar evolution for low- and intermediate-mass stars (1–8 $M_{\odot}$ on the main sequence). The Sun is expected to reach this stage in about 5 billion years. The circumstellar shell was produced by mass-loss processes during the previous evolutionary stage, the asymptotic giant branch (AGB). As the central star evolves from the AGB towards the PN phase, the effective temperature increases, and the circumstellar material in the nebula is photo-ionised. PNe are regarded as a typical case of a photon-dominant region. Moreover, a fast but low mass-loss rate stellar wind from the PN central star catches up with the slow but dense AGB wind, and so the circumstellar envelopes

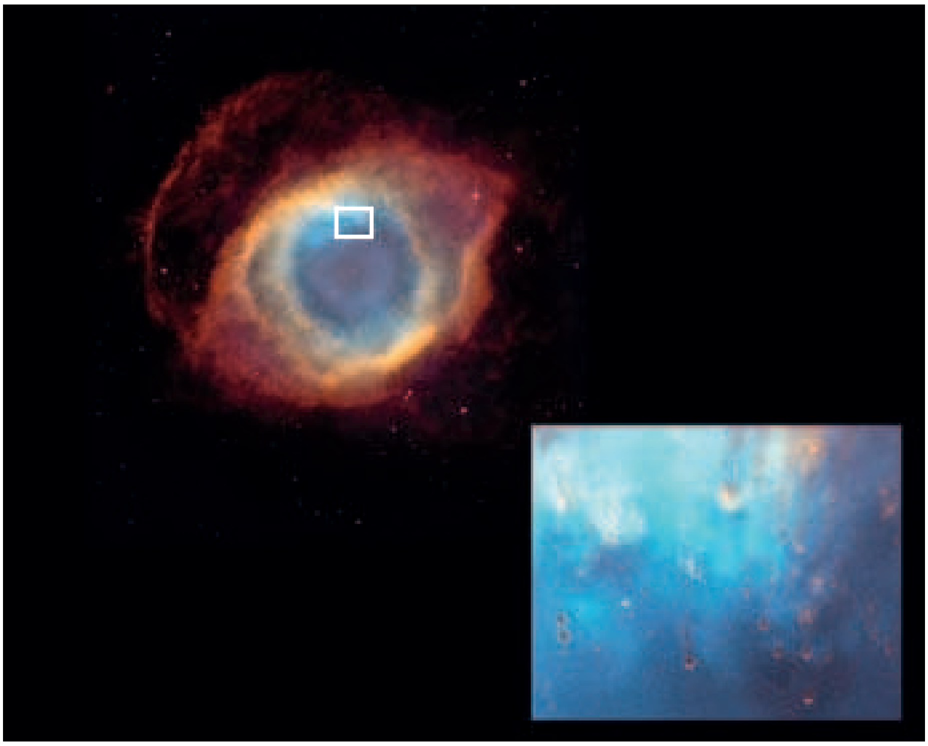


Figure 1. The optical image of the Helix Nebula (top) formed from images in a 502 nm filter ([O III]) and 658 nm filter (Hα and [N II]) is shown. The square region is enlarged in the lower panel to show the knots in the inner region of the Helix Nebula. Adopted from images taken with HST and NOAO. (Credit: NASA, NOAO, ESA, M. Meixner and T. A. Rector)

of PNe are a good test case for hydrodynamic simulations.

The power of SINFONI

Integral field spectrometers allow the simultaneous measurements of an image and many spectra on an individual pixel basis, and so these instruments are ideal for investigating spatial variation of line intensities, and thus line excitation mechanisms within nebulae (e.g. Tsamis et al., 2008). SINFONI is a near-infrared integral field spectrometer, covering the wavelength range which contains molecular hydrogen rotational-vibrational lines around 2 microns. SINFONI can be supported by an adaptive optics (AO) system, which allows observations to be taken with high spatial resolution. Thus it is an ideal instrument to investigate the structure of small-scale (a few arcsec) objects, such as knots in planetary nebulae.

We used SINFONI to obtain 2 micron integral field spectra of a knot within the Helix Nebula (Matsuura et al., 2007). There are many field stars inside this nebula, and we chose a knot close to one of the field stars, which was used as a guide star for the AO system. The images obtained with AO assistance achieve the highest angular resolution of any images of the Helix Nebula, up to about 70 milliarcsec. Figure 2 shows the SINFONI image of the knot in the Helix Nebula. The knot was clearly resolved into an elongated head and two narrow tails. The overall shape resembles that of a tadpole. The brightest emission is found in a crescent within the head. The diameter of the head is approximately 2.5 arcsec, while that of the tails is about 2.9 arcsec. We found that the tails are brighter in H_2 than in optical H-alpha+[N II] emission (Figure 3). In the optical, almost only the crescent at the head is found and the tail is barely seen.

As an integral field spectrometer, SINFONI can provide a spectrum at every single spatial pixel over the field. Figure 4 shows representative spectra within the knot obtained by the SINFONI instrument. Integral field spectroscopy enables the spatial variation of the intensities of H_2 lines to be studied. This is the first time that spatially resolved H_2 spectra have been obtained within a knot. The SINFONI data also provide line ratio maps, which gives a measure of the H_2 excitation temperature. The line ratio maps ap-

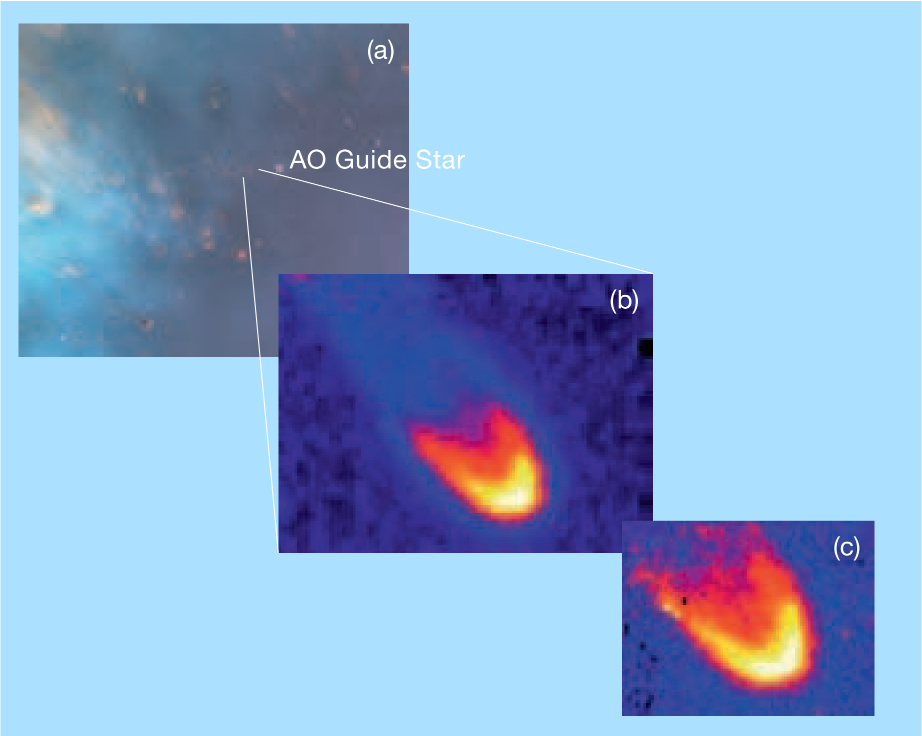


Figure 2. (a) Optical image showing the location of the target and a nearby field star which was used for adaptive optics. (b) The SINFONI image of the knot at 2.12 micron covering the H_2 v = 1–0 S(1) line; (c) close-up of the crescent taken with SINFONI at a scale of 100 milliarcsec per pixel but resampled to 50 milliarcsec pixels. The image size is 4.2 arcsec by 3.9 arcsec.

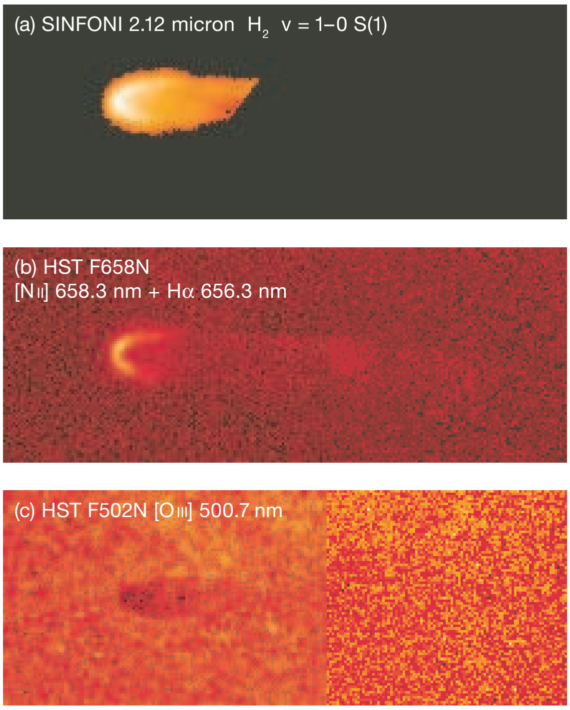


Figure 3. A comparison of SINFONI H_2 and optical images. The tails are much more obvious in the H_2 line (a) than in the 658 nm image (b). The knot is found to be negative in 500.7 nm [O III] line (c), because the dust in the knot absorbs the background emission, while the surrounding area has diffuse [O III] emission unaffected by dust.

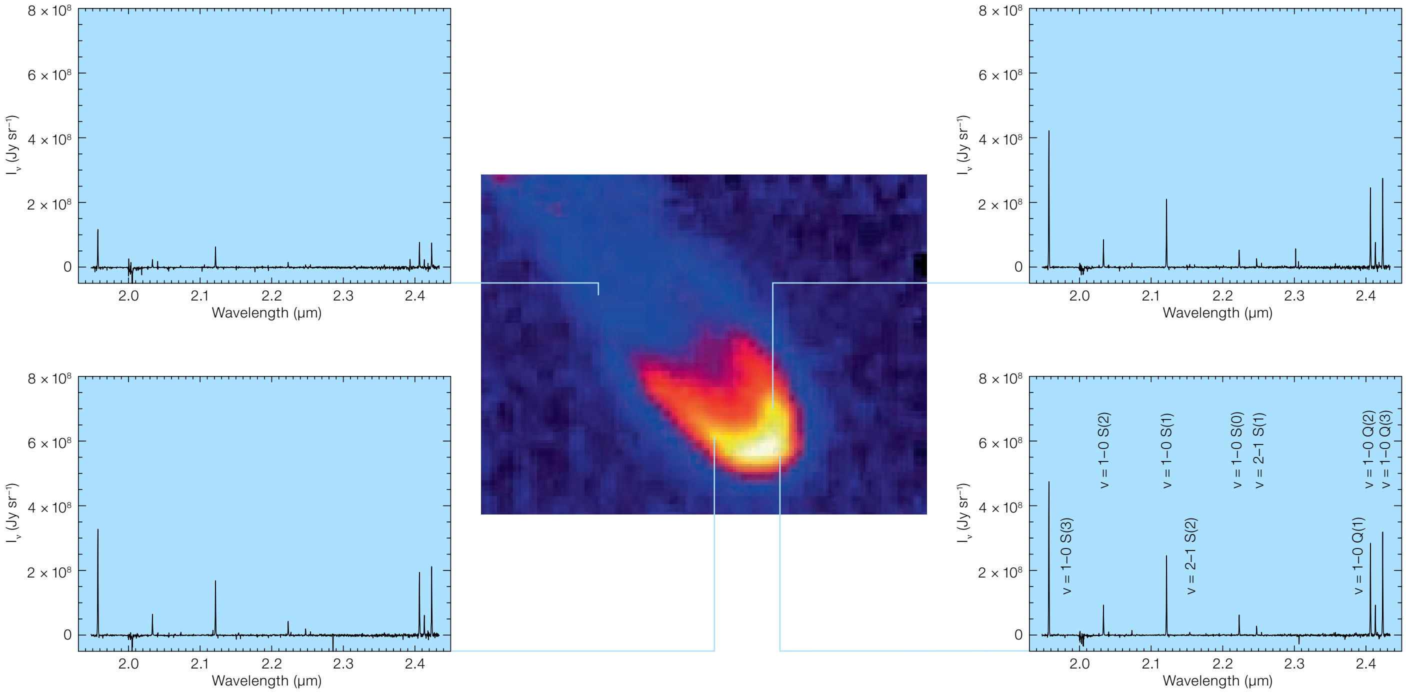
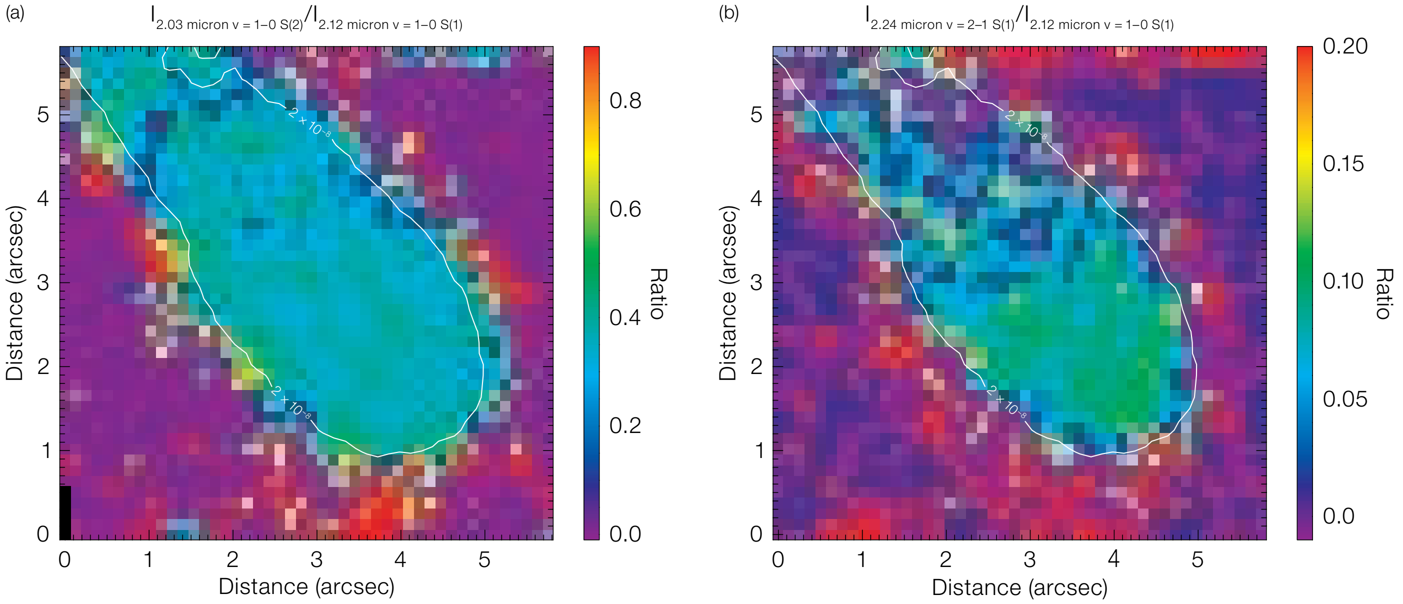


Figure 4 (above). SINFONI spectra of H_2 lines, with identification of transitions in the right bottom panel, at different locations around the knot shown in the central image.

Figure 5 (below). Line ratio maps, showing (a) the rotational temperature and (b) the vibrational temperature of H_2 molecules. The excitation temperatures appear to be uniform within the knot, outlined by a white line.



pear to be uniform within the knot (Figure 5). Using all of the H_2 lines detected at 2 microns (up to 12 lines), we derived an excitation temperature of 1800 K, and all of the intensities follow local thermodynamic equilibrium (LTE).

Shaping of the knots

The mechanism responsible for the formation and shaping of the knots has been the subject of a long-term debate. The long tails of the tadpole-like knots indicate the involvement of hydrodynamics. The bright crescent is a bow shock and the stellar wind from the central star blows the material off, or alternatively radiation from the central star heats the core evaporating the gas which forms a pony-tail pointing away from the central star. The tail is narrower than the head, probably because of the pressure difference behind the head caused by the stellar wind (Figure 6). One of the best models to reproduce the tadpole shape has been developed by Pitterd, Dyson, and their colleagues (e.g. Dyson et al., 2006). According to their model, the tadpole shape can be produced if material is constantly removed from the core of a knot by the stellar wind, and if the velocity of the wind is about supersonic. Their models show that the velocity of the ambient gas is between 26 and 38 km/s in the case of the Helix knots. Such a high expansion velocity component has been detected in the outer part of the Nebula (Walsh and Meaburn, 1987), but not yet in the inner part; in the inner part, only slower (10 km/s) winds have been detected so far. The detection of high velocity components from the knotty region would be of further interest.

The excitation mechanism of molecular hydrogen

The excitation mechanism of molecular hydrogen in PNe has been a long-term controversy. From the knots, CO molecular emission has been detected but their upper level energy is only 6 K, much lower than that for H_2 (typically from 6000 to 8000 K for the rotational-vibration lines at 2 microns). In order to reach the energy of such an upper level and to acquire an excitation temperature of thousands of K, a line excitation mechanism should be present. There are two major mechanisms proposed to excite rotational-vibration lines of molecular hydrogen at 2 microns: collisional and fluorescent excitation. For shock excitation, kinetic energy is absorbed in increasing the internal energy of the molecules, and the H_2 line intensities follow a thermal population distribution. However UV radiation in photon-dominant regions increases the population of rotation-vibrationally excited states, and vibrationally excited molecules then decay by emitting photons in the near-infrared. The population of UV excited states are often detected in non-LTE in rotational-vibration lines, but in an intense UV field, and depending on the gas density, fluorescence can create a thermal population distribution.

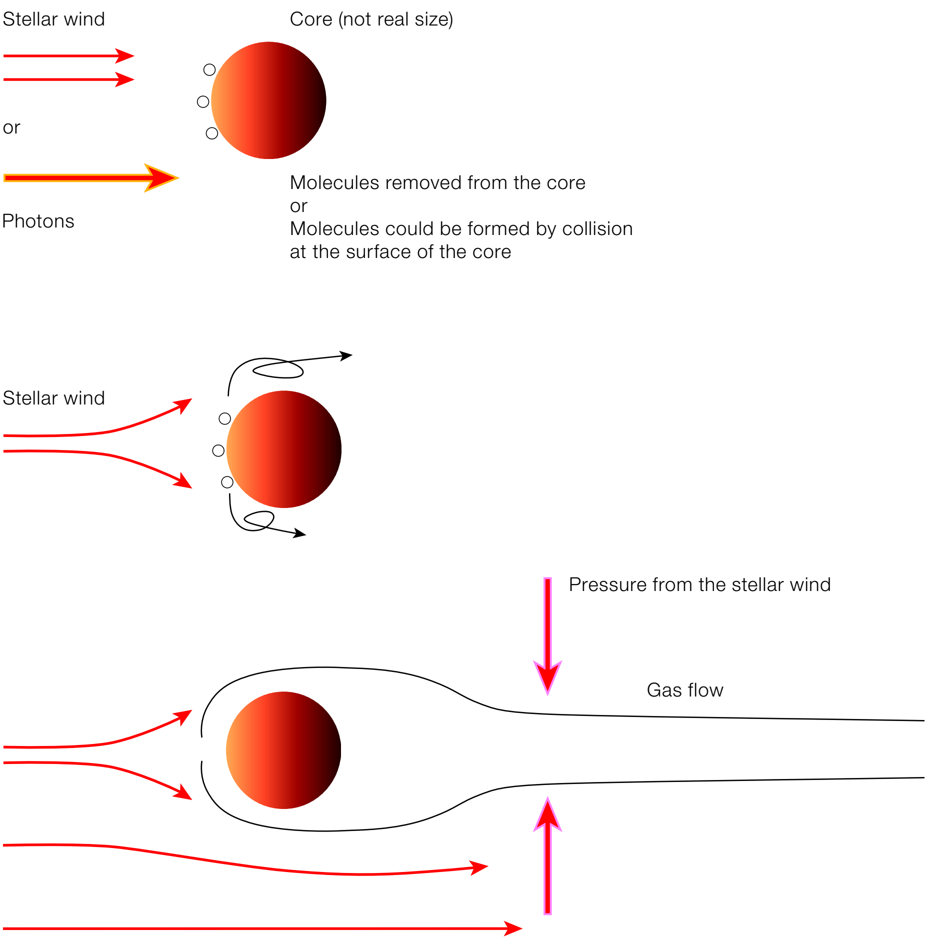


Figure 6. A schematic view of the formation of a knot in a planetary nebula by the effects of the stellar wind.

Within the choice of existing models and their parameter ranges, C-type (continuous) shock models with an ambient gas velocity of 27 km/s (Burton et al., 1992) can reproduce the measured H_2 intensities in the Helix Nebula. In contrast, UV radiation models can fit the observations, only if the UV flux is increased by a factor of 250 above that expected from the central star. Within the current choice, our observations favour shock excitation of H_2 lines.

The non-detection of a shocked region in the SINFONI image still remains a mystery: if the H_2 lines are excited by shocks, the excitation temperature should be highest at the tip of the tadpole, i.e., on the crescent. However, our SINFONI observations did not detect such a shocked region (Figure 5). This could be because the scale of the shocked region is still too small to be resolved even with SINFONI.

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