Integral-field Spectroscopy of Galactic Planetary Nebulae with VLT FLAMES

Yiannis G. Tsamis[1]
Jeremy R. Walsh[2]
Daniel Péquignot[3]
Michael J. Barlow[1]
Xiao-Wei Liu[4]
John Danziger[5]

[1] Department of Physics and Astronomy, University College London, United Kingdom
[2] ST-ECF, ESO
[3] LUTH, Observatoire de Paris-Meudon, France
[4] Department of Astronomy, Peking University, China
[5] INAF – Osservatorio Astronomico di Trieste, Italy

Results from the first dedicated observations of three Galactic planetary nebulae (NGC 5882, 6153 and 7009) made with VLT FLAMES and the Giraffe/Argus integral-field unit are discussed. The unique capabilities of the Giraffe/Argus spectrograph allowed construction of two-dimensional spectral maps of one nebula and of large portions of the other two, and to record in exquisite detail the weak optical recombination lines emitted from carbon, oxygen and nitrogen ions.

A long-standing problem

Planetary nebulae are superb laboratories for the study of the late evolutionary stages of low- and intermediate-mass stars, and of stellar nucleosynthesis, and can be used to probe the chemical history of galaxies as they trace a stellar population that was born earlier (up to several billion years). Their rich emission-line spectra, now observable even to distances beyond the Local Group, offer us the possibility to use them also as test beds of atomic data delivered by the latest theoretical calculations, plus working with planetary nebulae proves to be an inspiration for much other astrophysical work. Here we pursue a physicochemical analysis of three representative nebulae belonging to the Galactic disc population. The traditional forbidden-line methods (based on the bright, collisionally-excited lines) and metallic recombination lines have been used to map the nebular plasma temperature and density, as well as the abundances of various ions and elements relative to hydrogen. We specifically investigated in detail the occurrence of the 'abundance discrepancy problem', whereby abundances in planetary nebulae of elements of the second row of the periodic table (such as carbon, nitrogen, oxygen and neon) when derived from their recombination lines are *much higher* than abundances of the same elements derived from their forbidden lines (e.g. [O III] 495.9 nm) – by as much as factors of 30 for oxygen. The resolution of this problem is important, since knowing which diagnostics to trust and how to interpret complex nebular spectra is vital if we want to have accurate information on the properties of these fascinating objects; we can then safely use them as tools for other work.

Previous studies with smaller telescopes, such as the now decommissioned ESO 1.52-m, relying on 'one-dimensional' long-slit spectroscopy had revealed the presence of large 'abundance discrepancy factors' in the targets (*adfs*; that is, the ratio of abundances from the two categories of spectral line), ranging between two and ten. In total about 100 nebulae have now been surveyed, the majority by long-slit spectroscopy, and most of them show *adfs* larger than two (Liu 2006). The most likely explanation for this spectroscopic anomaly was judged to be the presence of cold plasma regions embedded in the nebular gas in the form of relatively dense, hydrogen-poor condensations – clumps or filaments (Liu et al. 2000; Tsamis et al. 2004). Due to their elevated content in heavy elements (several times Solar), this plasma would have cooled down much faster than the ambient 'normal' composition gas by emitting far-infrared lines, the primary nebular thermostat in relatively low plasma temperatures. Since the emissivity of metallic recombination lines is enhanced at lower temperatures, while at the same time that of the classical forbidden lines is diminished, the hydrogen-poor, metal-rich clumps would emit metallic recombination lines profusely, yielding a truer estimate of the heavy element content of these regions. Whereas the large long-slit survey yielded concrete evidence for elevated recombination-line abundances, the temperature of the suspect metal-rich clumps was tougher to determine since the diagnostic lines involved are faint and often suffer from blends in lower-resolution spectra. Nevertheless, there was some evidence deduced from those studies for temperatures lower by several thousand K than the typical temperatures of photoionised nebulae. This is one aspect of the proposed 'dual abundance model' solution that renders it self-consistent, something rather lacking from alternative propositions which do not invoke metal-rich plasma to explain the discrepancies, such as small-scale temperature fluctuations in a chemically homogeneous medium (e.g. Peimbert et al. 2004). A major unresolved issue remains the, as yet, unknown origin of the high abundance plasma.

The current study

Metallic recombination lines in nebulae can be a thousand times fainter, or even more, than hydrogen recombination lines, in sharp contrast to the luminous forbidden lines emitted by the same heavy ions. The VLT with its light-collecting power, coupled with the ability to make spatially resolved spectral maps across the face of the nebulae, settled the choice of the VLT FLAMES instrument and the Giraffe spectrograph with the Argus integral-field unit, mounted on UT2/Kueyen, for our study. The target sample comprised three nebulae belonging to the Galactic disc population: we used the large Argus unit (12 × 7 $arcsec^2$) to observe NGC 5882, NGC 7009 and NGC 6153 in the 396–508 nm range at a spatial resolution of 0.52 arcsec per spatial pixel (*spaxel*), as well as the small 6.6 × 4.2 $arcsec^2$ field of view to observe a portion of NGC 7009 in the 419–439 nm and 454–476 nm ranges at 0.30 arcsec per spaxel. The small field spectra of NGC 7009 were taken in high-resolution mode (R = 32 500) allowing us to measure gas velocities to an accuracy of a few km/s, while the remaining spectra had a resolution of 25–30 km/s comparable to the typical expansion velocity of a planetary nebula and thus optimal for the detection of faint recombination lines. Our main goals were to map: (i) the spatial distributions of metallic recombination lines from heavy ions (e.g. C II, O II, N II);

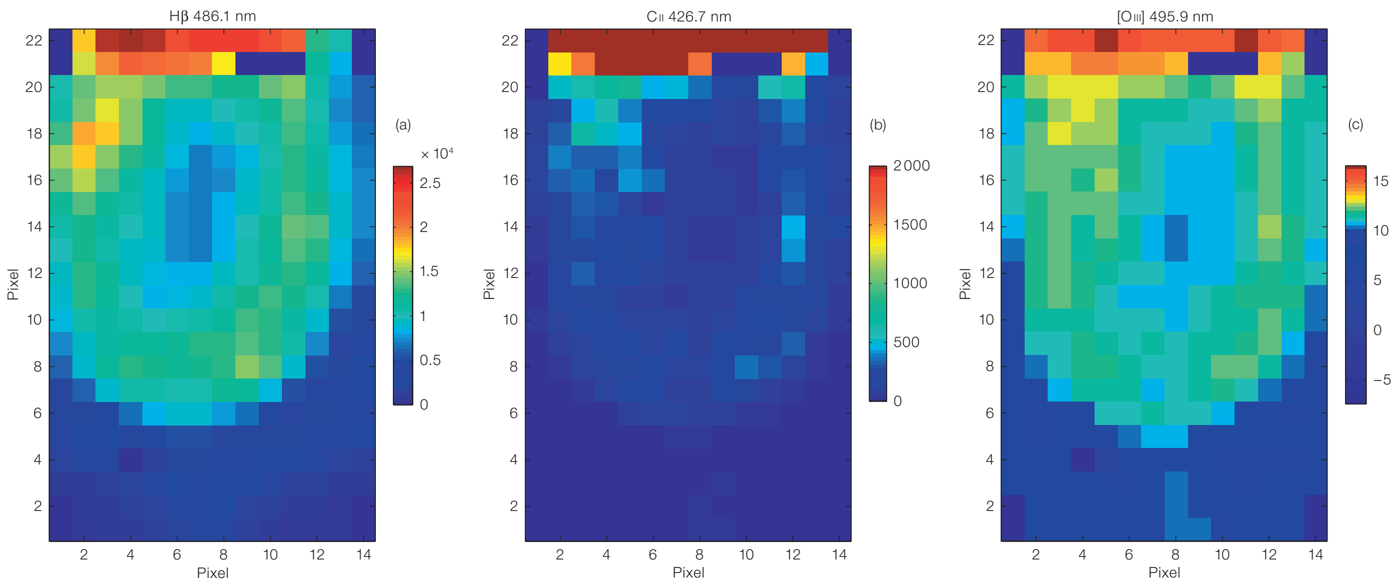


Figure 1: Narrowband emission line maps of NGC 5882 taken with the 12 × 7 arcsec^2 Argus unit in the light (a) of Hβ, (b) the C II 426.7 nm recombination line, and (c) the [O III] 495.9 nm forbidden line (the log is shown). The blank corner spaxels correspond to sky-fibres, and three blank spaxels in the second row from top correspond to dead fibres.

(ii) the corresponding two-dimensional chemical abundance distributions from both recombination lines and forbidden lines; and (iii) to investigate the resulting pattern of *adfs*, temperatures and densities derived from recombination lines in order to probe the physical properties of the posited super-metal-rich component. The high spectral resolution data of NGC 7009 were aimed at revealing whether there is any *kinematical* evidence for the existence of hydrogen-poor regions embedded in the nebula with velocities different from the bulk velocity of the normal gas component.

The spectra were reduced with the dedicated girBLDRS pipeline provided by the Geneva Observatory and were flux-calibrated within IRAF. Custom-made routines allowed us then to convert the row by row stacked CCD nebular spectrum to a 'data cube', this in the terminology of integral-field spectroscopy denoting a three-dimensional array incorporating the two spatial dimensions, and the astrophysical flux as a function of wavelength in the third dimension (hence the term '3D spectroscopy' for this kind of observations). The emission-line spectra in each spaxel of the data cubes were fitted by Gaussians using a dedicated tool which also allows interactive fitting for individual spaxels, such as those over the central star. Maps of the emission in each line species were then constructed from the Gaussian fits. The maps were corrected for interstellar extinction using the *c*(Hβ) extinction constants derived from a comparison of the observed and predicted relative intensities of H I recombination lines (the Balmer decrement). In Figure 1 we show maps of NGC 5882 outlining the bright shell of the nebula in the light of the hydrogen Balmer recombination line Hβ, the metallic recombination line C II 426.7 nm (emitted when C^{2+} ions recombine with free electrons), and the forbidden line [O III] 495.9 nm (emitted following electron-impact excitation of O^{2+} ions). C II 426.7 nm is typically the strongest heavy ion optical recombination line emitted from planetary nebulae and H II regions (up to a few per cent of Hβ 486.1 nm). Observations of this line in the early 1980s first exposed the nebular abundance anomaly when comparisons were made between the high carbon abundance measured from it *versus* that from the collisionally-excited C III] 190.8 nm line, which had just become accessible with the International Ultraviolet Explorer (e.g. Barker 1982). In Figure 2 we show a representative spectrogram of NGC 6153 registered by a *single* 0.52^2 arcsec^2 spaxel, highlighting the superb quality of the FLAMES Giraffe data and the prominent high signal-to-noise metallic recombination lines of CNONe ions: all these are useful abundance indicators provided that appropriate recombination coefficients are used for their interpretation. The spectrum has been smoothed using a five-point average; even so, almost all features seen down to the noise limit are nebular emission lines.

A strange nebular phase: very high metal abundance, low-temperature gas

We proceeded by investigating the nebular physical conditions; plasma temperatures and densities were first derived from the dereddened forbidden-line ratios [O III] 436.3 nm/495.9 nm and [Ar IV] 471.1 nm/474.0 nm respectively. These were subsequently adopted for the calculation of nebular abundances: forbidden-line abundances relative to hydrogen depend strongly on the adopted temperature via an exponential factor (being higher when temperatures are lower and vice versa), whereas metallic recombination line abundances have a much weaker temperature dependence (a shallow, inverse power law).

In Figure 3a we show a temperature map of the south-eastern quadrant of NGC 6153. The temperature which has a mean value of 9 400 ± 145 K shows a shallow positive gradient averaging about 1000 K from the outer to the inner regions (top to bottom) – the central star is at spaxel (9, 3). This gradient reflects

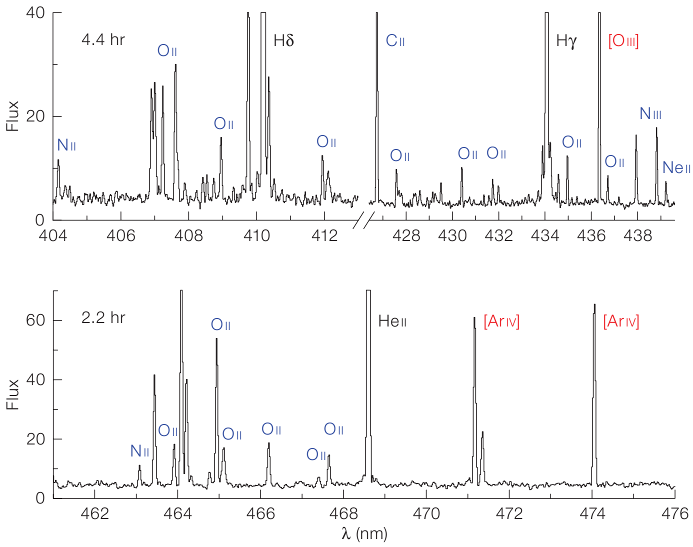


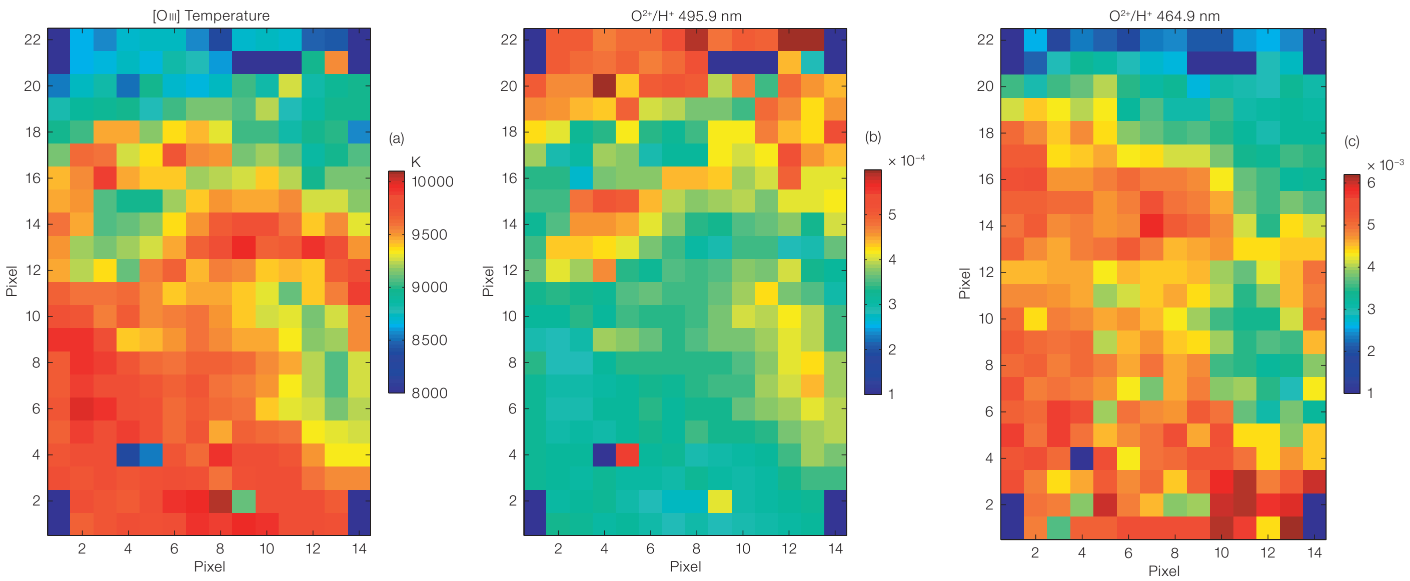
Figure 2: Single spaxel spectrum of NGC 6153 showing the prominent recombination lines of CNONe ions. The metallic recombination lines are marked in blue and the collisionally excited lines are marked in red.

directly on the O^{2+}/H^{+} abundance ratio derived from the forbidden 495.9 nm line, which shows a rough trend in the opposite direction, with a mean value very close to the Solar abundance of oxygen (Figure 3b). On the other hand, the same abundance ratio derived from the recombination line 464.9 nm is highest in the inner nebular regions, peaking close to the central star (Figure 3c), and the resulting abundance of oxygen there (even without taking into account other ionic stages) is at least 10 times Solar. In this sense the recombination- and forbidden-line abundances of doubly-ionised oxygen increase in opposite directions. The ratio of the two (the *adf*) thus becomes smaller for increasing radial distance from the central star and has a mean value of 16 in a 2.4 arcsec^2 area centred on the nucleus of NGC 6153. This can be better seen in Figure 4 where we respectively plot the radial variation of the oxygen *adf* for NGC 6153 by binning the spaxels at successive radial increments, weighting them by the total number of non-zero signal spaxels at each radius.

The oxygen abundance discrepancy thus correlates with distance from the planetary nebula nucleus. The carbon abundance derived from the C II 426.7 nm line also behaves in a similar manner (displaying values several times higher than Solar throughout the nebulae). It is not yet clear what the reasons for this is, though one possibility could be that the *adf* is caused by metal-rich, clumped plasma ejected from the central star during its post-AGB evolution, becoming more 'dilute' as it progressively mixes with the 'normal' nebular component further out in the nebula. If this picture is true then the highest concentration of high-abundance gas will be found close to the central star. On the other hand, the two different O II lines used to compute the *adf* in the upper and lower panels of Figure 4 show slightly different radial trends. The exact trends depend also on the temperatures and densities adopted as representative for the emitting regions of these lines – here the plasma conditions corresponding to the hot gas were used (from forbidden-line ratios). These nebular parameters, as we show later, are probably not appropriate. But just what are the physical conditions of the postulated clumps, other than their obvious metal-rich nature, and how do we get a handle on them?

The weak temperature sensitivity of the emissivities of O II recombination lines can be used to provide a temperature estimate via the O II 408.9 nm/464.9 nm ratio. We have used this diagnostic cou-

Figure 3: Physical properties across the south-eastern quadrant of NGC 6153: (a) The electron temperature measured from the forbidden line ratio [O III] 436.3 nm/495.9 nm; (b) The O^{2+}/H^{+} abundance ratio derived from [O III] 495.9 nm, and (c) The same abundance ratio derived from the O II 464.9 nm recombination line.



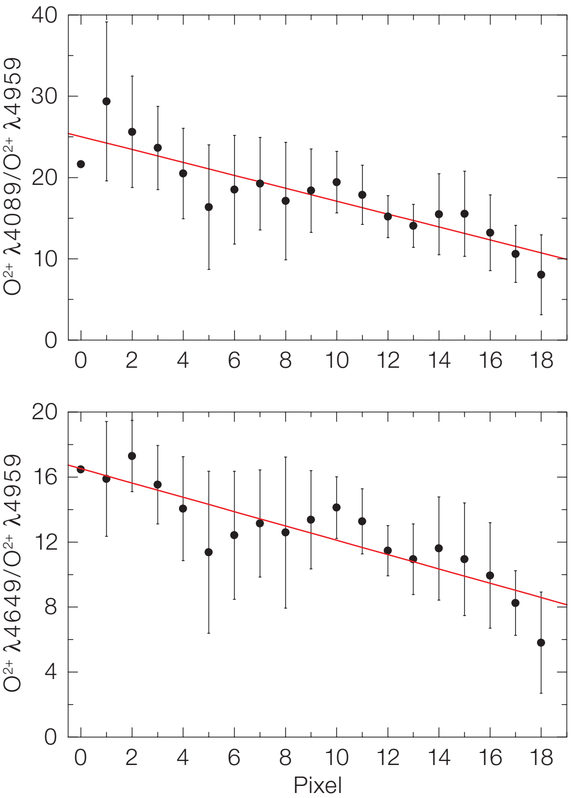


Figure 4: The radial profile of the O^{2+} abundance discrepancy factor for NGC 6153.

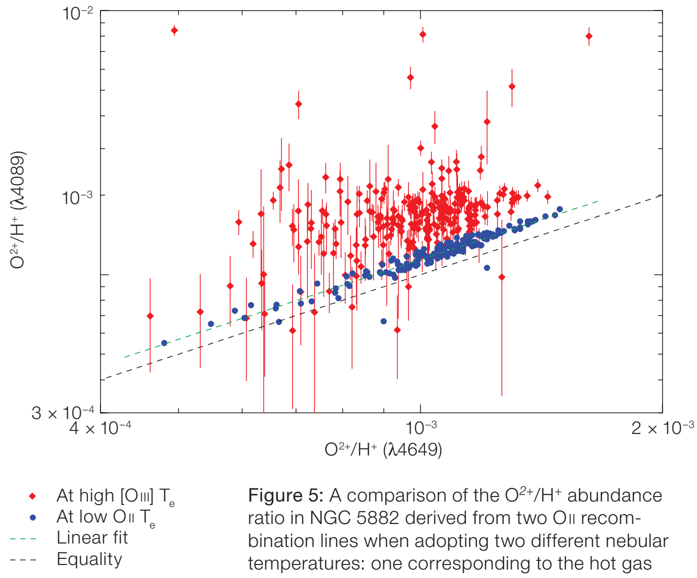


Figure 5: A comparison of the O^{2+}/H^{+} abundance ratio in NGC 5882 derived from two O II recombination lines when adopting two different nebular temperatures: one corresponding to the hot gas component, and another corresponding to the cold O II gas component.

pled with the latest theoretical O II recombination coefficients and found mean temperatures as low as about 5 300 K for NGC 6153, 2 400 K for NGC 5882, and 2 500 K for NGC 7009; importantly these appear to be even lower near the central stars. The associated errors are quite large but, assuming that the O II diagnostic ratio is a valid thermometer, there seems to be good evidence for the existence of a cold plasma phase at temperatures several thousand K lower than the normal nebular component. We stress again the self-consistency of this component being *both* cold *and* metal-rich (hydrogen-deficient). Another piece of evidence supporting this point is shown in Figure 5; there we compare the spaxel to spaxel variation of the O^{2+}/H^{+} abundance ratio derived from the 408.9 and 464.9 nm lines (both emitted by the same ions) for NGC 5882: when the high temperatures derived from the classical [O III] diagnostic (mean of 9160 K) are adopted for the computation, the scatter of the data is very large. In contrast, when the much lower O II ratio temperatures are adopted (mean of 2 400 K), the two lines yield almost exactly equal abundances with minimal scatter. Thus the O II lines cannot be compatible with an emitting region of high temperature. Importantly, it seems that this is true even for NGC 5882 which is our 'control' object, and a nebula previously known, from long-slit spectra, to exhibit a mild abundance discrepancy of a factor of two.

In order to add more weight to the above discussion we show in Figure 6 the spectrum of a 0.9 × 0.9 arcsec^2 region in NGC 7009 straddling the interface between the bright inner nebular shell and the fainter outer envelope. This spectrum was taken with the small Argus unit in high spectral resolution mode (32 500) and covers several C III and O II recombination lines near 465.0 nm. At this resolution each line is split into three components with central wavelengths at about −93, −60 and −28 km/sec, probably corresponding to the edge of the inner nebular shell (central peak) and the expanding outer shell (peaks on either side). In the upper panel the observed (red) and synthetic (green) spectra are shown. Also overplotted are the intrinsic synthetic spectra, before convolution with the instrumental profile, of C III (orange) and O II (blue). We specifically wanted to compare the widths of the metallic recombination lines to those of the forbidden [O III] 436.3 nm line to uncover any evidence of different temperature nebular phases in this way. The synthetic O II line profiles were thus replaced by the profile of [O III] 436.3 nm and in the bottom panel the difference between the observed and synthetic spectra is shown: this yielded large residuals, especially for the central O II peak, meaning that the O II lines have significantly narrower thermal widths than [O III] 436.3 nm. This indicates that, even though they are emitted from the same O^{2+} ion, the O II spectrum and [O III] 436.3 nm cannot originate from material of identical physical properties. This constitutes extra evidence for lower temperature gas associated with the metallic recombination lines.

All these results are strongly in favour of the dual abundance model for planetary nebulae, whereby a portion of the gas that has distinctly different properties from the gas emitting the collisionally excited lines, predominantly emits the metallic recombination lines. At the time of writing we are investigating the possibility of using the relative intensities of

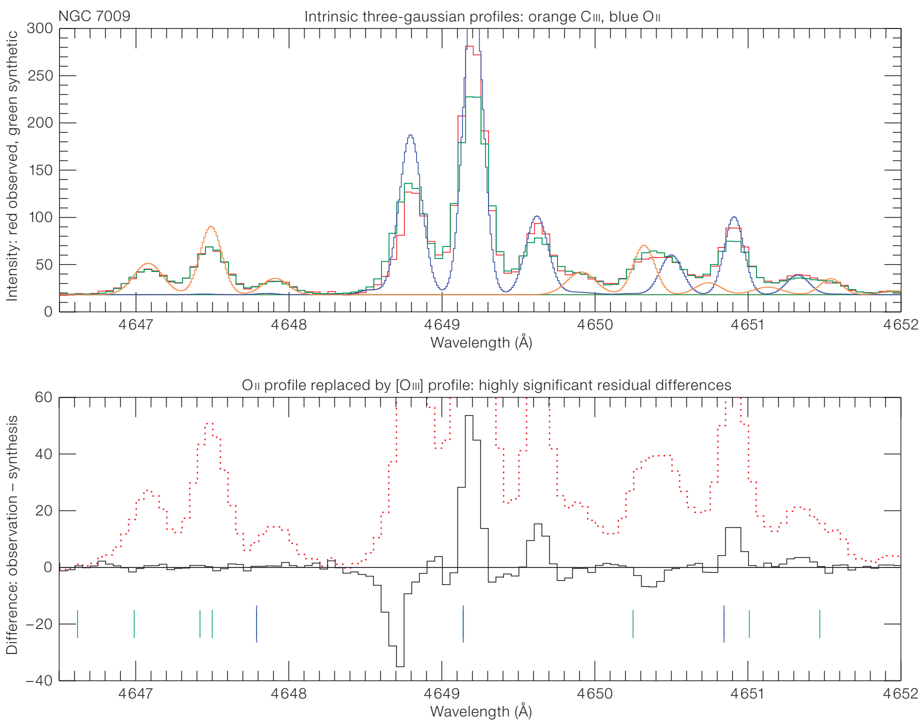


Figure 6: High-resolution spectrum of NGC 7009 in the 465.0 nm region showing in the top panel the observed profiles of C III and O II recombination lines split into three components (red line), and overlaid a synthetic spectrum (green line). Synthetic spectra associated with C III (orange) and O II (blue) are also shown. In the bottom panel the difference between the observed (red) and synthetic (green) spectra is shown.

certain O II lines as a probe of the density of their emitting regions: such lines can be found in the 465.0 nm spectral region (see bottom panel of Figure 2) and a group of some seven lines belonging to the V1 multiplet are a sensitive density diagnostic (Tsamis et al. 2003; Bastin and Storey 2006). Once the density and temperature of the region emitting the O II spectra is measured, the mass of the strange nebular phase can be safely estimated and we shall know what fraction of the total mass in a given nebula was 'hidden' from view in this way. Photoionisation modelling studies have to this date indicated that the H-poor gas constitutes only a few per cent of the total *ionised* mass in a nebula (Péquignot et al. 2002). If instead the cold component is found to have significant mass this will have important implications, as the heretofore 'established' average abundances of important heavy elements in planetary nebulae will only be lower limits, with repercussions on the study of the whole class of these objects.

The obscure origin of the hidden nebular phase and further work

We mentioned that one scenario that has been put forward to explain the origins of the cold component is mass ejection from the planetary nebula nucleus. This may happen during the thermally pulsing AGB stage or even after this has terminated in the form of a late thermal pulse that could result in a hydrogen-poor stellar atmosphere and parallel ejection of hydrogen-deficient clumped gas in the nebula. There is precedent for this in the class of objects such as Abell 30, which possess hydrogen-poor knots embedded near the centres of their nebulae emitting carbon and oxygen recombination lines. *HST* has imaged the optically resolved knots of Abell 30 and Abell 78 (Borkowski et al. 1993), but as yet no such features have been recorded in run of the mill nebulae like the ones in our sample. However, from the long-slit survey of a large sample it has emerged that when one compares the abundance ratio of heavy elements (e.g. C/O, Ne/O) measured from one type of emission line with that obtained from the other type of line, the ratios are often quite similar, showing that the nucleosynthetic histories of the posited H-poor clumps and the normal nebular component may not be very different, as if the whole nebula was born out of similarly processed gas. When the C/O ratio for several nebulae measured from recombination lines is less than unity, it points towards an oxygen-rich nature for the ejected clumps (Tsamis 2002; Ercolano et al. 2004), something contrary to the expectations of standard scenarios for late thermal pulses which result in central stars with carbon-rich atmospheres. Other hypotheses include the evaporation of planetary bodies predating the formation of the nebula (Liu 2003), or cometary-knot complexes (Tsamis et al. 2004) such as those originally observed in the planetary nebula nearest to us – NGC 7293 (the Helix) – but now shown to be a common occurrence in many more objects. The Argus data are of sufficient quality to allow us to investigate in detail the relative abundance ratios of carbon, oxygen, nitrogen, and neon from recombination lines across the face of the targets and can shed more light on the chemical history of the mysterious nebular component, and its likely origin. Finally, the high-resolution kinematical data of NGC 7009 have yet to be examined in detail. It's no exaggeration therefore to say that VLT FLAMES has afforded us a truly rare view of planetary nebulae and their well-hidden secrets have started to unravel.

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View of the 5000-m high Llano de Chajnantor towards Cerro Toco.

Photo: H. H. Heyer, ESO