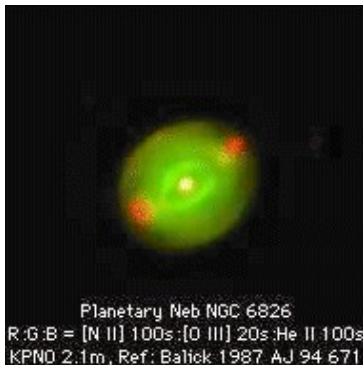
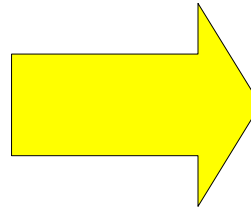
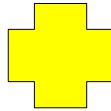


# Reduction and analysis of data of Planetary Nebulae using FLAMES/ARGUS and other IFUs



(ESO)



(Bruce Balick)

A&A 486, 545–567 (2008)  
 DOI: 10.1051/0004-6361/200809635  
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**Astronomy  
& Astrophysics**

## Spatially resolved spectroscopy of planetary nebulae and their halos<sup>\*,\*\*</sup>

### I. Five galactic disk objects

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Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 144 82 Potsdam, Germany  
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Received 22 February 2008 / Accepted 20 May 2008

**ABSTRACT**

Strong mass loss off stars at the tip of the asymptotic giant branch (AGB) profoundly affects properties of these stars and their surroundings, including the subsequent planetary nebula (PN) stage. With this study we wanted to determine physical properties of mass loss by studying weakly emitting halos, focusing on objects in the galactic disk. Halos surround the, up to several thousand times, brighter central regions of PNe. Young halos, specifically, still contain information of the preceding final mass loss stage on the AGB. In the observations we used the method of integral field spectroscopy with the PMASS instrument. This is the first committed study of halos of PNe that uses this technique. We improved our data analysis by a number of steps. In a study of the influence of scattered light we found that a moderate fraction of intensity in the inner halo originates in adjacent regions. As we combine line intensities of distant wavelengths, and because radial intensity gradients are steep, we corrected for effects of differential atmospheric refraction. In order to increase the signal-to-noise of weak emission lines we introduced a dedicated method to bin spectra of individual spatial elements. We also developed a general technique to part the temperature-sensitive oxygen line [OH] 44563 from the adjacent telluric mercury line Hg 44538 – without using separate sky exposures. By these steps we avoided introducing errors of several thousand Kelvin to our temperature measurements in the halo. For IC 3568 we detected a halo. For M2-2 we found a halo radius that is 2.5 times larger than reported earlier. We derived radially density sampled temperature and density structures for four nebulae, which all extend from the central regions and out into the halo. NGC 7662, IC 3568, and NGC 8269 show steep radially increasing temperatures and a hot halo, indicating that the gas in the halo is not in thermal equilibrium. M2-2 shows a larger temperature in the central region and an otherwise constant value. From the density structures we made estimates of core and halo masses and – for the first time reliable – mass loss rates at the tip of the AGB. All four objects show towards radially increasing mass loss rate structures, which represent a rise by a factor of about 4–7, during the final mass loss phase, that covers a time period of approximately 10<sup>5</sup> years. Within a factor of two, the average of the maximum mass loss rates, which are distance dependent, is  $\dot{M}_{\text{max}} \approx 10^{-4} M_{\odot} \text{yr}^{-1}$ .

**Key words.** methods: data analysis – techniques: spectroscopic – stars: mass-loss – ISM: planetary nebulae: general

**1. Introduction**

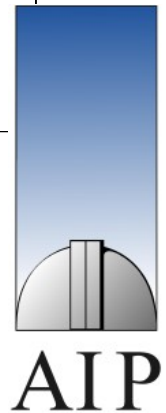
Stars on the thermally-pulsing asymptotic giant branch (AGB) are in the final stages of evolution before they turn into cooling white dwarfs. During this phase these stars lose nearly all of the mass outside their core in an increasingly strong stellar wind. The matter of such winds is enriched with nucleosynthetized elements, which have been dredged up from the interior during the evolution, thereby contributing to the galactic chemical evolution. Models of strong (dust-driven) stellar winds are described by, for example Bowen (1988), Fleischer et al. (1992), Winters et al. (2000), Höfner et al. (2003), and Sandin (2003, 2008). Two recent overviews of mass loss from cool stars are given by Willson (2000) and Höfner (2005). Although there is progress in understanding both stellar evolution and mass loss theoretically, observational details of, in particular, the last phase at the tip of the AGB have remained obscure. The lifetime of the final mass loss stage is short, and selection therefore works against its detection, making detailed observational studies difficult.

Planetary nebulae (PNe) are in transit between the tip of the AGB and the white dwarf domain of the Hertzsprung-Russell diagram. These extended objects occur in rather large numbers and can readily be observed in the visible wavelength range, where a significant fraction of the luminosity is emitted in a few emission lines. The morphological variation of PNe is large (see, e.g., Balick & Frank 2002; Sahai et al. 2007, and references therein). Of those nebulae with a spherical or elliptical shape the central parts consist of a relatively bright rim with a fainter attached shell; both are built-up by an interplay between photo-ionization and wind interaction (see, for example, Frank et al. 1990; Marten & Schönberner 1991; Frank 1994; Mellem 1994; Perinotto et al. 2004). Often a faint, and in many cases relatively large, halo surrounds the central PN region; see the PN halo atlas of Corradi et al. (2003, hereafter CS03) for examples. Such halos are with the help of models identified as the ionized AGB wind (Steffen & Schönberner 2003; Villaver et al. 2002a,b). Halos of younger nebulae are less affected by PN shaping processes than the central parts are, and therefore contain information about the preceding mass loss episode; this is not the case with so-called recombination halos of older nebulae (see,

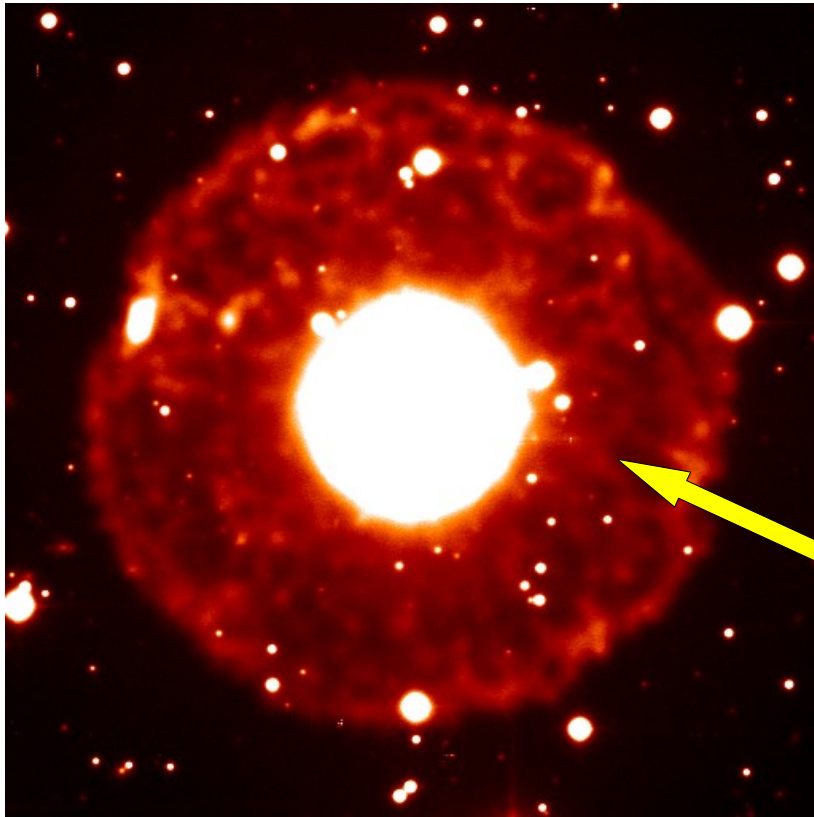
Article published by EDP Sciences

**Christer Sandin**  
**Astrophysikalisches Institut Potsdam**

2008.12.03, Six Years of FLAMES operations, ESO Garching

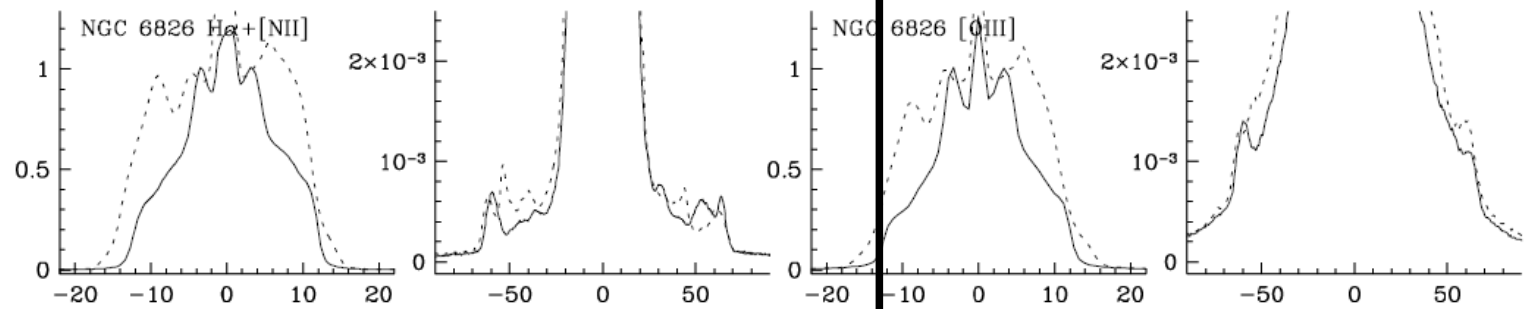


# Intensities of Planetary Nebula change by 1000× and more between the central parts and the halo

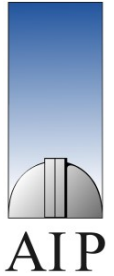


The PN halo

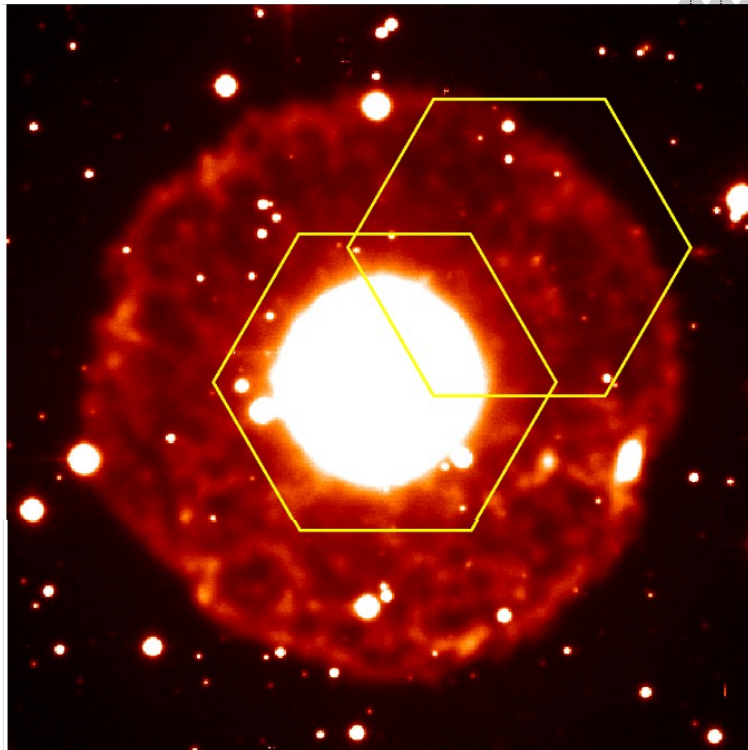
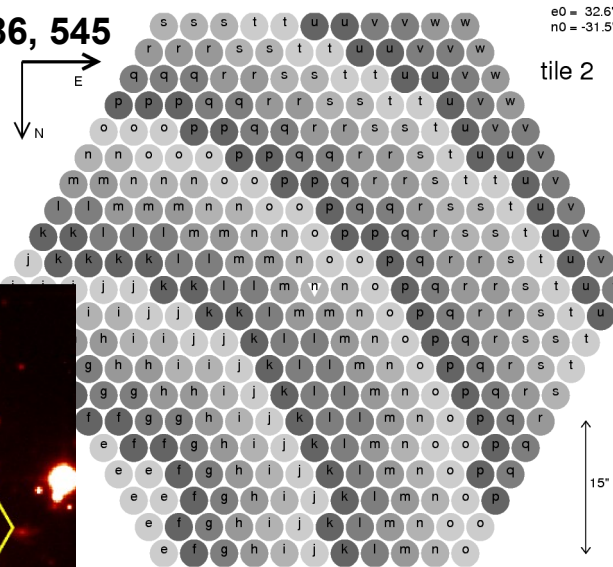
NGC 6826



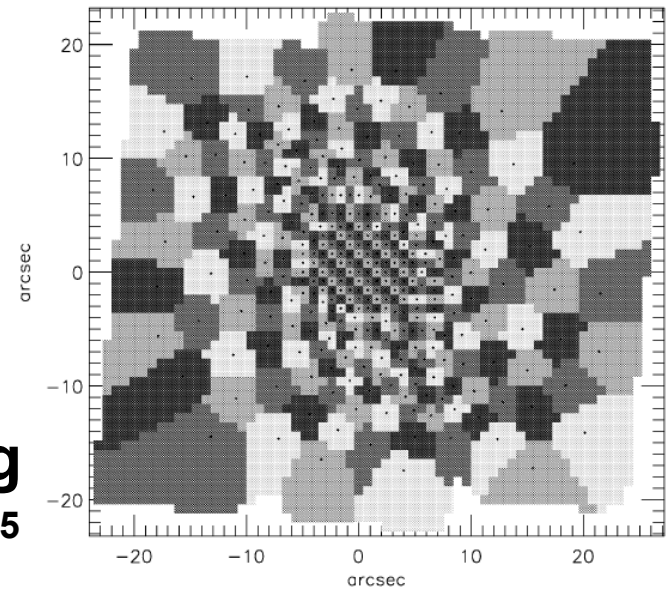
# IFU data can be used either binned, or unbinned – whatever is needed



Sandin et al. 2008, A&A, 486, 545



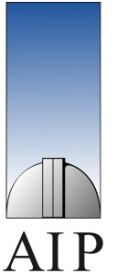
Sandin 2009, PASP, in prep.



## 2D adaptive binning

Cappellari & Copin 2003, MNRAS, 342, 345

# It may be necessary to correct the data for differential atmospheric refraction (DAR)



If the airmass is large;  $>$  about 1.1

If intensities of different wavelengths are combined

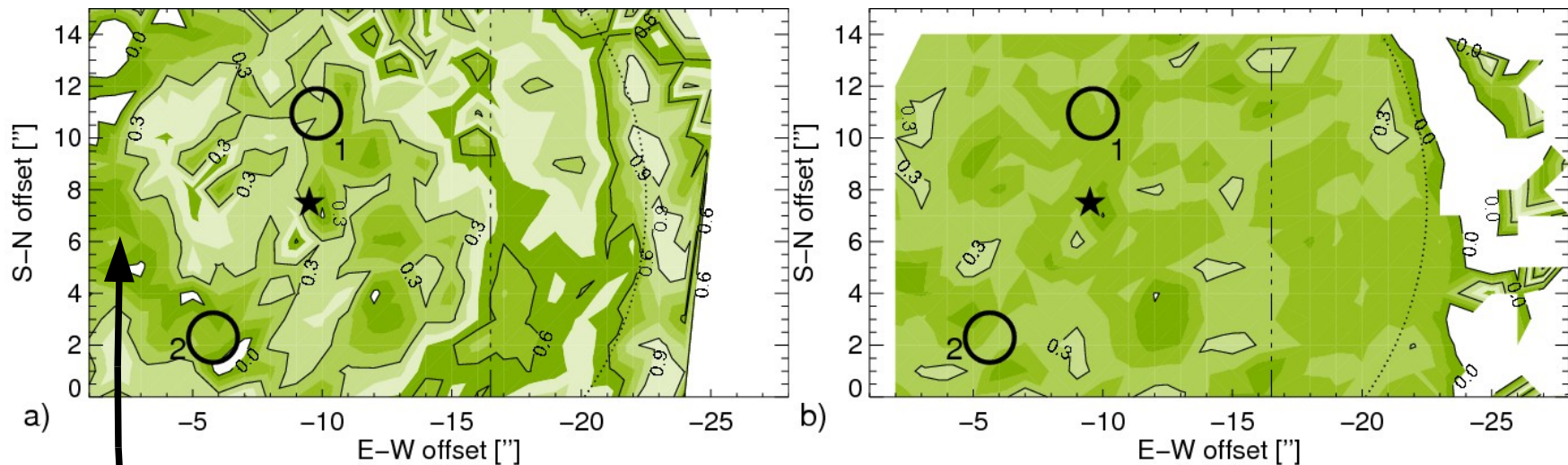
If spatial elements are small

If there is a significant intensity gradient in the object



# It may be necessary to correct the data for differential atmospheric refraction (DAR)

(Sandin et al. 2007, in press; Asymmetrical PNe IV, NGC 7662)

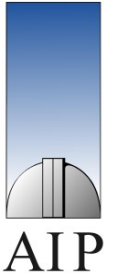


**NOT corrected for DAR**

**Corrected for DAR**

**More structure is visible in c without a correction!**

# What steps do we take in order to make the DAR-correction?



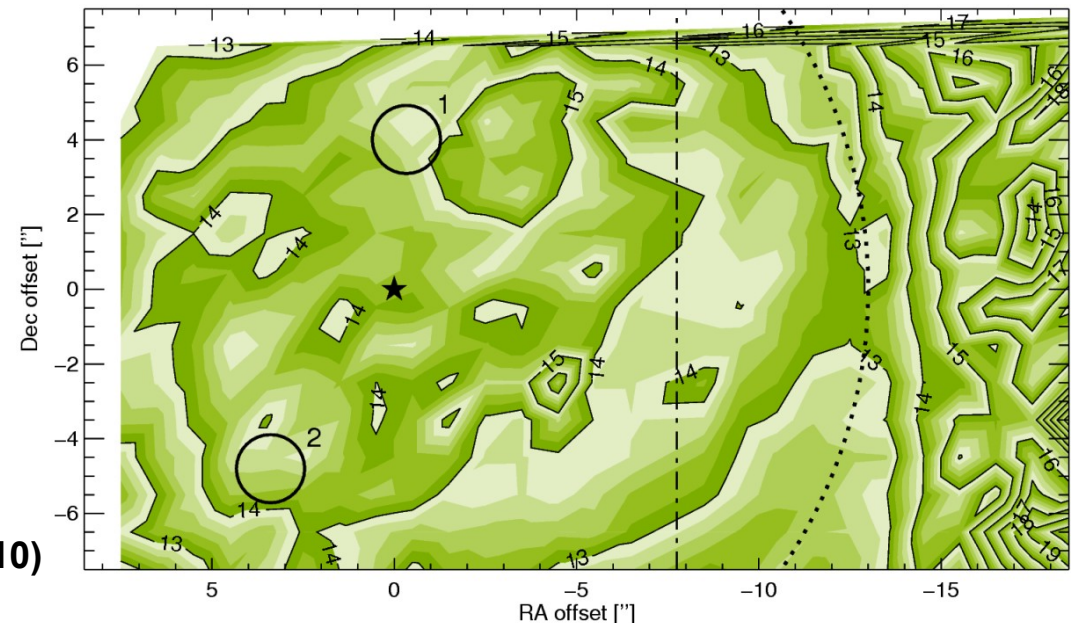
1. The parallactic angle

2. Reference wavelength

(Filippenko 1982, PASP, 94, 715)

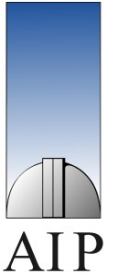
3. The spatial offset for every wavelength bin;  $f(R,P,T)$

4. Shifting the data of every wavelength bin



(Sandin et al. 2008, A&A, 486, 545; fig. 10)

# Instead of reducing IFU data by hand it seems more productive to use an automated tool



**FLAMES/ARGUS**

GIRBLDRS, GIRAFFE pipeline

**VIMOS**

VIMOS pipeline

**SAURON**

Sauron pipeline

**VIRUS**

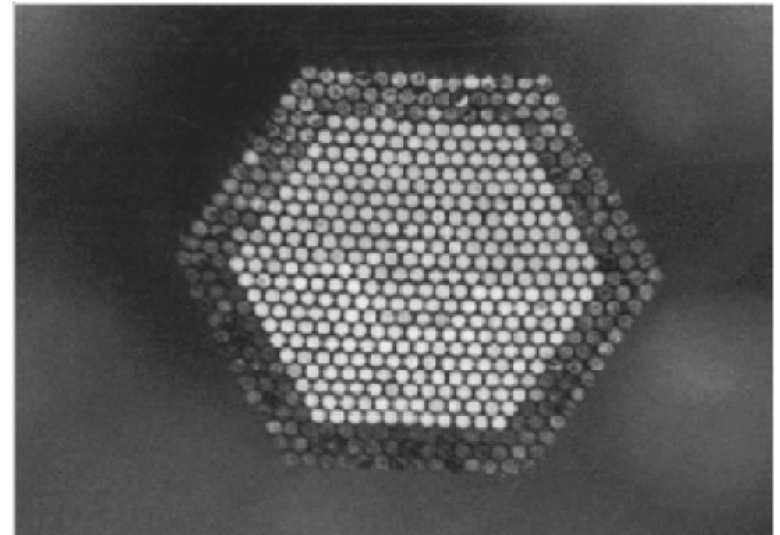
VIRUS\_online (P3d)

**PMAS/[LARR,PPAK]**

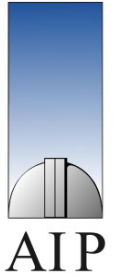
P3d, R3d

(this is no complete list)

**The PPAK IFU fiber bundle**  
(Kelz et al. 2006, PASP, 118, 129)



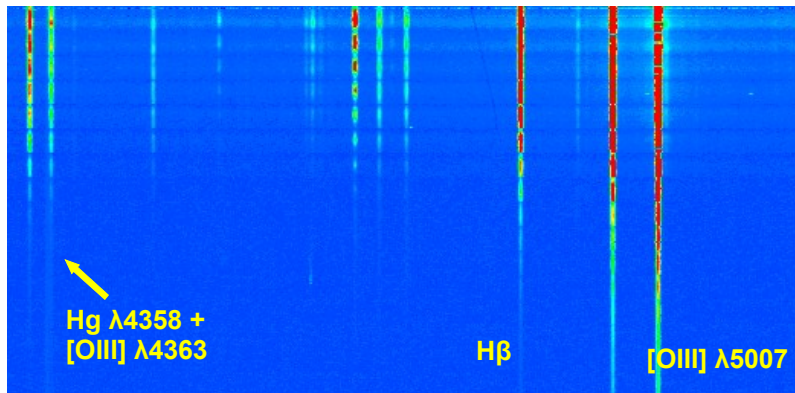
# Our proprietary data reduction software P3d has been successfully made to work with several IFUs



→ **R3d** (Sánchez 2006, AN, 327, 850)

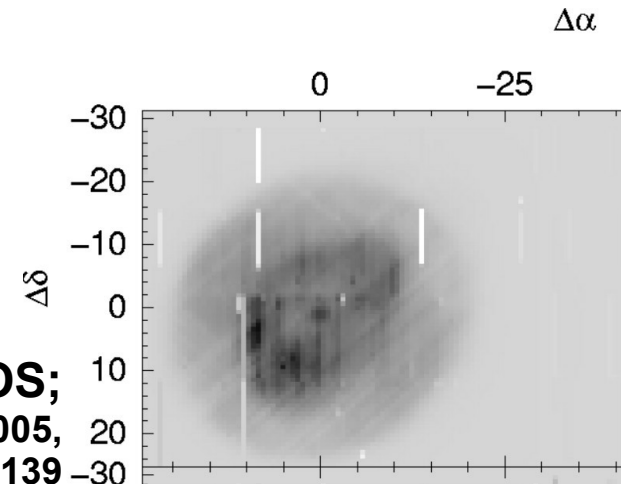
**P3d was originally developed by Thomas Becker (AIP) for PMAS**

Becker 2002, PhD Thesis; Roth et al. 2005, PASP, 117, 620

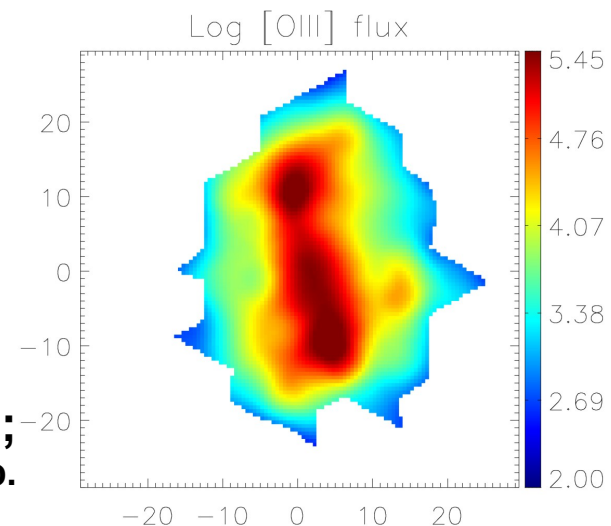


**Used with PMAS/LARR;**  
Sandin et al. 2008 (NGC 7662), A&A, 486, 545

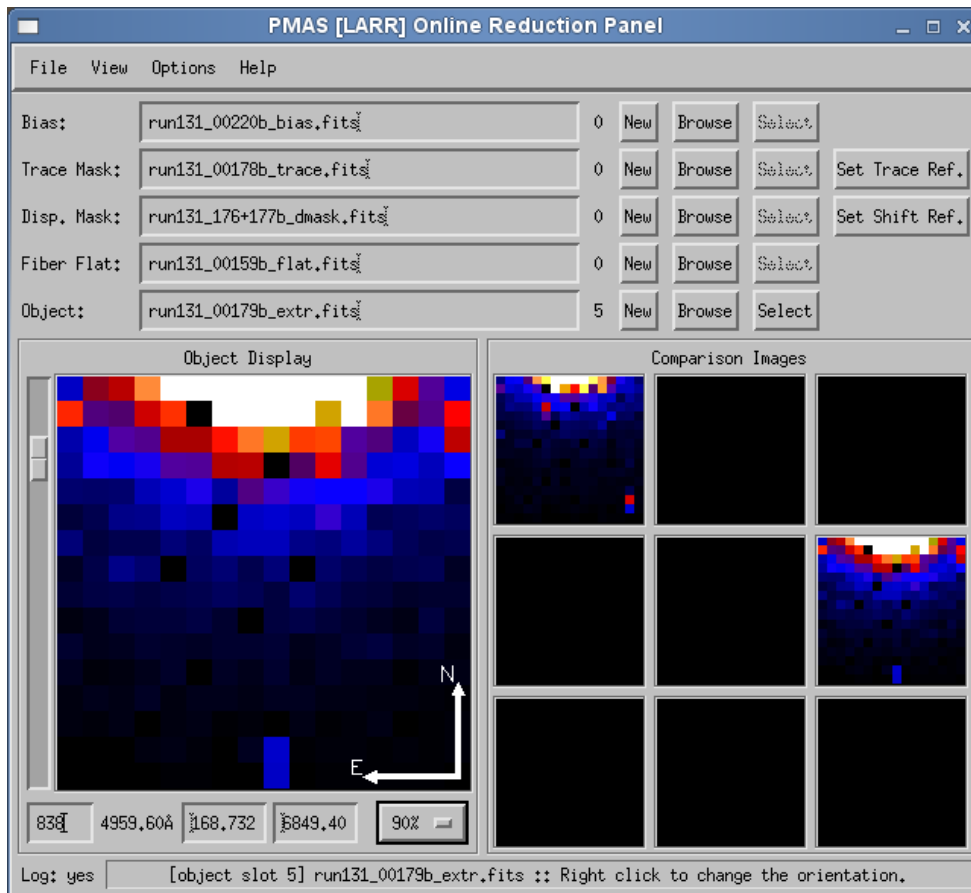
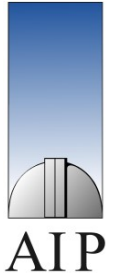
**Used with VIMOS;**  
Monreal-Ibero et al. 2005,  
ApJ, 628L, 139



**Used with VIRUS (BCD - IIZW33);**  
Cairós et al. 2009, A&A, in prep.



# We are preparing a public release of a general and improved version of our data reduction tool P3d



**Designed for PMAS – at first  
...VIRUS...VIMOS...FLAMES...(GMOS)...**

**IDL-based**

**Version  $\geq$  6.2; Linux, Solaris, Mac, Win**

**Graphical tool**

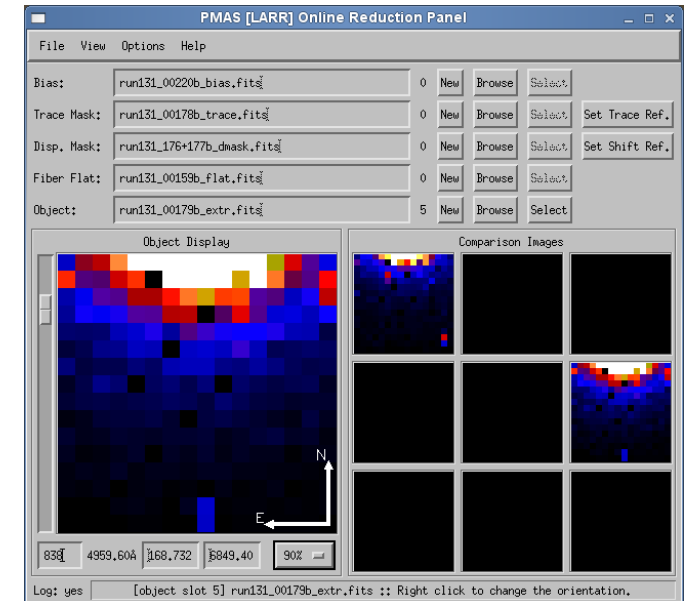
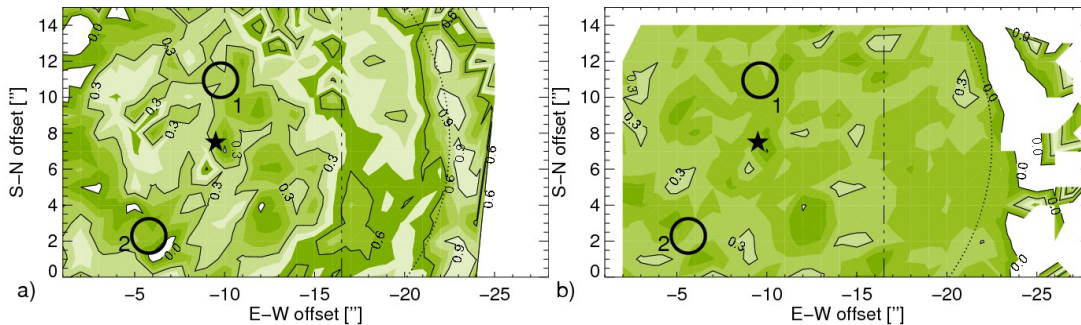
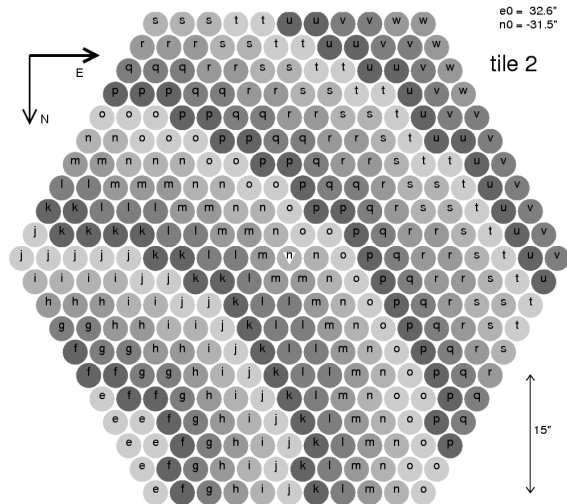
**A script-based version is planned**

**GPLv3**

**Improving suggestions welcome**

**(Sandin et al. 2009, PASP, in prep.)**

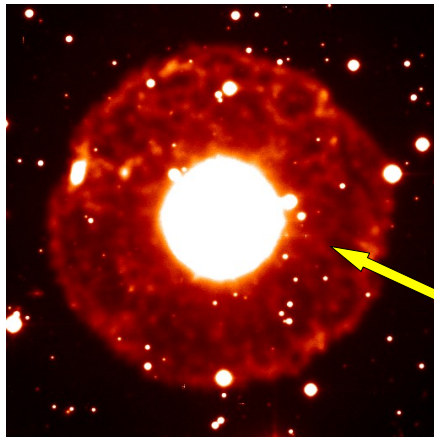
# I have presented general issues of concern for data reduction and data analysis using IFUs



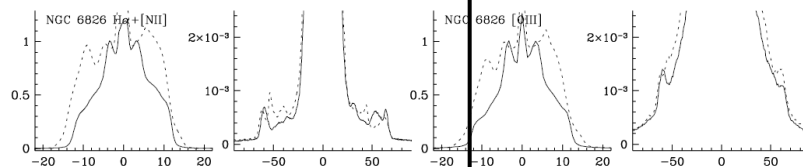
**Collaborators:** Petra Böhm, Luz Marina Cairós, Joris Gerssen, Andreas Kelz, Matthias Reis, Martin Roth, Peter Weilbacher (3D spectroscopy at AIP); Thomas Becker (prev. at AIP)



## Intensities of Planetary Nebula change by 1000× and more between the central parts and the halo



NGC 6826



Corradi et al. 2003, MNRAS, 340, 417; fig. 20

When measuring mass loss rates we are interested in observing weak and extended halos of planetary nebulae. Such halos form when the PN is a few thousand years old and the ionization front has moved outside the shell.

The intensity changes rapidly by a factor of a thousand and more between the PN center and the halo. The figures indicate how the intensity changes for NGC 6826.

Because intensities are so weak in the halo – they are even weaker for all the physics-sensitive emission lines – it is useful to make use of IFUs in order to allow for a co-adding of spectra and thereby increase the signal-to-noise of individual lines. Another useful property of an IFU is the straightforward possibility to correct for differential atmospheric refraction.

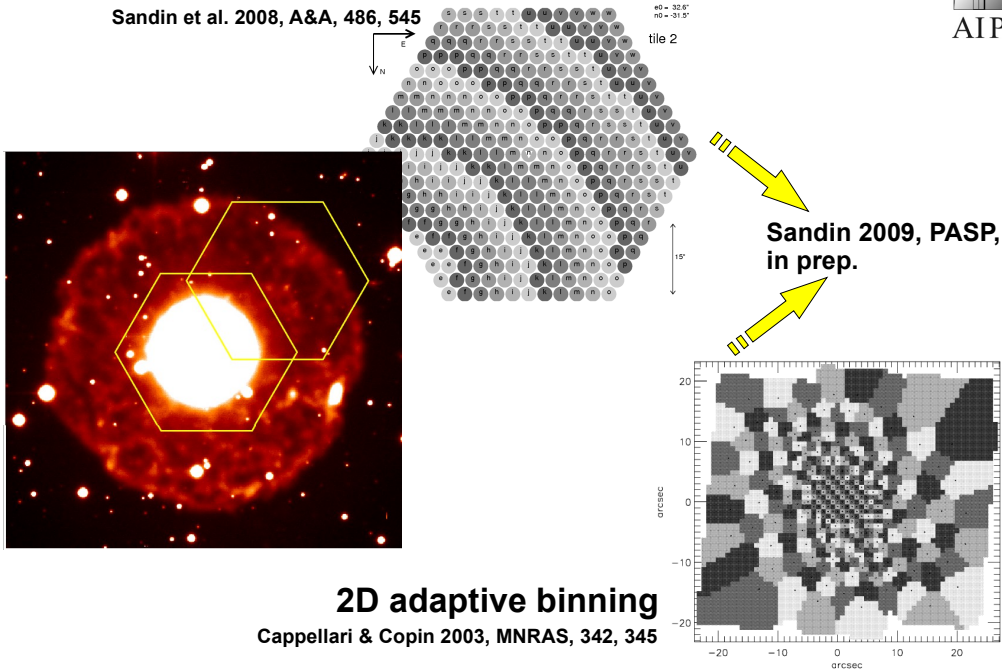
The study of halos of PNe with FLAMES/ARGUS is perhaps not the ideal combination since one requires a large number of different setups and very long exposure times in order to cover all emission lines of interest.

The approach I will describe is, however, general, and will work with any object and setup.

## IFU data can be used either binned, or unbinned – whatever is needed



Sandin et al. 2008, A&A, 486, 545



With extended objects the data which has been sampled with an IFU can either be used in 0D, 1D, or 2D. Two-dimensional structures are useful if intensities are roughly the same across the object surface.

An adaptive binning – using Voronoi tessellations – is an option where the resulting data is still two-dimensional.

If the physical structure is spherically symmetric – as we assume it is in our planetary nebula halos – we can use bins in the form of concentric arcs, which are centered on the central star.

I am preparing a public release of the line fitting routines we used with the observations of mass loss rates in Sandin et al. 2008. This package handles arbitrary methods of binning for any IFU – including FLAMES/ARGUS.

It also includes a routine to correct for differential atmospheric refraction.

## It may be necessary to correct the data for differential atmospheric refraction (DAR)

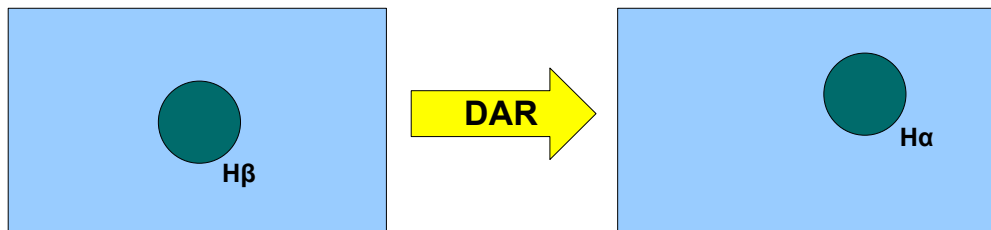


If the airmass is large; > about 1.1

If intensities of different wavelengths are combined

If spatial elements are small

If there is a significant intensity gradient in the object



4

If there is no automatic corrector for atmospheric refraction in the optical path it may in many cases be necessary to correct the data after the observations.

There is by default no refraction when the telescope is pointed at zenith, but for larger angles it becomes growingly significant. In practice it means that images of different wavelengths are shifted relative to each other on the surface of the IFU.

If intensities of two different wavelengths are compared, when for instance calculating a line ratio of an extended object, one will compare different regions – unless only a surface-integrated intensity is used. No issue when only one line is measured.

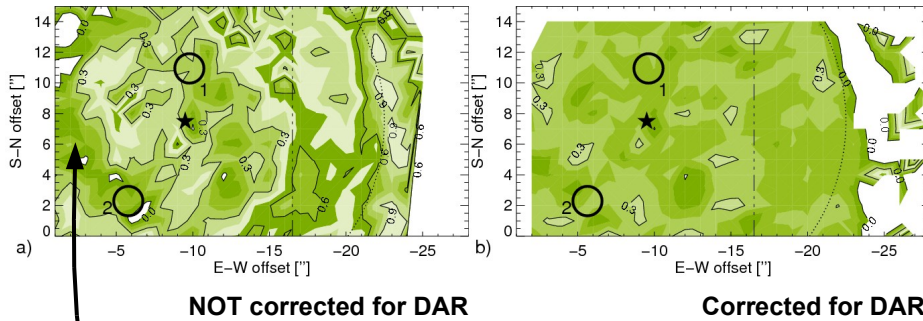
With small spatial elements of the IFU light of different wavelength belonging to the same region will end up on separate spatial elements. With large elements, like for PPAK or VIRUS, this effect is mostly negligible.

If there are large intensity gradients in the object effects become more obvious.

## It may be necessary to correct the data for differential atmospheric refraction (DAR)



(Sandin et al. 2007, in press; Asymmetrical PNe IV, NGC 7662)



More structure is visible in c without a correction!

5

For our PN project we have in every case calculated extinction coefficients using the ratio of  $H\gamma$  to  $H\beta$  – separated by  $520\text{\AA}$ . We also had the two lines on the CCD simultaneously.

When we at first calculated a two-dimensional extinction coefficient across the surface of NGC 7662 we found that it was structured across the rim. This is also where the intensity gradient is the largest.

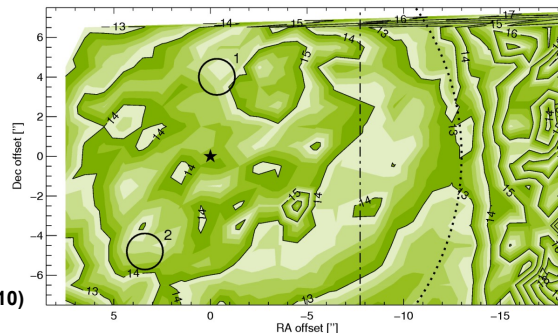
Later we recalculated the same extinction coefficient – after first having corrected for DAR – and the structure had then more or less disappeared. It then seemed less of a problem to use a constant value –  $c=0.23$ .

## What steps do we take in order to make the DAR-correction?



1. The parallactic angle
2. Reference wavelength
3. The spatial offset for every wavelength bin;  $f(R,P,T)$
4. Shifting the data of every wavelength bin

(Filippenko 1982, PASP, 94, 715)



(Sandin et al. 2008, A&A, 486, 545; fig. 10)

In order to correct for DAR we take the following steps:

1. We calculate the parallactic angle, which is the orientation of the IFU with respect to the downwards direction.
2. A reference wavelength is selected against which offsets are calculated.
3. The spatial offset for every wavelength bin is calculated using formulae such as those given by Filippenko (1982) – using physical conditions at the time of the observations. Relative humidity, pressure, and temperature are required.

If one uses observations with different gratings or setups, then one must ensure that one knows what the offset is. For instance by guiding with the same filter. FLAMES already makes a correction for DAR and places the central wavelength of the grating on the same spot → effects are smaller, but can still be of importance.

4. In a final step every wavelength bin is shifted – this is a step which requires interpolation; bi-linear seems to be the best alternative.

The figure shows the temperature of the central parts of NGC 7662. Note that the upper and left regions are missing – they depend on values outside the observed region.

## Instead of reducing IFU data by hand it seems more productive to use an automated tool



**FLAMES/ARGUS**

GIRBLDRS, GIRAFFE pipeline

**VIMOS**

VIMOS pipeline

**SAURON**

Sauron pipeline

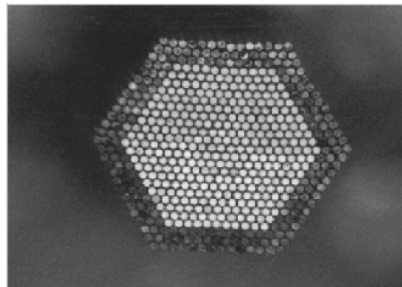
**VIRUS**

VIRUS\_online (P3d)

**PMAS/[LARR,PPAK]**

P3d, R3d

(this is no complete list)



The PPAK IFU fiber bundle  
(Kelz et al. 2006, PASP, 118, 129)

If the data reduction of IFU observations is to be any efficient it is necessary to use an automatized tool – such as a pipeline.

Here is a list of some of the existing IFUs, and corresponding – and existing – pipelines.

The idea with a pipeline is that it is more or less a black box, that creates spectra for the user so that he or she can focus on the science.

It might happen that the user wants to have a better control of what is going on. What if crosstalk is an issue? How can that be checked? How does error propagation work? Should one then use MIDAS or IRAF instead?

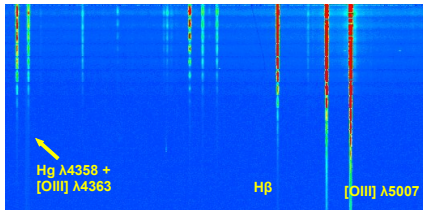
**Our proprietary data reduction software P3d has been successfully made to work with several IFUs**



→ **R3d** (Sánchez 2006, AN, 327, 850)

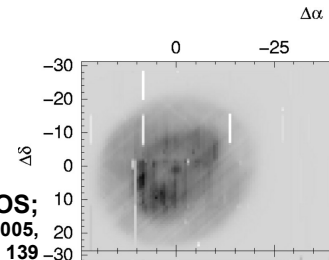
**P3d was originally developed by Thomas Becker (AIP) for PMAS**

Becker 2002, PhD Thesis; Roth et al. 2005, PASP, 117, 620

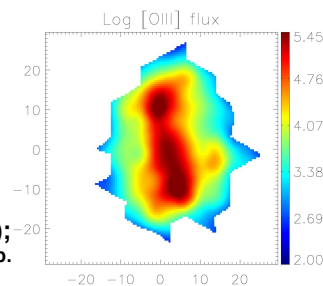


**Used with PMAS/LARR;**  
Sandin et al. 2008 (NGC 7662), A&A, 486, 545

**Used with VIMOS;**  
Monreal-Ibero et al. 2005, ApJ, 628L, 139



**Used with VIRUS (BCD - IIZW33);**  
Cairós et al. 2009, A&A, in prep.



8

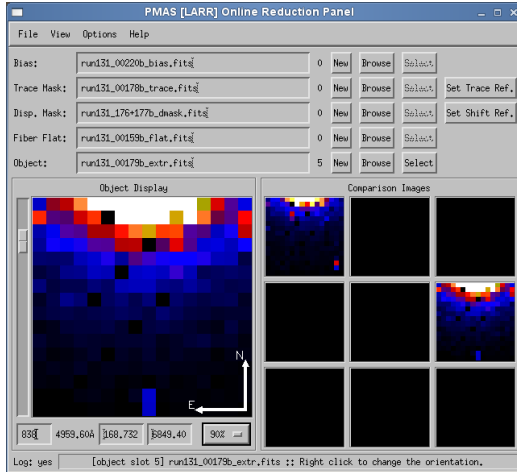
P3d was originally developed by Thomas Becker at AIP for his thesis. P3d is an IDL-based graphical data reduction tool, that is designed to work with data of IFUs.

This software was written in two versions, one graphical version for quick analysis at the telescope, and one script-based version for scientific reductions in the office.

P3d was later successfully extended to work also with data of VIMOS and VIRUS.

P3d was never intended to be used outside AIP – the software works like a black box and lacks comments in most places.

## We are preparing a public release of a general and improved version of our data reduction tool P3d



(Sandin et al. 2009, PASP, in prep.)

**Designed for PMAS – at first  
...VIRUS...VIMOS...FLAMES...(GMOS)...**

**IDL-based**  
Version  $\geq 6.2$ ; Linux, Solaris, Mac, Win

**Graphical tool**  
A script-based version is planned

**GPLv3**  
Improving suggestions welcome

9

We have refurbished our proprietary code P3d to make a public release of this stand-alone tool. In comparison to our old code this program is fully commented and pretty much self-explanatory. Documentation and/or tutorials will be prepared.

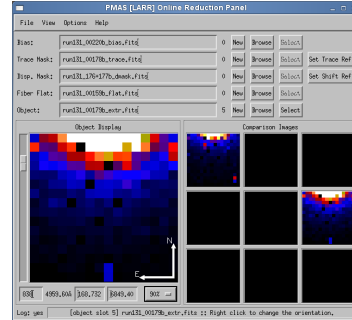
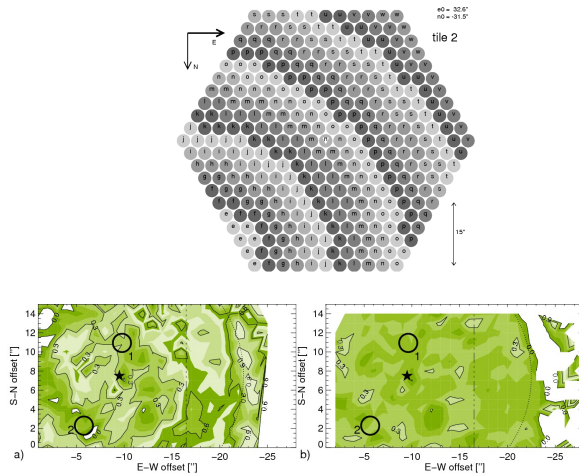
At first the tool is prepared for PMAS (LARR & PPAK), the plan is to also make it work with VIRUS and VIMOS. The code is so general that further improvements for FLAMES and GMOS (for instance) will be straightforward.

The program is based on IDL and should work with all available platforms. It has been re-designed to work with the IDL virtual machine – this means that no license is required to use the tool; modifications still require a license.

Currently provides a graphical user-interface – allowing an immediate inspection of the results. A scripting version of individual routines is planned.

The tool will be released under GPLv3, which means that the tool can be used and modified as required by the community. Suggestions for improvement are always welcome, and will be implemented as time permits. Users who would like to contribute with support for another instrument will be considered to join the team.

# I have presented general issues of concern for data reduction and data analysis using IFUs



**Collaborators:** Petra Böhm, Luz Marina Cairós, Joris Gerssen, Andreas Kelz, Matthias Reis, Martin Roth, Peter Weilbacher (3D spectroscopy at AIP); Thomas Becker (prev. at AIP)

10

I have here presented a few issues of general concern when it comes to the data reduction and data analysis of data which has been obtained with IFUs.

These aspects are:

- How we bin elements on IFUs.
- How we correct for differential atmospheric refraction
- A brief presentation of our data reduction tool P3d.