# Planetary Nebulae expansion velocities

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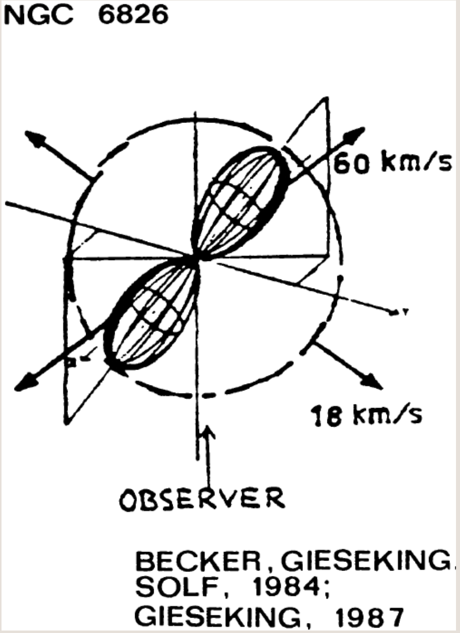
**APN 6 conference**
**Riviera Maya, Mexico**

**November 4 - 8, 2013**



# something from history

Zanstra (1932)
"The expansion hypothesis for planetary nebulae",

*Summary.*—The observed fact that the emission lines of an appreciable number of planetaries are doubled or broadened at the centre shows that these nebulæ at any rate cannot be in equilibrium but must be expanding, since the radial velocity with respect to the star is larger than the parabolic velocity under gravity. An expansion of this kind may also be expected if planetary nebulæ originate from novæ, for which conception, as is well known, there is considerable evidence.

Weinberger (1989)
"A catalogue of expansion velocities of galactic planetary nebulae"





TABLE I. — *Expansion velocities of galactic planetary nebulae.*

| P & K | Name | $2V_{exp}$ (km s-1) 1=[OIII];2=HI; 3=[NII] | Ref. | Notes | Adopt. $2V_{exp}$ 1 | 2 | 3 | D kpc | r pc | Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| 0+12°1 | II4634 | 1=29;[NeIII]=29<br>2=27 | Wi50<br>CSO88 | | 29 | 27 | | 3.5 | 0.073 | C |
| 1-6°2 | SwSt1 | diff.ions=26<br>2=18;3=19 | Ac76<br>BGBD88 | | 26: | 18 | 19 | 1.2 | 0.002 | |
| 2+5°1 | NGC6369 | 1=83 | MWF88 | | 83 | | | 0.8 | 0.059 | |
| 2-2°2 | M3-20 | 1=47;2=44 | Sh87 | | 47 | 44 | | <3.1 | <0.037 | |
| 2-4°2 | M1-42 | 1=50;[OII]<12;<br>HeII=25 | MWF88<br>MWF88 | | 50 | | <12 | 6.1 | 0.118 | |
| 2-9°1 | Cn1-5 | diff.ions=36 | Ac76 | | 36: | | | | | |
| 2-13°1 | II4776 | 2=20;3=35 | BGBD88 | | | 20 | 35 | 4.7 | 0.079 | |
| 2-52°1 | II5148-50 | 1=107 | MWF88 | | 107 | | | | | |
| 3+2°1 | Hb4 | 1=46 | RRA82 | | 46 | | | 3.1 | 0.046 | C |
| 3-2°3 | II4673 | 1=50;HeII=29 | MWF88 | | 50 | | | 3.5 | 0.127 | |
| 3-4°5 | NGC6565 | 1=29;[OII]=42;<br>HeII=17 | MWF88<br>MWF88 | | 29 | | 42 | **1.0** | 0.025 | B |
| 4-11°1 | M3-29 | diff.ions=14 | Ac76 | | 14: | | | 4.2 | 0.083 | |
| 7+1°1 | Hb6 | 1=40 | RRA82 | | 40 | | | 2.7 | 0.043 | |
| 8+3°1 | NGC6445 | 1=76 | Sm71,73 | | 76 | | | 1.4 | 0.102 | B |
| 9+14°1 | NGC6309 | 1=65<br>1=68;2=50 | SBH83b<br>Sa84b | <br>sk.m. | 68 | 50 | | 3.0 | 0.145 | C |
| 9-5°1 | NGC6629 | diff.ions≤12<br>2=6<br>2=15<br>1<12;[OII]=13 | Ac76<br>MKHHG88<br>BGBD88<br>MWF88 | | <12 | 11 | 13 | **2.4** | 0.087 | C |
| 10+18°2 | M2-9 | <br><br>2=60<br><br><br><br><br><br>2=64 | As72<br><br>Wa81<br><br>CS83<br><br>Ca83<br><br>Ca83<br>BGBD88 | compl. motion<br><br>compl. motion<br><br>compl. motion<br><br>compl. motion<br><br>sk.m. | | 62 | | 1.1 | 0.014 | B |
| 10+0°1 | NGC6537 | diff.ions=20<br><br><br><br>1=36;HeII=21 | Ac76<br>BeS83<br><br>BeS83<br>MWF88 | <br>h.vel. comp.<br>sk.m. | 36 | | | **2.4** | 0.058 | B |
| 11+5°1 | NGC6439 | 1=48 | RRA82 | | 48 | | | 5.3 | 0.072 | C |
| 11-0°2 | NGC6567 | 1=37;2=36;3=72;<br>[NeIII]=30 | Wi50<br>Wi50 | | 37 | 36 | 72 | **1.7** | 0.036 | C |
| 11-9°1 | H2-48 | 2=10;3=5 | OS85 | | | 10 | 5 | 5.0 | 0.024 | B |
| 13+32°1 | Sn1 | 1<20 | SBH83b | | <20 | | | 8.0 | 0.047 | |
| 13+4°1 | M1-33 | 1=25 | Sa84a | | 25 | | | 3.7 | 0.044 | |
| 13-2°1 | M1-89 | 2=24 | SW87 | | | 24 | | | | B |
| 15-3°1 | A44 | 1=12 | MWF88 | | 12 | | 12 | 2.5 | 0.345 | |
| 15-4°1 | M1-53 | 1=26 | Sa84a | | 26 | | | 5.1 | 0.075 | |
| 16-1°1 | M1-46 | 1=14 | MWF88 | | 14 | | | 3.4 | 0.123 | |
| 17-10°1 | A51 | 1=84 | MWF88 | | 84 | | | 2.6 | 0.427 | C |
| 17-21°1 | A65 | 1=22 | MWF88 | | 22 | | | 2.1 | 0.192 | |
| 18+20°1 | Na1 | 1=60;2=52 | Sh87 | | 60 | 52 | | 4.3 | 0.052 | |
| 19+3°1 | M3-25 | 1=25<br>1=23;2=33;3=44 | SBH84b<br>Sh87 | | 24 | 33 | 44 | 3.2 | 0.030 | |
| 21-5°1 | M1-63 | 1=15 | SBH84b | | 15 | | | 4.5 | 0.046 | |
| 23-2°1 | M1-59 | 1=26 | SBH84b | | 26 | | | 3.5 | 0.038 | B |
| 25+40°1 | II4593 | diff.ions=25<br>2=24<br><br>2=16 | Vi69<br>We83<br>AB88<br>DBG88 | <br><br>2 sep. sheets<br> | 25: | 20 | | 3.4 | 0.106 | C |
| 25-17°1 | NGC6818 | 1=56;2=56;[OII]<br>=60;[NeIII]=58;<br>HeII=42;[NeV]=33<br><br>diff.ions=38<br>diff.ions=56<br>1=50<br>1=54;2=52;3=64 | Wi50<br>Wi50<br>Wi50<br>We68<br>Vi69<br>Ac76<br>RRA82<br>Sa84b | <br><br><br>sk.m.<br><br><br><br>sk.m. | 54 | 54 | 61 | 2.1 | 0.095 | B |



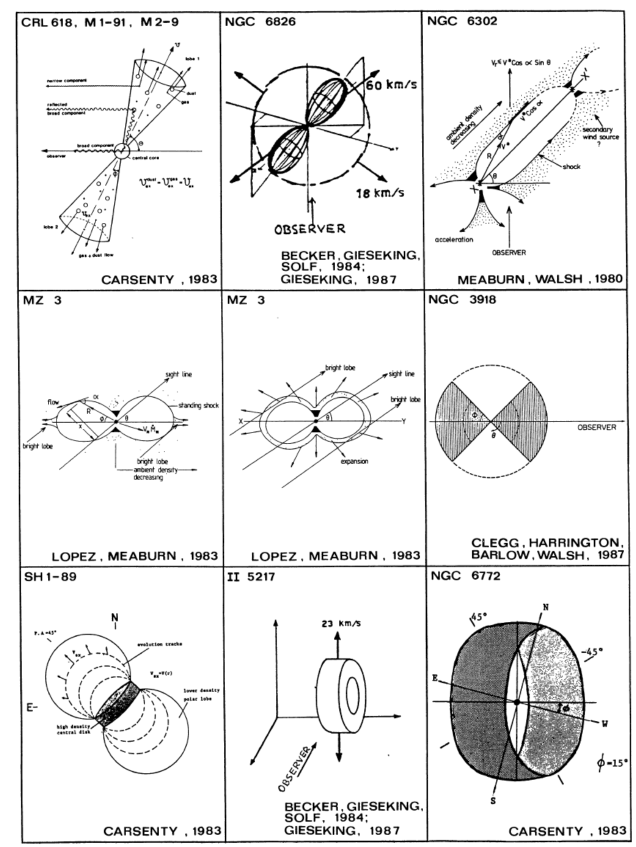



FIGURE 4. — Sketches of spatiokinematical models taken from the literature.

**2.3 SPATIOKINEMATICAL MODELS.** — Apart from the disillusion with figure 2, spatiokinematical models are of utmost importance to get deep insights in the often very complex expansion characteristics of planetaries. By these models, main conclusions from this short historical introduction:

- since long time it was known that the planetary nebulae are expanding

- many older publications contained long tables
    with numerical values of expansion velocities
    obtained with different methods

- before the end of last century it was already certain that
    the expansion of a planetary nebula is a quite complex phenomenon
        only roughly represented by a single number
            more elaborated analysis is required

in the following brief review we will discuss two contemporary methods
that provide velocity field **within** a planetary nebula:

- hydrodynamical modelling

- kinematical reconstruction

# spherically symmetric hydrodynamical models from Potsdam

first paper in the series comes from 1991

Marten & Schönberner (1991) published hydrodynamical calculations of a planetary nebula that surrounds an evolving star

most recent results with summary of previous work

are published by Jacob et al. (2013)

these models are 1D radiation-hydrodynamics simulations

of the initial envelope density distribution (AGB material)

which is influenced by

- the ionizing radiation from the evolving star
- the fast wind blowing from the evolving star

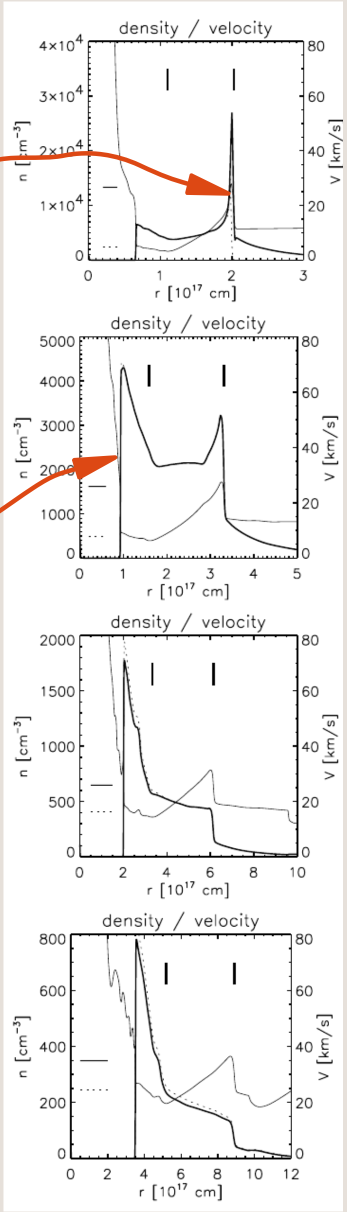
# spherically symmetric hydrodynamical models from Potsdam

Schönberner et al. (2005)
defined a canonical model of PN evolution

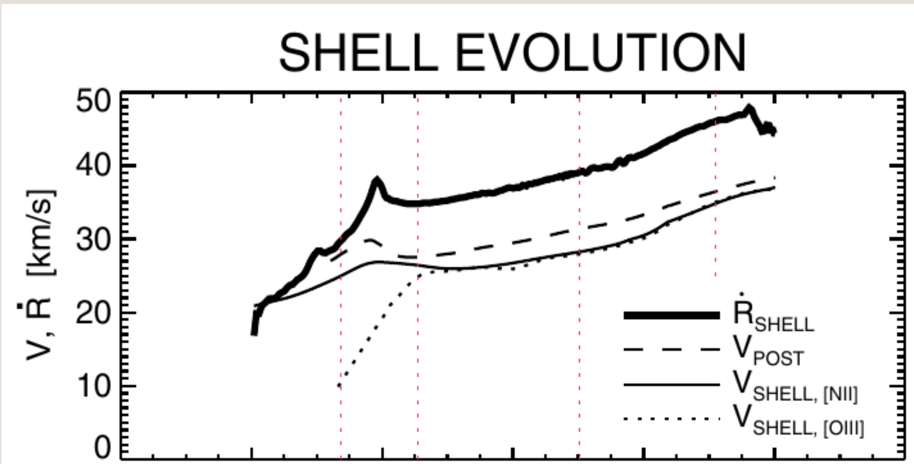
the **shell** is driven by the thermal pressure

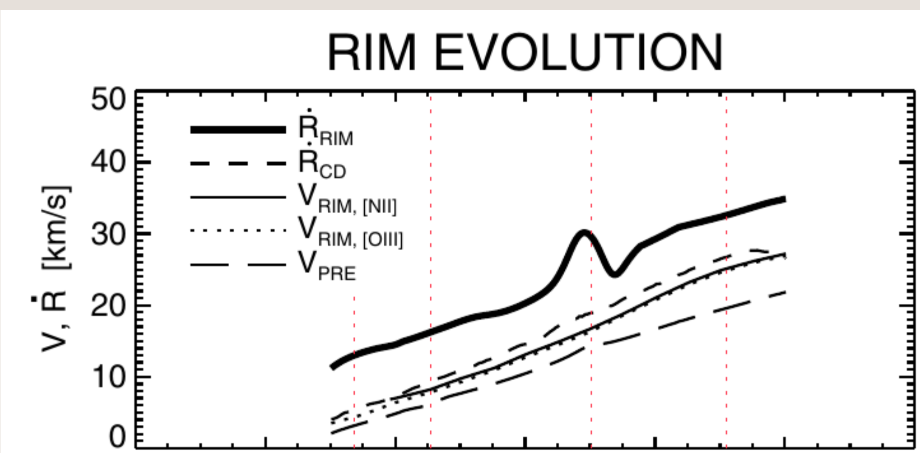
the **rim** is driven by the stellar wind

both agents modify the inner structure of the nebula
i.e. density and velocity fields



# spherically symmetric hydrodynamical models from Potsdam




the linear x-axis shows time from 0 to 12 000 yrs

Schönberner et al. (2005)

also have shown that
the shell and the rim expansion
is **accelerated**

what complicates determination
of kinematical ages

# spherically symmetric hydrodynamical models from Potsdam

Jacob et al. (2013)
considered four different velocities of an expanding nebular shell:

1. the propagation of the (outer) shock
   whose distance from the star defines the actual PN radius, Rout,
   and dRout/dt is the **true expansion** velocity of a PN

2. the **post-shock** velocity

3. a representative velocity derived from the **peak separation**
   of Doppler split emission lines,
   provided the spatial resolution is sufficiently high

4. a representative velocity from the **half width** of emission lines
   of spatially unresolved objects

# spherically symmetric hydrodynamical models from Potsdam

plots like that from Jacob et al. (2013) show the **true nebular expansion**
i.e. the propagation of the (outer) shock

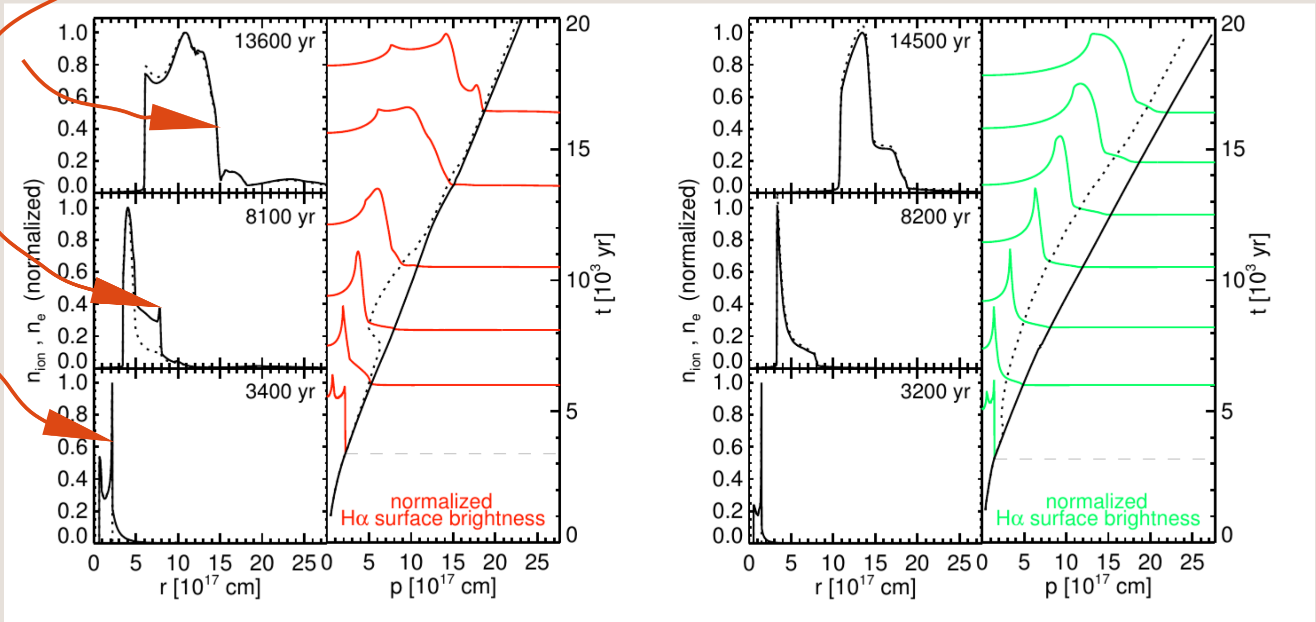



**Fig. 3.** Snapshots of model density structures and H$\alpha$ intensity distributions for 3 hydrodynamical

this velocity
is easy to be seen
in models

but is difficult
to be determined
observationally

# spherically symmetric hydrodynamical models from Potsdam

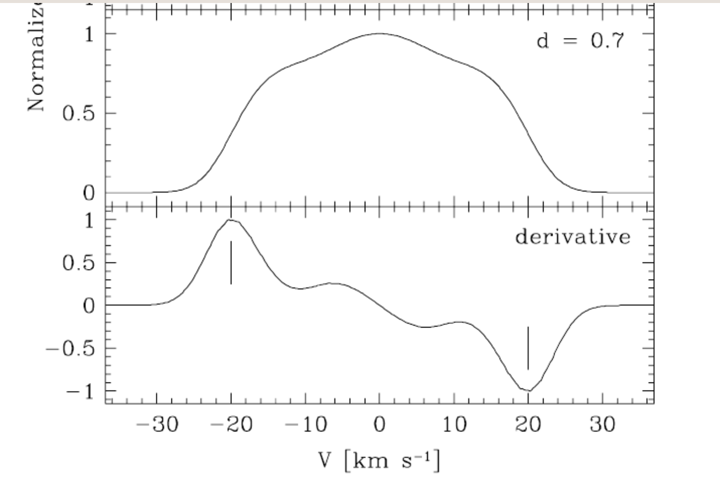
Corradi et al. (2007)

proposed to use **post-shock velocity** $V_{post}$ as a measure of true nebular expansion

$V_{post}$ can be obtained from the derivative of the emission line profile

$V_{true}$ needs **correction** by 1.2 - 1.3

this result was confirmed recently by Jacob et al. (2013)




. Line profiles and their derivatives for the central profile

the method requires very good spectroscopy

it is described in details in the cited paper from which the figure shown above is taken some comments concerning the hydrodynamical Potsdam models:

- a very elaborated physics and fairly sophisticated methods are applied

- the assumed spherical symmetry
  - simplifies computations
  - allows to pinpoint the most important processes
  - but is unable to reproduce complicated observed structures

- out of the four defined velocities the most interesting one is
  - the true expansion velocity
  - however it cannot be determined spectroscopically

- the proposed method to derive the true nebular expansion velocity
  - requires high spatial and spectral resolution
  - did not became popular

below we will discuss another useful velocity definition
that characterizes the global expansion properties of planetary nebulae

# kinematical reconstruction from Toruń

kinematical reconstruction is a way of analysis of nebular structure
that avoids the time consuming hydrodynamical modelling
and provides the characteristics of a particular observed object

for a guessed nebular structure a fast photoionization code is run
resulting in emissivity radial distributions for selected spectral lines

then with an assumed velocity field the emission profiles are calculated
and compared with the observed ones

the structure is improved and the procedure is repeated

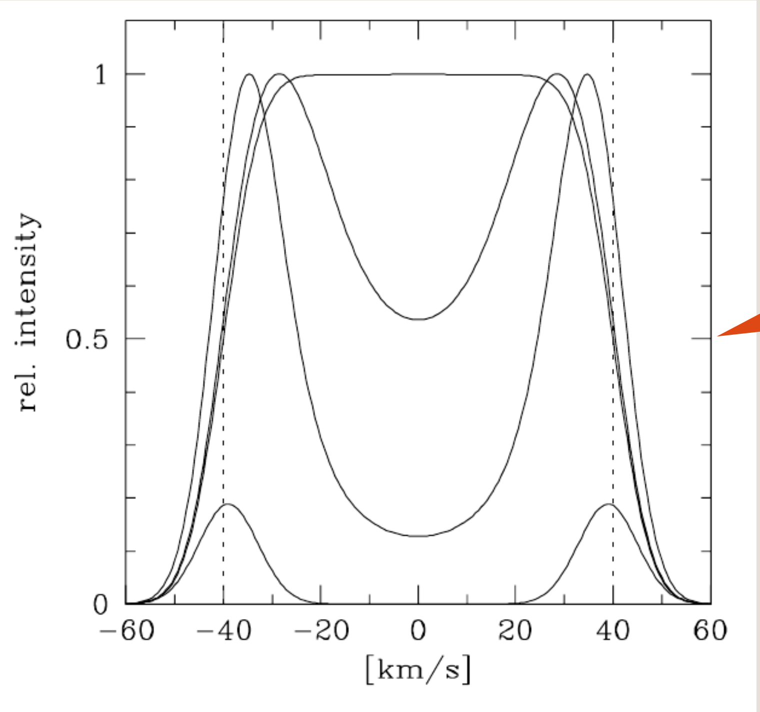
Torun models
assume spherical symmetry
the search for best-fit parameters is aided by a genetic algorithm

details are described in Gesicki, Acker & Zijlstra (2003) and Gesicki et al. (2006)

# kinematical reconstruction from Toruń

Gesicki & Zijlstra (2000) presented a simple example

plotted below are the modelled [O III] lines for a simplified spherical nebula
with constant velocity and emissivity.
this artificial nebula is observed with a centred circular aperture:
the profiles are given for aperture size relative to the PN diameter of: 1.0, 0.8, 0.5, 0.2
the vertical dashed line indicates the true expansion velocity of 40 km/s




this example shows that
measured at half maximum **$V_{HWHM}$**
**is not so bad approximation**
to the true expansion velocity

| aperture | $V_{split}/V_{exp}$ | $V_{HWHM}/V_{exp}$ | $V_{HWTP}/V_{exp}$ |
|---|---|---|---|
| 1 | – | 1.00 | 1.13 |
| 0.8 | 0.73 | 1.00 | 1.10 |
| 0.5 | 0.80 | 1.08 | 1.10 |
| 0.2 | 0.89 | 1.15 | 1.16 |

# kinematical reconstruction from Toruń

real nebulae usually do not expand with constant velocity

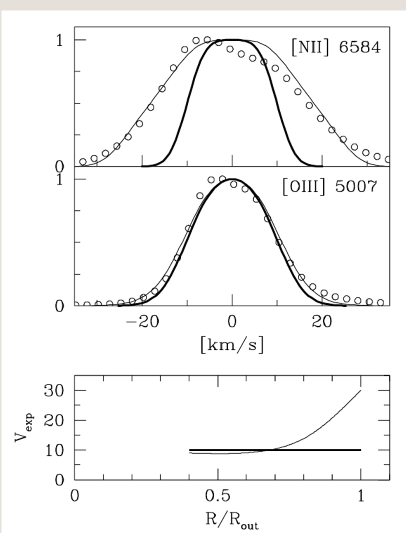
to be more precise:

the constant velocity models did not reproduce well the observed lines

assuming **complex velocity fields improves the fits** significantly

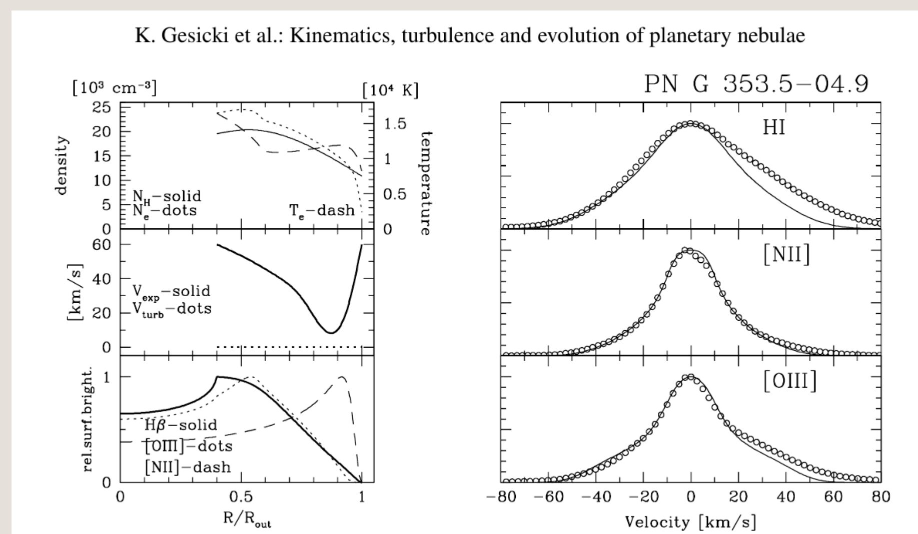
as is shown in the selected examples

accelerated outer region




Gesicki & Zijlstra (2000)

U-shaped velocity



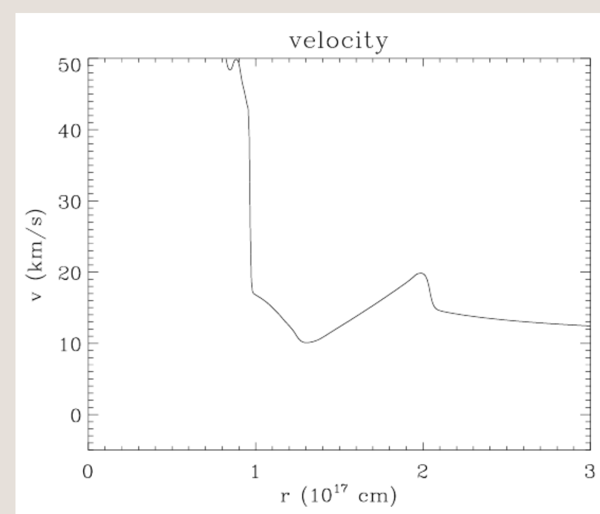

Gesicki, Acker & Zijlstra (2003)

# kinematical reconstruction from Toruń

in Gesicki, Acker & Zijlstra (2003)
we found that **"U"-shaped velocity profile** is quite common,

with the highest velocities near the outer edge
(as predicted by hydrodynamical models)

and additionally near the inner edge
(which was less expected at that time)




this kind of velocity field was confirmed later
by hydrodynamical computations of Potsdam group,
first published in Perinotto et al. (2004)

# kinematical reconstruction from Toruń

already in Gesicki et al. (1998)
we introduced the **mass averaged velocity $V_{av}$**

We define $V_{av}$ as the radially averaged value of the expansion velocity over the shell, weighed by the density distribution:

$$V_{av} = \frac{\int_{R_i}^{R_o} 4\pi r^2 \rho(r) V(r) dr}{\int_{R_i}^{R_o} 4\pi r^2 \rho(r) dr}$$

It mainly represents the area of higher density, but takes into account the increase of the expansion velocity in the lower-density outer regions, which we require to explain the shape of the line wings. It does not include turbulent motions which can broaden the spectral lines. The value of $V_{av}$ is larger than the expansion velocity estimated from the separation of the double line peak, but is comparable to the velocity estimated from the FWHM

it was defined
as a single number,

expected to
represent a general
expansion properties,

intended to be used
to estimate
the kinematical age

fifteen years later,
in Gesicki, Acker & Zijlstra (2003)
we concluded:

We found that the mass-averaged expansion velocity is a reasonably robust parameter. It is well determined even from a single emission line, if this line doesn't exhibit unusual features. The recently derived "U"-shape velocity fields result in much improved fits to the line wings, but the $V_{av}$ are almost the same as obtained with simple linearly increasing velocity. We conclude that $V_{av}$ is the proper parameter to describe the main nebular flow.

# kinematical reconstruction from Toruń

recently we computed $V_{av}$ for a number of models of D.Schönberner
for a nebula evolving around star of mass 0.565 $M_{sun}$ and 0.605 $M_{sun}$

for the **true** and the **mass-averaged** velocities
we found a consistent and well-defined **ratio of 1.4 +/- 0.1**

this agrees well with the correction factor to the expansion parallaxes derived by
Schönberner et al. (2005) as 1.3 - 1.4

this is also very close to correction factor of 1.2 - 1.3
derived by Corradi et al. (2007)

this allows to define the **kinematical age**
of a planetary nebula in terms of $V_{av}$

$$t_{kin} = \frac{R_{out}}{1.4 \times V_{av}}$$

# what else?

Steffen et al. (2009) presented

3D hydrodynamical velocity fields
however without photoionization effects

they obtained interesting results that

except of the obvious radial dependence of velocity
there should exist also a non-negligible poloidal velocity component
which indicates deviation from pure radial direction

such deviations can produce deformations in later 3D reconstructions
that assumed homologous expansion

in consequence questions come up:

how such 3D effects may affect

- spherical kinematic reconstructions ?
- the mass averaged velocity ?

# conclusions

the mass-averaged expansion velocity $\mathbf{V_{av}}$
is not bad approximation to the global expansion properties of PNe

it can be used for deriving kinematical ages
it has been verified

using different observed data sets
using spherical hydrodynamical models

it would be worth to check its validity on 3D models

we already have the appropriate tools therefore it is time now
to verify the methods of kinematical reconstruction

with full 3D hydrodynamical models
searching for possible artefacts that may disturb the interpretation

more observations focused on velocity fields

would also be very welcomed

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# acknowledgements


this publication was supported by the Polish National Science Centre (NCN) through the grant 2011/03/B/ST9/02552