Narrow-Line Regions of Seyfert Galaxies

Optical Integral-Field Spectroscopy

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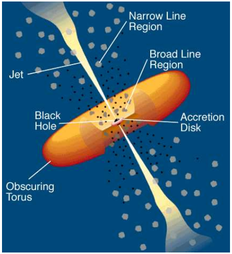
Ondřejov 15.1.2009

Narrow-Line Regions (NLRs)

Unified Model of AGN



Urry & Padovani (1995)

Seyfert galaxies:

- Low luminosity AGN (L$\sim 10^{40-43}$ erg s^{-1})
- Hosts: S0–Sbc

NLRs: Ionized gas

- T $\sim 10^4$ K
- $n_e \sim 10^2 - 10^3$ cm^{-3}
- Extent: $10^2 - 10^3$ pc
- Spatially resolved
  - The only AGN part
- Ionization source: AGN radiation
- Velocities: $10^2 - 10^3$ km s^{-1}
- Forbidden lines

Narrow-Line Regions (NLRs)

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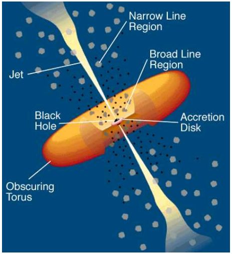

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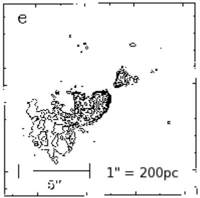
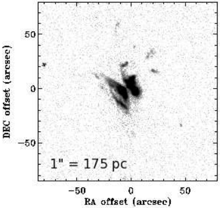
Optical imaging (HST)



NGC 5728 Wilson et al. (1993)

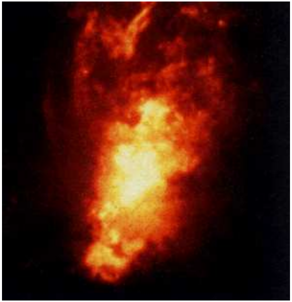


NGC 2992, Allen et al. (1999)

Complex Structure of NLRs

Filamentary structure

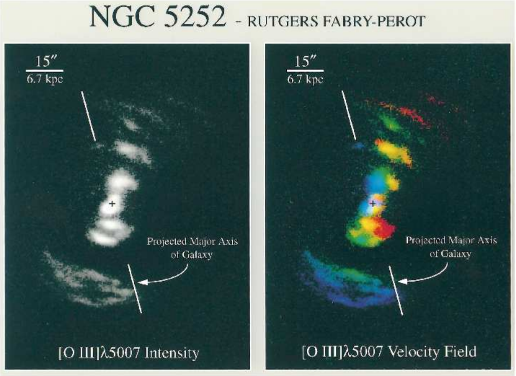
NGC 1068



Central 200 pc in [O III]

Macchetto et al. (1994), HST

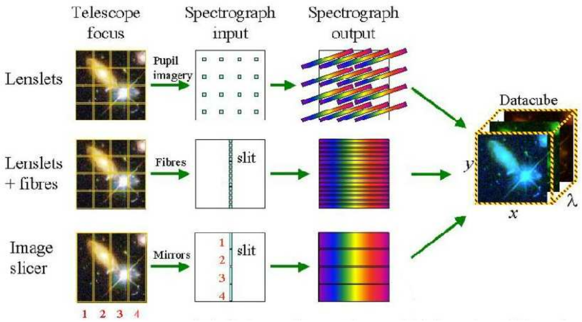
Kinematics



Morse et al. (1996)

Integral-Field Spectroscopy (IFS)

- Spatially resolved spectroscopy
- <u>Simultaneous</u> acquisition of $10^2 - 10^4$ spectra
- Datacube $(x, y, \lambda) \rightarrow$ "3D" spectroscopy



Principles of different integral-field units (IFUs). Credit: University of Durham.

Thesis Data

- 16 nearby Seyfert galaxies, redshifts $z \in (0.002, 0.05)$
  - 11 Sey 2s
  - 3 Sey 1.5s
  - 2 Sey 1.2s
- Optical IFU: OASIS at 3.6m CFHT (Mauna Kea, Hawaii)
  - observations in 2 spectral domains ($\sim$ 1000 Å each)
  - OASIS constructed in CRAL, Lyon
  - $\sim$ 1000 spectra simultaneously
  - array of hexagonal lenslets (close packing)
  - spatial sampling $0.27'' - 0.41''$
  - spectral sampling 1.92 $-$ 1.95 Å
  - field of view (FOV) $10'' \times 8''$ or $15'' \times 12''$
- Observations in 2000 $-$ 2002, P. Ferruit et al.

Thesis Objectives

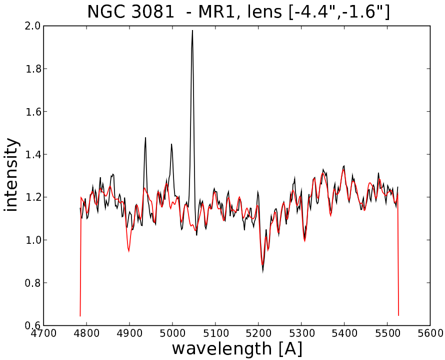
1. Kinematics of ionized gas in NLRs
    - Rotation
        - gravitational potential
    - Outflow or inflow motions
        - AGN influence
2. Properties of ionized gas
    - Electron density
    - Ionization structure
    - Dust distribution
    - Source of ionization
3. Underlying stellar populations
    - Age and metallicity
    - Stellar kinematics

Stellar Population Modelling

Modelling of the Spectra

Two steps:

- Stellar component
  - continuum emission, line absorption
- Emission lines of gas



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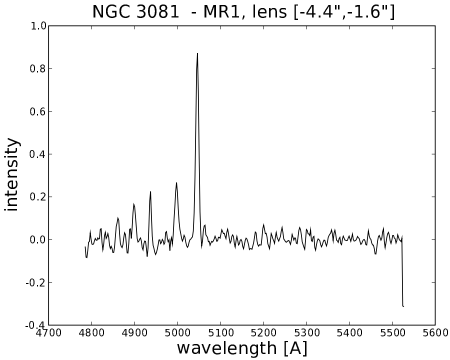

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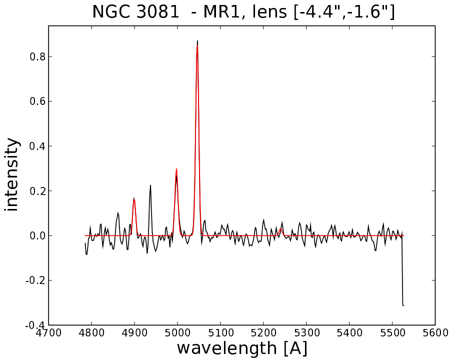

Models of Stellar Component

Degrees of approximation

- Smooth continuum – polynomial fit
- Galaxy spectrum from outside of NLR
- Individual stellar spectra
- Synthetic evolutionary spectra of stellar populations

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Motivation

- Correction of the hydrogen lines for underlying absorption
- Stellar velocities
- Composition of stellar ages (and metallicities)

Stellar Population Modelling

Synthetic evolutionary models of stellar populations

- GALAXEV library, Bruzual & Charlot (2003)

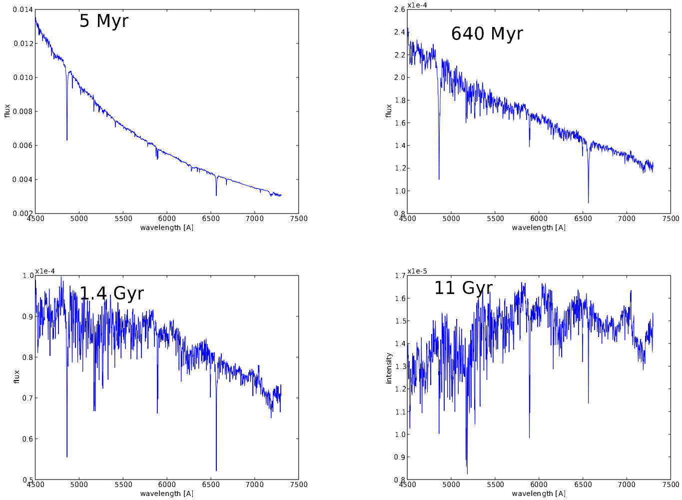
Modelling directly in the wavelength (not Fourier) space

- "Penalized Pixel Fitting", Cappellari & Emsellem (2004)

Homogenized S/N across FOV, irregular bins of S/N = 50

- Voronoi tesselation, Cappellari & Copin (2003)

Stellar populations of different ages ($Z=Z_\odot$)



LOSVD Modelling

(Line Of Sight Velocity Distribution)

Recovering LOSVD – directly in wavelength space (no FT)

- LOSVD Gauss-Hermite series:

$$\mathcal{L}(v) = \frac{e^{-\frac{1}{2}(v-\bar{v})^2/\sigma^2}}{\sigma\sqrt{2\pi}} \left[1 + \sum_{m=3}^{M} h_m H_m\right]$$

- Model spectrum (templates T_k, Legendre pol. P_l):

$$G_{\rm mod}(u) = \sum_{k=1}^{K} w_k [\mathcal{L} \star T_k](u) + \sum_{l=0}^{L} b_l P_l(u)$$

Model Parameters

Stellar templates

- Two simple stellar populations (SSPs): 11 Gyr, 100 Myr
  - from library Bruzual & Charlot (2003)
  - selection based on Cid Fernandes et al. (2004)

IMF

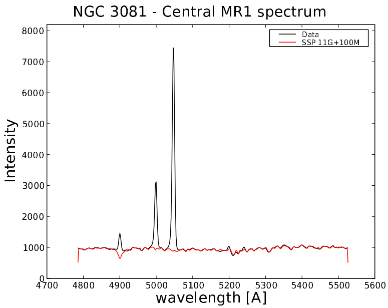
- Salpeter
- Cut-offs: $m_{\min} = 0.1\,M_\odot$, $m_{\max} = 100\,M_\odot$

Stellar evolution

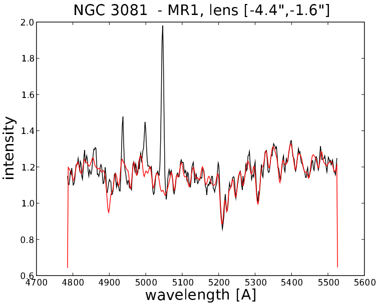
- Padova evolutionary tracks

Examples of stellar fits

Central spectrum

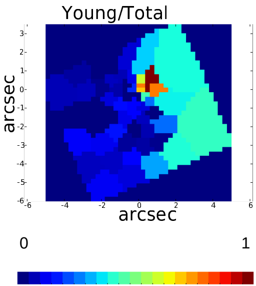


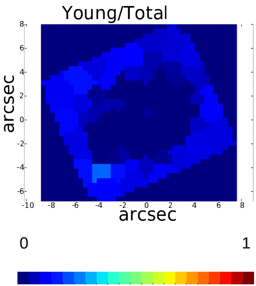
Off-centre

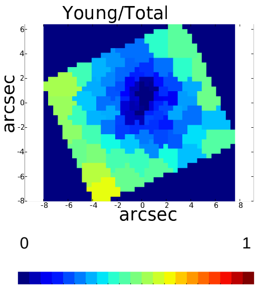


Mass Fractions of Young Stars

NGC 2992	NGC 3081	NGC 5929





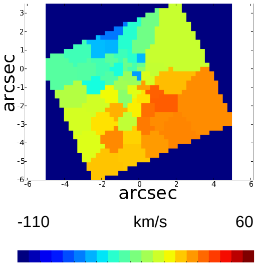


$1'' \leftrightarrow 175\,\mathrm{pc}$	$1'' \leftrightarrow 180\,\mathrm{pc}$	$1'' \leftrightarrow 170\,\mathrm{pc}$

Stellar Velocities

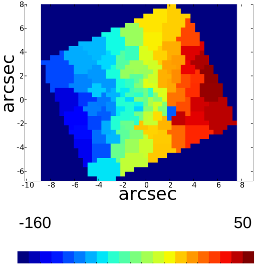
- Mean LOS motions (LOS = Line Of Sight)
- Computed from Doppler shift

NGC 2992



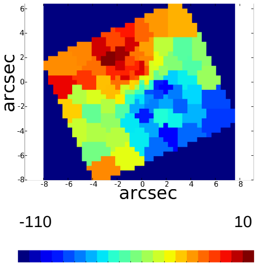
$1'' \leftrightarrow 175\,\text{pc}$

NGC 3081



$1'' \leftrightarrow 180\,\text{pc}$

NGC 5929

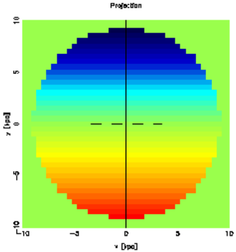


$1'' \leftrightarrow 170\,\text{pc}$

Analytic Velocity Fields

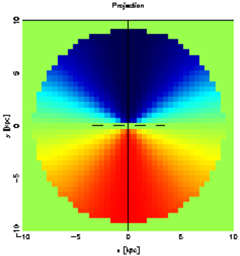
Flat disk with circular motion

Linear rotation curve



$$y = \text{const}$$

Flat rotation curve

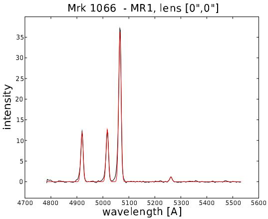


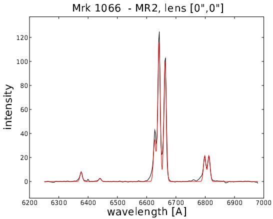
$$|x| = |y|\,|\cos i|\,\frac{\sqrt{v_0^2 \sin^2 i - v_i^2}}{|v_i^2|}$$

Morphology and Kinematics of Gas

Gas Emission Lines

- Recombination lines (Balmer series of H):
  - Hα λ 6563 Å
  - Hβ λ 4861 Å
- Forbidden lines (collisionally excited):
  - [O III] $\lambda\lambda$ 4959, 5007 Å
  - [N I] $\lambda\lambda$ 5198, 5200 Å
  - [O I] $\lambda\lambda$ 6300, 6364 Å
  - [N II] $\lambda\lambda$ 6548, 6583 Å
  - [S II] $\lambda\lambda$ 6717, 6731 Å



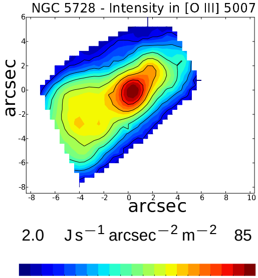


Emission Line Modelling

- Line profiles:
  - Single-Gaussian models of narrow lines
  - Add a broad Gaussian in Sey 1s
- Fitting software: FIT/SPEC (Rousset 1992)
  - Allows fits on whole datacubes
  - Constraints on intensities, velocities and FWHM
  - Constraints on forbidden line ratios
  - Non-linear least squares
  - Interface: ESO MIDAS
  - Created at CRAL – Observatoire de Lyon

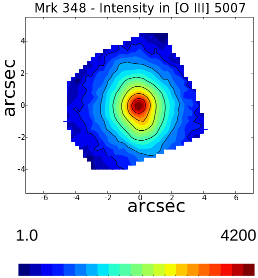
NLR morphologies – [O III]

NGC 5728 (Sey 2)



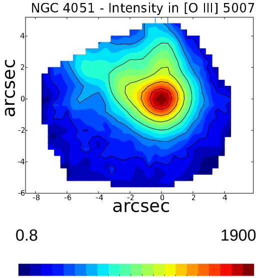
$1'' \leftrightarrow 200\,\mathrm{pc}$

Mrk 348 (Sey 2)



$1'' \leftrightarrow 275\,\mathrm{pc}$

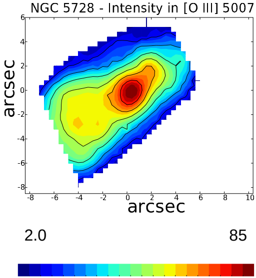
NGC 4051 (Sey 1.5)



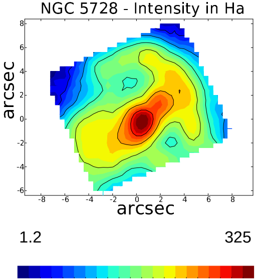
$1'' \leftrightarrow 60\,\mathrm{pc}$

Misalignments – NGC 5728

[O III]

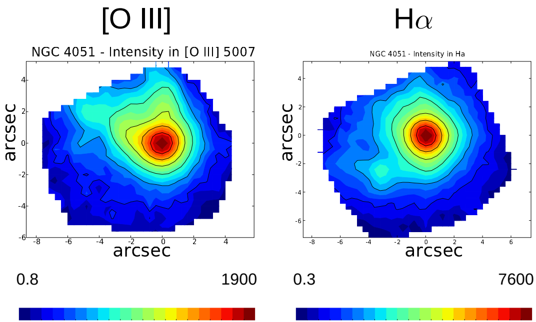


Hα



$1'' \leftrightarrow 200\,\mathrm{pc}$

Misalignments – NGC 4051



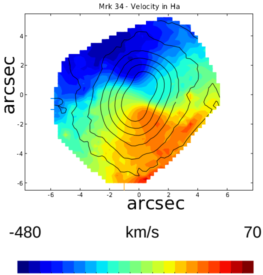
$1'' \leftrightarrow 60\,\mathrm{pc}$

S-shaped velocity isocontours (Hα)

Signatures of non-circular motions due to

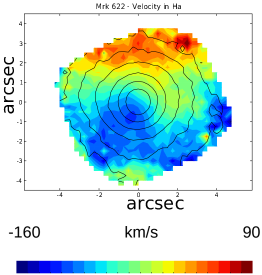
- non-axisymmetric potentials (bars, warps, spirals)
- radial flows

Mrk 34



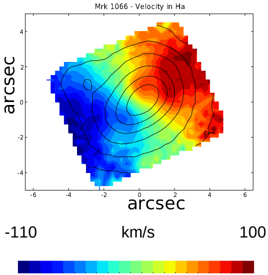
$1'' \leftrightarrow 960\,\mathrm{pc}$

Mrk 622



$1'' \leftrightarrow 460\,\mathrm{pc}$

Mrk 1066



$1'' \leftrightarrow 225\,\mathrm{pc}$

Twisted isovelocity contours – models

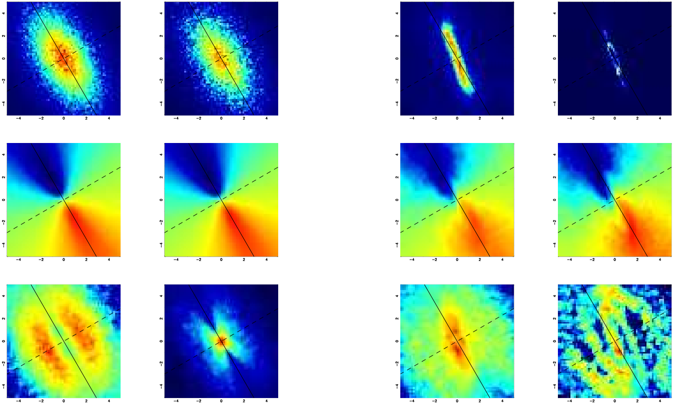
Axisymmetric distribution — Non-axisym. distribution

Stars — Gas — Stars — Gas

Surf.dens.

LOS vel.

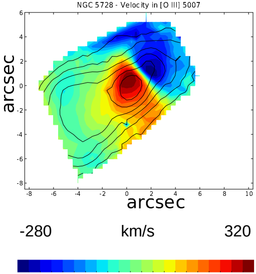
Vel. disp.



Jungwiert et al. (2003)

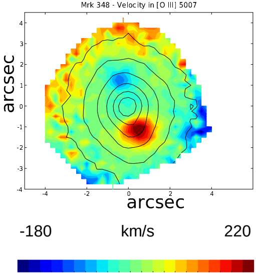
Mean LOS velocities of gas

NGC 5728
(Sey 2)



$1'' \leftrightarrow 200\,\mathrm{pc}$

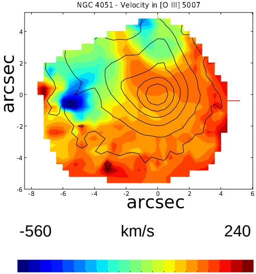
Mrk 348
(Sey 2)



$1'' \leftrightarrow 275\,\mathrm{pc}$

Ring?

NGC 4051
(Sey 1.5)

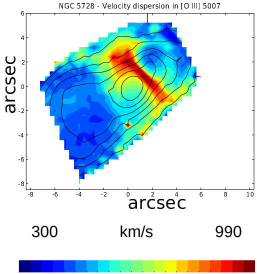


$1'' \leftrightarrow 60\,\mathrm{pc}$

Radio jet: NE

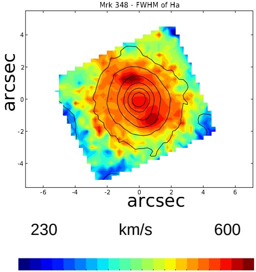
LOS velocity dispersion

NGC 5728



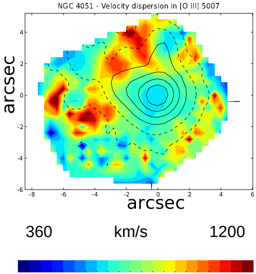
1″ ↔ 200 pc

Mrk 348



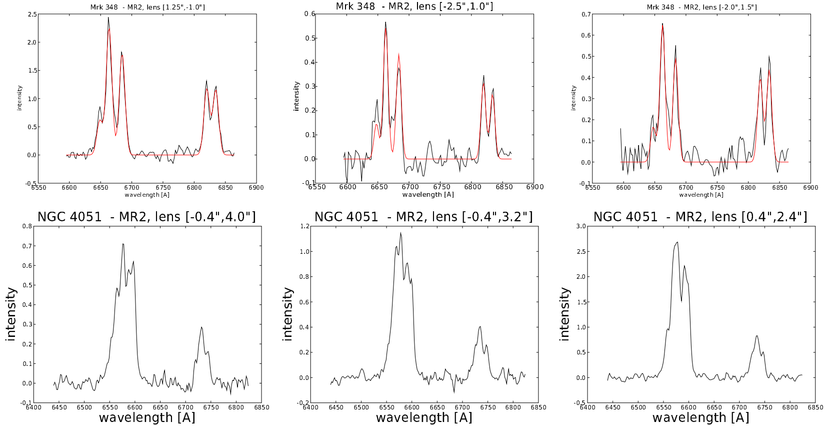
1″ ↔ 275 pc

NGC 4051



1″ ↔ 60 pc

Line Splitting – Mrk 348, NGC 4051



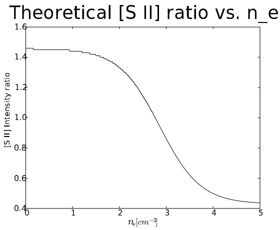
Properties of NLR Gas

Electron densities

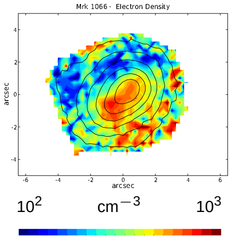
Ratio of [S II] lines sensitive to n_e in the range $10^2 - 10^4\ \mathrm{cm}^{-3}$

Critical densities:

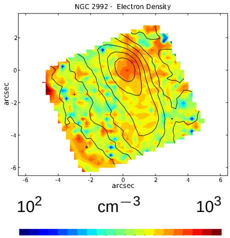
- for [S II] 6717 Å:
  $1.5 \times 10^3\ \mathrm{cm}^{-3}$
- for [S II] 6731 Å:
  $3.9 \times 10^3\ \mathrm{cm}^{-3}$

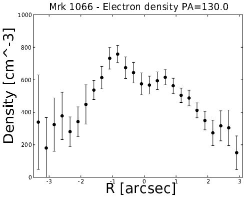


Mrk 1066

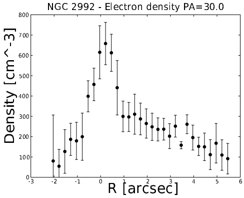


NGC 2992





$1'' \leftrightarrow 225\ \mathrm{pc}$



$1'' \leftrightarrow 175\ \mathrm{pc}$

Interstellar Extinction

Balmer decrement $H\alpha/H\beta$

- Intrinsic value
  - 2.86 in gas ionized by stellar radiation
  - 3.1 in gas ionized by AGN

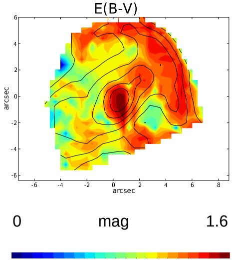
Measured I_1/I_2:

$$\frac{I_1}{I_2} = \left(\frac{I_1}{I_2}\right)_0 e^{-C(f(\lambda_1)-f(\lambda_2))}$$

Assumption:

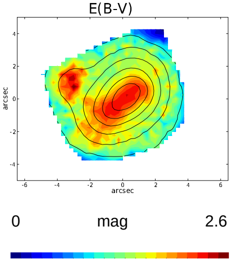
- Extinction law $f(\lambda)$
  – Osterbrock (1989)

NGC 5728



$1'' \leftrightarrow 200\,\mathrm{pc}$

Mrk 1066



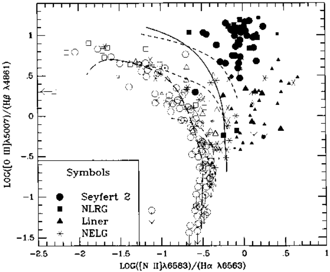
$1'' \leftrightarrow 225\,\mathrm{pc}$

Classification of emission objects

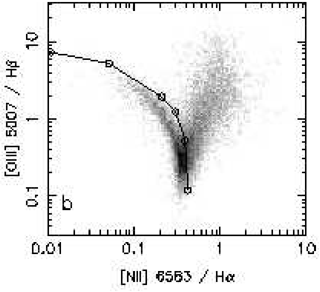
Diagnostic diagrams

- combinations of forbidden and permitted lines
  - e.g. [O III]/Hβ vs. [N II]/Hα

$\Rightarrow$ Separation of emission objects by the ionizing source



Veilleux & Osterbrock (1987)

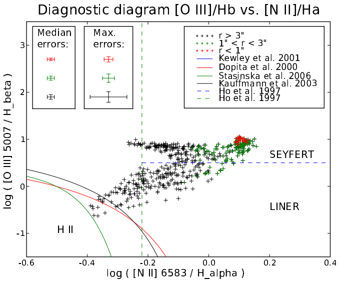


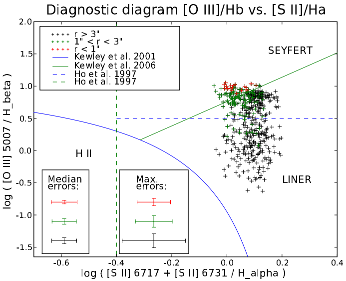
Stasińska et al. (2006), SDSS

Diagnostic Diagrams NGC 5728

Spatially resolved diagnostic diagrams

- Ionization structure of the NLR
- Classification and models only valid for global spectra
- Detailed photoionization modelling necessary
  - Derive ionization parameter, temperature, density
  - Ionization source(s), edge of AGN-ionized NLR





Summary

NLRs of 16 nearby Seyfert galaxies studied by IFS

1. Kinematics of gas
   - S-shaped velocity fields found in 80% of Sey 2s
     - Non-axisymmetric potentials? Outflows?
   - Outflow detected in NGC 4051
   - Tilted ring detected in Mrk 348
   - Emission line splitting in 80% of objects
     - Need of better models
2. Gas properties
   - Electron densities are strongly peaked
   - Interstellar extinction distributed unevenly
     - Dust necessary to include in models
   - Radial gradient of ionization structure
     - Future photoionization modelling
3. Stellar populations
   - Radial gradients of stellar age
   - Stellar velocity fields to be modelled

Future Perspective

Objectives:

- Interpretation of 3D structure of the NLRs
- Dynamics of host galaxies
- Role of NLRs in AGN feeding

Methods:

- Kinematic modelling
  - Analytic models – developed with B.Jungwiert
  - Elliptical rings, tilted rings
  - Fourier analysis
  - N-body models
  - Make use of velocity channel maps, p-v diagrams
- Ionization structure modelling
  - Numerical photoionization codes – CLOUDY, MAPPINGS

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- 205/03/H144/2003/02 of the Czech Science Foundation
- PhD fellowship provided by the French government

Forbidden Transitions

Ion	Transition			Wavelength	Probability [s^{-1}]
[O I]	$^3P_2$	$\rightarrow$	$^1D_2$	6300.3 Å	6.3×10^{-3}
[O I]	$^3P_1$	$\rightarrow$	$^1D_2$	6363.8 Å	2.1×10^{-3}
[O III]	$^3P_2$	$\rightarrow$	$^1D_2$	5006.9 Å	2.0×10^{-2}
[O III]	$^3P_1$	$\rightarrow$	$^1D_2$	4958.9 Å	6.7×10^{-3}
[N I]	$^2D^o_{3/2}$	$\rightarrow$	$^4S^o_{3/2}$	5197.9 Å	2.28×10^{-5}
[N I]	$^2D^o_{5/2}$	$\rightarrow$	$^4S^o_{3/2}$	5200.4 Å	6.13×10^{-6}
[N II]	$^3P_2$	$\rightarrow$	$^1D_2$	6583.4 Å	3.0×10^{-3}
[N II]	$^3P_1$	$\rightarrow$	$^1D_2$	6548.1 Å	1.0×10^{-3}
[S II]	$^4S_{3/2}$	$\rightarrow$	$^2D_{5/2}$	6716.4 Å	2.6×10^{-4}
[S II]	$^4S_{3/2}$	$\rightarrow$	$^2D_{3/2}$	6730.8 Å	8.8×10^{-4}

Emission Line Ratios

$$0.5 < [\text{N I}]\,\lambda 5198\,/\,[\text{N I}]\,\lambda 5200 < 1.5;$$
$$[\text{O III}]\,\lambda 5007\,/\,[\text{O III}]\,\lambda 4959 = 2.88;$$
$$[\text{O I}]\,\lambda 6300\,/\,[\text{O I}]\,\lambda 6364 = 3.0;$$
$$[\text{N II}]\,\lambda 6583\,/\,[\text{N II}]\,\lambda 6548 = 2.96;$$
$$0.35 < [\text{S II}]\,\lambda 6717\,/\,[\text{S II}]\,\lambda 6731 < 1.5\,.$$

Critical densities

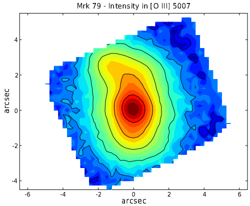
Ion	Wavelength	$n_e^{(\mathrm{crit})}$
[O I]	6300 Å	$1.8 \times 10^6\,\mathrm{cm}^{-3}$
[O III]	5007 Å	$7.0 \times 10^5\,\mathrm{cm}^{-3}$
[S II]	6717 Å	$1.5 \times 10^3\,\mathrm{cm}^{-3}$
[S II]	6731 Å	$3.9 \times 10^3\,\mathrm{cm}^{-3}$
[N I]	5200 Å	$2.0 \times 10^3\,\mathrm{cm}^{-3}$
[N II]	6583 Å	$8.6 \times 10^4\,\mathrm{cm}^{-3}$

Ionization Potentials

Atom	First	Second
O	13.618 eV	35.12 eV
S	10.36 eV	23.34 eV
N	14.534 eV	29.60 eV
He	24.59 eV	54.42 eV

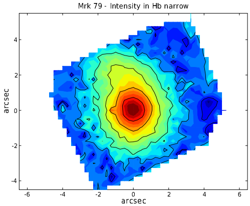
Seyfert 1 – Morphology – Mrk 79

[O III]



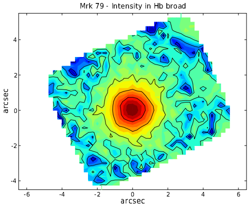
0.1 100

Hβ narrow



1.1 260

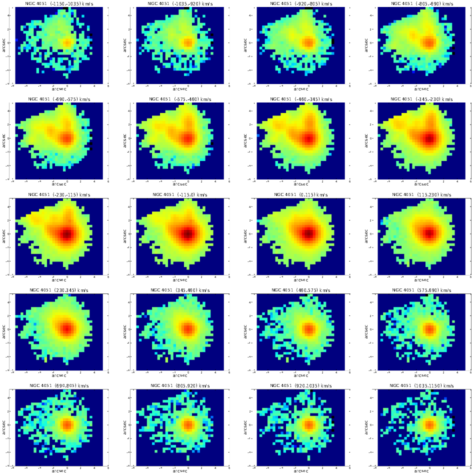
Hβ broad



0.8 3100

$1'' \leftrightarrow 440\,\mathrm{pc}$

Tomography – Velocity Channel Maps – NGC 4051

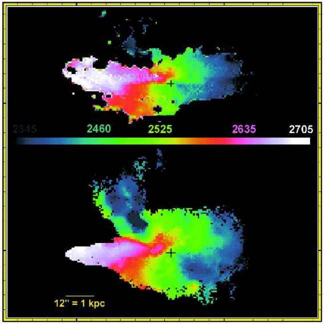


Elliptical streaming – NGC 4388

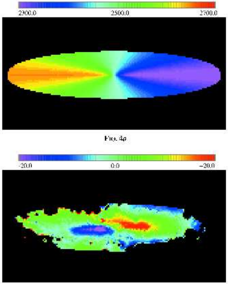
Veilleux et al. (1999)

Velocities

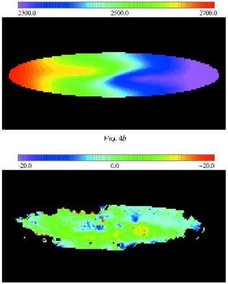
Observations [O III], Hα



Circular model



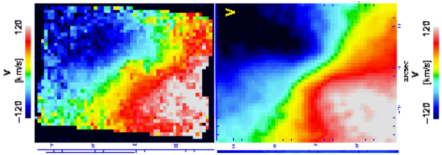
Elliptical model



N-body simulations – NGC 1068

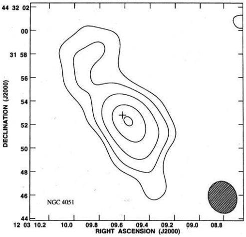
Emsellem et al. (2004)

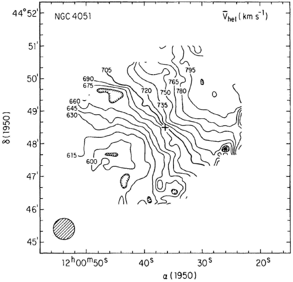
Observations and model (central 20″)



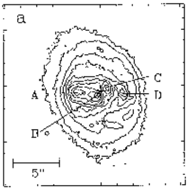
Modelling: N-body + SPH hydrodynamics

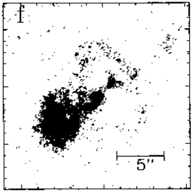
Radio emission – NGC 4051

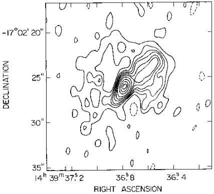




Radio emission – NGC 5728



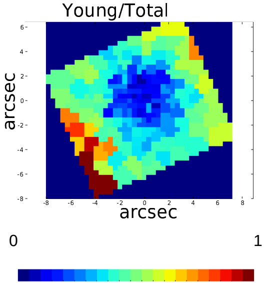




Stellar population ages

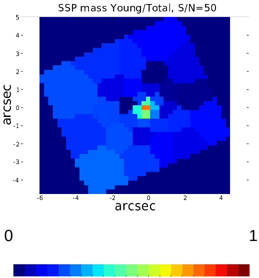
(Mass fractions of young stars)

NGC 5728



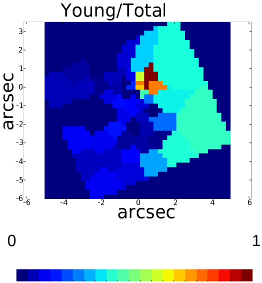
$1'' \leftrightarrow 200\,\mathrm{pc}$

Mrk 348



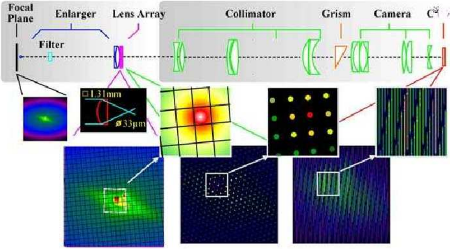
$1'' \leftrightarrow 275\,\mathrm{pc}$

NGC 2992



$1'' \leftrightarrow 175\,\mathrm{pc}$

OASIS optical scheme



Bacon et al. (2001)

Synthetic Stellar Populations

The GALAXEV code [Bruzual & Charlot 2003]

– Evolutionary population synthesis of stellar spectra

- Basic ingredients
  - input: libraries of stellar spectra
    (observational STELIB [LeBorgne et al. 2003],
    theoretical [LeJeune et al. 1997,1998])
  - stellar evolution prescription (Padova models)
    – temporal evolution of single stellar populations (SSPs)
- Assumed IMF: Salpeter or Chabrier
  - Cutoffs: $m_L = 0.1\,M_\odot$, $m_U = 100\,M_\odot$

Initial Mass Functions

- Salpeter IMF (1955):

$$\Phi(\log m) \propto m^{-1.35}$$

- Chabrier IMF (2003):

$$\Phi(\log m) \propto \begin{cases} \exp\left[-\frac{(\log m - \log m_c)^2}{2\sigma^2}\right] & \text{for } m \leq 1\, M_\odot \\ m^{-1.3} & \text{for } m > 1\, M_\odot \end{cases}$$

with $m_c = 0.08 M_\odot$, $\sigma = 0.69$