The host galaxies of compact radio sources

Joanna Holt

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Introduction

- why is it important to study the host galaxies?

- physical properties
  - morphology
  - stars
  - gas & dust

- the bigger picture
  - how do we get a compact radio source?
  - influence of host on AGN
  - influence of AGN on host
Why study the host galaxies?

- **basic parameters**
  - optical/IR ID
  - redshift

- **compact radio sources for compact radio sources’ sake**
  - magnitude (size, luminosity, mass)
  - morphology
  - stellar content
  - gas (& dust) content: cold/warm/hot

- **galaxy evolution**
  - frustration versus youth
  - radio source versus stellar evolutionary timescales
  - triggering & feedback of nuclear activity

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see also review by P. Best

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Why? • Morphology • Stars • Gas • Summary & Big Picture
Morphology: what we knew in 2002

de Vries (2003) & refs within

• galaxies & quasars
  - similar numbers of galaxy & quasar hosts
  - distorted morphologies
  - z distribution of CSS & GPS similar
  - highest z sources tend to be quasars (all z>2 are quasars)
  - z>2 quasars are preferentially GPS rather than CSS

• host sizes
  - giant ellipticals
  - not the most massive galaxies (i.e. not Brightest Cluster Galaxies)
Galaxies versus Quasars

• a lot of time spent discussing this
  - are the properties different?

Why? • Morphology • Stars • Gas • Summary & Big Picture
Galaxies versus Quasars

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is this really the issue?
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• unification
  - same central engine, different viewing angles
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- AGN triggering/mergers
  - injection of large amounts of gas & dust into central regions
  - early evolution hidden from view by natal cocoon
    - e.g. Silk & Rees (1998); Fabian (1998)
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  e.g. Silk & Rees (1998); Fabian (1998)

PKS 1549-79

- core-jet source pointing close to L.O.S.

- quasar nucleus completely hidden at optical wavelengths

Holt et al. (2006)

Why? • Morphology • Stars • Gas • Summary & Big Picture

Sterrewacht Leiden, Leiden University
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28th May 2008
Disturbed morphologies

PKS 1549-79

5 arcsec

VLT+FORS1: Gunn r

Holt et al. (2006)

Why? • Morphology • Stars • Gas • Summary & Big Picture
Disturbed morphologies

High surface brightness elongation (4 arcsec/10 kpc)

Holt et al. (2006)
Disturbed morphologies

PKS 1549-79

high surface brightness elongation (4 arcsec/10 kpc)

fainter jet-like feature (12 arcsec/29 kpc)

Holt et al. (2006)
Disturbed morphologies

PKS 1549-79

- High surface brightness elongation (4 arcsec/10 kpc)
- Pair of tidal tails/edge on loop (10 arcsec/24 kpc)
- Fainter jet-like feature (12 arcsec/29 kpc)

Holt et al. (2006)

Why? • Morphology • Stars • Gas • Summary & Big Picture
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PKS 1549-79

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Pair of tidal tails/edge on loop (10 arcsec/24 kpc)

Fainter jet-like feature (12 arcsec/29 kpc)

Knots of emission

Holt et al. (2006)
Disturbed morphologies

PKS 1345+12 (MDM Kitt Peak): V

Emonts (priv. comm.)
Disturbed morphologies

PKS 1345+12 (MDM Kitt Peak): V

Why? • Morphology • Stars • Gas • Summary & Big Picture

Emonts (priv. comm.)
Disturbed morphologies

Why? • Morphology • Stars • Gas • Summary & Big Picture
Disturbed morphologies

PKS 1345+12 (VLT/FORS): R

- diffuse halo/common envelope
- double nucleus
- companion?

Why? Morphology • Stars • Gas • Summary & Big Picture
Disturbed morphologies

PKS 1345+12 (HST/ACS): [O III]

Rodriguez et al. (2007)
Disturbed morphologies

**Super Star Clusters (SSCs)**

- Diffuse halo/common envelope
- Emission line arc

PKS 1345+12 (HST/ACS): [O III]

Rodriguez et al. (2007)

**Why?**

- Morphology
- Stars
- Gas
- Summary & Big Picture
Morphology

indicative of recent mergers which induce star formation in the halo

- Super Star Clusters in halo
- double nuclei
- common envelope
- emission line arcs
- tidal tails
- distorted isophotes
- companion galaxies
- Why?

- Morphology
- Stars
- Gas
- Summary & Big Picture
Stars: what we knew in 2002

- optical & near-IR imaging
  - luminosity profiles consistent with giant elliptical galaxies
    (but not most massive ellipticals/BCGs)
  - similar to FRII hosts
    (absolute magnitudes, colours & surface brightness profiles)
  - broad band colours/SEDs (J,H,K,R)
    OSPs (formation: $z \gtrsim 5$)
    with solar metallicity

- redshift evolution consistent with passive evolution

e.g. de Vries (2003); de Vries et al.
optical & near-IR imaging
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Redshift evolution consistent with **passive evolution**

**NOTED THAT**

- this seems to be at odds with the observed morphologies the host galaxies are clearly interacting
- explained away as 'observing the first of many interactions'

de Vries (2003)

e.g. de Vries (2003); de Vries et al. (1998,2000)
Recent developments

• strange to focus on near-IR colours alone

• hosts are similar to FRII hosts which have:
  - known UV excesses (IR-optical colours) e.g. Lilly & Longair (1984)
  - not consistent with non- or passively evolving ellipticals

• UV excess in radio galaxies
  - originally though to be YSPs (merger-induced star formation) e.g. Heckman et al. (1986); Smith & Heckman (1989)

  - other possibilities (e.g. AGN, scattered light, nebular continuum)
    e.g. Tadhunter et al. (1988); Fabian (1989); Dickson et al. (1995)

• last few years: clear evidence that the UV excess observed in some radio galaxies is due to the presence of young stars
  e.g. Tadhunter et al. (1996, 2002, 2005); Holt et al. (2007); Wills et al. (2002, 2004, 2008); Emonts et al. (2006); Rodriguez et al. (2007)
YSPs in radio galaxies

- detailed study optical SEDs of a sample of radio galaxies
  - VLT & WHT spectra
  - large spectral coverage
  - high S/N & good (few Å) resolution

- sample
  - selected radio galaxies (extended & compact) with known UV excess
  - of order 30 radio galaxies
  - includes 7 compact radio sources
    - 3C 213.1, 3C 236, 3C 459, PKS 0023-26,
    - PKS 1345+12, PKS 1549-79, PKS 2135-20

Why? • Morphology • Stars • Gas • Summary & Big Picture
YSPs in compact radio sources

3C 213.1: nucleus

Flux (10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1})

wavelength (Å)

[O II]3727

spectral signatures of a young or intermediate stellar population

Wills et al. (2008)
YSPs in compact radio sources

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Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture

Wills et al. (2008)
YSPs in compact radio sources

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Flux ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$)

[O II]3727

Ca II H 3969

Ca II K 3934

Balmer lines

spectral signatures of a young or intermediate stellar population

Wills et al. (2008)
YSPs in compact radio sources

PKS 1549-79

PKS 0023-26

plots show spatial variation in 4000Å break

large galaxy wide UV excess

Holt et al. (2007)

why? • morphology • stars • gas • summary & big picture
YSPs in compact radio sources

recent HST/ACS UV images also detect significant near-UV emission in the hosts which is often clumpy and NOT confined to the nuclear regions

Labiano et al. (2008)
YSPs in compact radio sources

PKS 0023-26

Flux (10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1})

rest wavelength (Å)

data

model

YSP: 0.03 Gyr; E(B-V) = 0.9

OSP: 12.5 Gyr

fit residuals

Holt et al. (2007)

Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
YSPs in compact radio sources

rest wavelength (Å)

Flux \((10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1})\)

E(B-V)

Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
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Holt et al. (2007)

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Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
# YSPs in compact radio sources

- results for the CSS & GPS sources

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YSP ages:
few Myr – 1 Gyr; most < 0.5 Gyr

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- results for the CSS & GPS sources

*Why?*
- Morphology
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- Gas
- Big picture
- Summary

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*YSP ages: few Myr - 1 Gyr; mostly < 0.5 Gyr*

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*YSP ages: less of a delay between triggering of starburst & AGN*
• YSP ages: few Myr – 1 Gyr; mostly < 0.5 Gyr & less of a delay between triggering of

**YSP mass:**

few–100% of stellar mass

> major galaxy-wide starburst

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• YSP mass: few-100% of stellar mass > major galaxy-wide starburst

YSPs are often reddened

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YSPs in compact radio sources

- in total, the UV emission/stellar content has now been investigated in 19 compact radio sources
  - 8 in detail in our study of radio galaxies
    Tadhunter et al. (2005), Holt et al. (2006, 2007), Rodriguez et al. (2007), Wills et al. (2008)
  - 5 more done 'quickly' in order to model the optical emission lines
    Holt (2005), Holt et al. (2008)
  - detailed study of 9C J1503+4528
    Inskip et al. (2006)
  - high resolution UV images of 9 sources
    (including PKS 1345+12, PKS 1934-63 which overlap with the above studies and PKS 1814-63 & 3C 303.1 which we were not able to model for various reasons)
    Labiano et al. (2008)
YSPs in compact radio sources

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- clear, unambiguous evidence for a YSP component in 9 compact radio sources

- possible YSPs in 4 more

Why? • Morphology • Stars • Gas • Summary & Big Picture
YSPs in compact radio sources

- **YOUNG**: few Myr – 1 Gyr
  - less evidence for ‘delay’ between onset of merger/triggering of starburst & triggering of AGN  Holt et al. (2007)
  - some sources in first throes of activity (very young YSP); others retriggered? (older YSP)  Wills et al. (2008)

- **GALAXY WIDE**
  - extended UV excess
  - YSPs modelled in extended apertures in some sources
  - SSCs in haloes of some objects

- **PROLIFIC** (some sources)
  - few-100% of stellar mass
  - several classified also as ULIRGs
    e.g. PKS 1345+12, PKS 1549-79, 3C 459

Tadhunter et al. (2005); Rodriguez et al. (2007); Holt et al. (2007); Wills et al. (2008); Labiano et al. (2008)
Gas & dust

• other main component of host

• different types of gas
  - warm gas (optical emission lines)
    >> focus on this
  - cold gas (atomic & molecular gas)
    >> see C. Fanti, M. Orienti & R. Morganti talks
  - hot gas (highly ionised)
    >> see session on X-ray properties

• gas properties
  - kinematics
  - physical conditions
  - ionisation state & mechanisms
Emission line gas kinematics

- Gelderman & Whittle (1994)
  - 20 CSS
  - relatively strong, high EQW emission lines
  - broad, structured [O III]

- smaller radio sources tend towards larger FWHM

- kinematic disturbance evidence for
  > non-gravitational motions
  > outflows?

Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
Outflow in the high ionisation lines?

PKS 1549-79: $z = 0.152$

[Wavelength (Å)]

- [O III]λλ4959,5007
  - $z = 0.1501 \pm 0.0002$
  - FWHM ~ 1350 km s$^{-1}$

- [O II]
  - [Ne III]
  - [O III] Hβ
  - [Ne V]

$\Delta z \sim 600$ km s$^{-1}$

- [O II]λ3727
  - $z = 0.1526 \pm 0.0002$
  - FWHM ~ 650 km s$^{-1}$

(Tadhunter et al 2001)

Why? • Morphology • Stars • Gas • Summary & Big Picture
Emission line gas kinematics

optical emission lines

- extended: up to ~ 20 kpc
- complex strong blue asymmetries
- multiple Gaussian components

Holt et al. (2003a,b; 2008)

WHT+ISIS spectrum of the GPS source: PKS 1345+12

Hβ
Accurate redshift determination

Extended [O II]3727 emission

Deep HI 21cm absorption
(Mirabel 89, Morganti et al 03)

Holt et al. (2003a,b; 2008)
Emission line outflows

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Emission line outflows

Extended [O II]3727 emission

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[O III] emission in the nucleus

broad blueshift ~ 2000 km s^-1

intermediate blueshift ~ 400 km s^-1

narrow

Holt et al. (2003a,b; 2008)
Extended [O II]3727 emission
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[O III] emission
in the nucleus
broad blueshift ~ 400 km s\(^{-1}\)
narrow
blueshift ~ 2000 km s\(^{-1}\)

Emission line outflows

inflows or outflows?

Holt et al. (2003a,b; 2008)
Emission line outflows

- reddening
  - Hydrogen Balmer line ratios
    \( \frac{H\alpha}{H\beta} \), \( \frac{H\gamma}{H\beta} \), etc
  - significant reddening in the nucleus in PKS 1345+12
    (particularly in the broader components: e.g. \( E(B-V) \leq 2.00 \))
  - regions beyond nucleus even more obscured

Holt et al. (2003a,b; 2008)
Emission line outflows

- 11/14 show evidence for fast outflows
  - systemic to broadest component
  - different distributions: K-S test significance: 99.9%

- fast outflows (300–500 km s\(^{-1}\)) are also observed in 3 CSS sources by O’Dea et al. (2002)

- size is important
orientation may also be important

Holt et al. (2008)
Outflow driving mechanism

• what causes the outflows?
  > expanding radio jets? (Bicknell, Dopita & O’Dea 97)
  > starburst-driven superwind? (Heckman, Armus & Miley 90)
  > quasar-induced winds? (Balsara & Krolic 93)

• tools
  > spectroscopy
  > imaging

Why? • Morphology • Stars • Gas • Summary & Big Picture
Outflow driving mechanisms

complete sample:
- gas kinematics (emission line profiles)
- gas physical conditions e.g. density, temperature (line ratios)
- gas ionisation state & likely ionisation mechanism (line ratios)

• tools
  - spectroscopy
  - imaging

Why? • Morphology • Stars • Gas • Summary & Big Picture
Physical conditions

• reddening
  - Balmer lines (Hα/Hβ; Hγ/Hδ)
  - significant in some sources, not in others
  - other studies also find this (e.g. Morganti et al. 1997; Labiano et al. 2005)

• high gas densities
  - (SII 6716/6731 ratio)
  - high, typically > ~few 1000 cm$^{-3}$
  - can't accurately measure due to complex line profiles
    >> new VLT data to try to resolve this

• high electron temperatures
  - high temperatures
  - similar issues to density

Holt (2005); Holt et al. (2008, in prep)
Shock ionisation?

- nuclear narrow components
  - 10/12 consistent with photoionisation
  - mixed-medium models & simple photoionisation

Holt (2005); Holt et al. (2008, in prep)
Shock ionisation?

- nuclear *shifted* components
  - shock + precursor models
  - fast shocks ($v > 300$ km s$^{-1}$)

Holt (2005); Holt et al. (2008, in prep)

intermediate:
$600 < \text{FWHM} < 1400$ km s$^{-1}$
broad:
$1400 < \text{FWHM} < 2000$ km s$^{-1}$
very broad:
$\text{FWHM} > 2000$ km s$^{-1}$

Why?  •  Morphology  •  Stars  •  Gas  •  Summary & Big Picture
HST/STIS of 3 CSS sources (3C 67, 3C 303.1 & 3C 277.1)

- mixture of shocked & photoionised gas
  - 3C 67 (0-50% shocks); 3C 303.1 (30-50% shocks); 3C 277.1 (100% precursor)
- 3C 303.1 (also 3C 67?) AGN doesn’t produce enough photons to ionise gas
- lower ionisation gas associated with higher gas velocities
- consistent with shocks

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Why? • Morphology • Stars • Gas • Summary & Big Picture
Outflow driving mechanism

HST high-resolution imaging:

• comparison of radio and optical emission locations
  e.g. de Vries et al. (1997, 1999); Axon et al. (2000); Privon et al. (2008)

• size, location and morphology of emission line region
  >> in case of PKS1345+12 & PKS1549-79 the outflowing region
  e.g. Batcheldor et al. (2007)

• clear advantages over absorption line studies
  • tools
    > spectroscopy
    > imaging

Why? • Morphology • Stars • Gas • Summary & Big Picture
Radio-optical alignment

CSS sources

strong R-O alignment

at all redshifts

e.g. de Vries et al. 1997, 1999;
Axon et al. (2000);
Privon et al. (2008)

c.f. extended sources: only at $z > 0.6$
Radio-optical alignment

CSS sources
strong R-O alignment
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Privon et al. (2008)
c.f. extended sources: only at z > 0.6

Radio-optical alignment now been observed in a few 10s of sources

3C 268.3
3C 305
3C 303.1
3C 124
3C 124
Radio-optical alignment

GPS sources

- tend not to show alignment
  \( \gg \) resolution issue?
- R & O emission is co-spatial
- tentative evidence for elongation along radio axis

\begin{itemize}
  \item PKS 1549-79
  \item 0.2 arcsec
\end{itemize}

e.g. Batcheldor et al. (2007)

\begin{itemize}
  \item 1 arcsec
  \item spatially resolved
  \item 0.18 arcsec (430 pc)
\end{itemize}
Radio-optical alignment

Why? ● Morphology
● Stars ● Gas
● Big picture ● Summary

3C 49

GPS sources

• tend not to show alignment
• R/O emission is co-spatial
• tentative evidence for elongation along radio axis
  e.g. Batcheldor et al. (2007)

PKS 1549-79

small emission line region

confidently rule out large-scale starburst-driven winds

from positions/morphologies, it is difficult to distinguish between quasar winds and radio-interactions

e.g. Batcheldor et al. (2007)

spatially resolved

0.18 arcsec (430 pc)
Radio-optical alignment

Why?
- Morphology
- Stars
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  - e.g. Batcheldor et al. (2007)

CSS sources
- (e.g. de Vries et al 1997, 1999; Axon et al 2000, Privon et al. 2008)
- co-alignment & similar scales of radio & optical emission line structures

PKS 1549-79
- 1 arcsec
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small emission line region

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PKS 1549-79
- 0.2 arcsec
- Relatively modest warm gas outflow

Combining imaging & spectroscopy results:

- Mass outflow rate: $0.12 \, M_\odot < M < 12 \, M_\odot$
- Mass in the outflow: $1.9 \times 10^4 \, M_\odot < M < 1.9 \times 10^6$
- Energy flux: $5.1 \times 10^{40} \, < E < 5.1 \times 10^{42} \, \text{erg s}^{-1}$
- $1.5 \times 10^{-6} < E/L_{edd} < 1.5 \times 10^{-4}$

Need accurate gas densities to resolve this

Spatially resolved
- 0.18 arcsec (430 pc)
- 1.5 arcsec
Host galaxy properties

- **disturbed morphologies**
  double nuclei, tidal tails, distorted isophotes, arcs, SSCs, companions

- **recent star formation**
  galaxy-wide UV excess, spectral signatures of YSPs, prolific star formation in some sources

- **dense & dusty environments**
  large reddening, high densities

- **fast outflows**
  large line widths & shifts (up to 2000 km s\(^{-1}\)), more extreme velocities in smaller sources

- **interactions between the radio jet & ISM**
  high temperatures, line ratios consistent with fast shocks, radio & optical emission aligned & co-spatial
Tadhunter et al. (2001): model for PKS 1549-79

Observer's L.O.S.

HI cloud

Bow shock

Jet

Shocked clouds

Quasar

[O II]-emitting disk/cocoon

major merger
(injection of large amounts of material into nuclear regions)

Activity and galaxy evolution

e.g. Silk & Rees 1998;
    Fabian 1999;
    Hopkins et al. 2005;
    di Matteo et al. 2005

Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
Activity and galaxy evolution

BH grows rapidly through accretion
(much of this phase hidden by natal cocoon; accretion possibly close to Eddington rate)

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trigger AGN & major starburst

e.g. Silk & Rees 1998; Fabian 1999; Hopkins et al. 2005; di Matteo et al. 2005

AGN drives powerful winds
(shedding the natal cocoon & revealing the quasar)

Why? • Morphology • Stars • Gas • Summary & Big Picture
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eventually activity & star formation cease

‘fuel’ (ISM) is blown out of galaxy

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Why? • Morphology • Stars • Gas • Summary & Big Picture
BH grows rapidly through accretion (much of this phase hidden by natal cocoon; accretion possibly close to Eddington rate) major merger (injection of large amounts of material into nuclear regions) 'fuel' (ISM) is blown out of galaxy

models require 5-10% of the accretion power of the AGN to drive the winds AGN drives powerful winds (shedding the natal cocoon & revealing the quasar)

eventually activity & star formation cease

trigger AGN & major starburst

Why? ● Morphology ● Stars ● Gas ● Summary & Big Picture
Radio-optical alignment

PKS 1549-79

outflow in the warm gas is not currently capable of clearing the nuclear regions

energy flux: $5.1 \times 10^{40} < E < 5.1 \times 10^{42} \text{ erg s}^{-1}$

$1.5 \times 10^{-6} < E/L_{\text{edd}} < 1.5 \times 10^{-4}$

need accurate gas densities to resolve this

relatively modest warm gas outflow

PKS 1549-79

$0.2 \text{ arcsec}$

spatially resolved

$0.18 \text{ arcsec} (430 \text{ pc})$

GPS sources

• tend not to show alignment

• R/O emission is co-spatial

• tentative evidence for elongation along radio axis

3C 49

3C 303.1

$1 \text{ arcsec}$

energy flux:

$1.5 \times 10^{-6} < E/L_{\text{edd}} < 1.5 \times 10^{-4}$

$0.18 \text{ arcsec} (430 \text{ pc})$

PKS 1549-79

$0.2 \text{ arcsec}$

$0.18 \text{ arcsec} (430 \text{ pc})$

PKS 1117-31

$0.2 \text{ arcsec}$

$0.18 \text{ arcsec} (430 \text{ pc})$

PKS 1352+101

$0.2 \text{ arcsec}$

$0.18 \text{ arcsec} (430 \text{ pc})$

PKS 1549-79

$0.2 \text{ arcsec}$

$0.18 \text{ arcsec} (430 \text{ pc})$
Summary

• evolution of AGN & their host galaxies intricately intwined

• compact radio sources are key objects
  - highlight objects in the early stages of evolution
  - AGN triggering
  - AGN feedback

• key object: PKS 1549-79
  - tie together several important classes of AGN: CSO/ULIRG/NLS1
  - all associated with triggering/feedback of AGN
  - a rapidly evolving galaxy in the local universe

Important probes of AGN-induced feedback in the early stages of radio source evolution