Studies of high redshift radio galaxies

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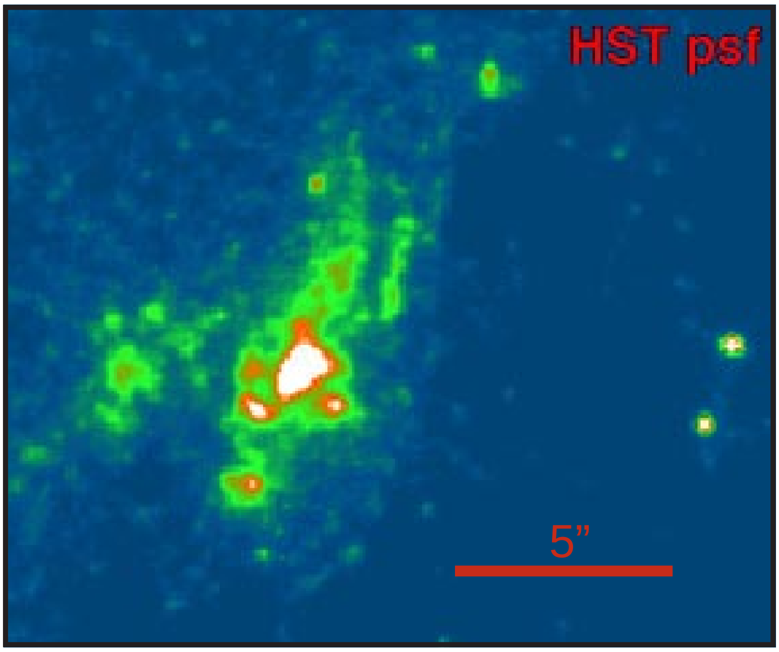
3C 265, z = 0.81
HST + Keck
image combination
V-band

(Hook, Tran & Fosbury)



Basic questions to be addressed

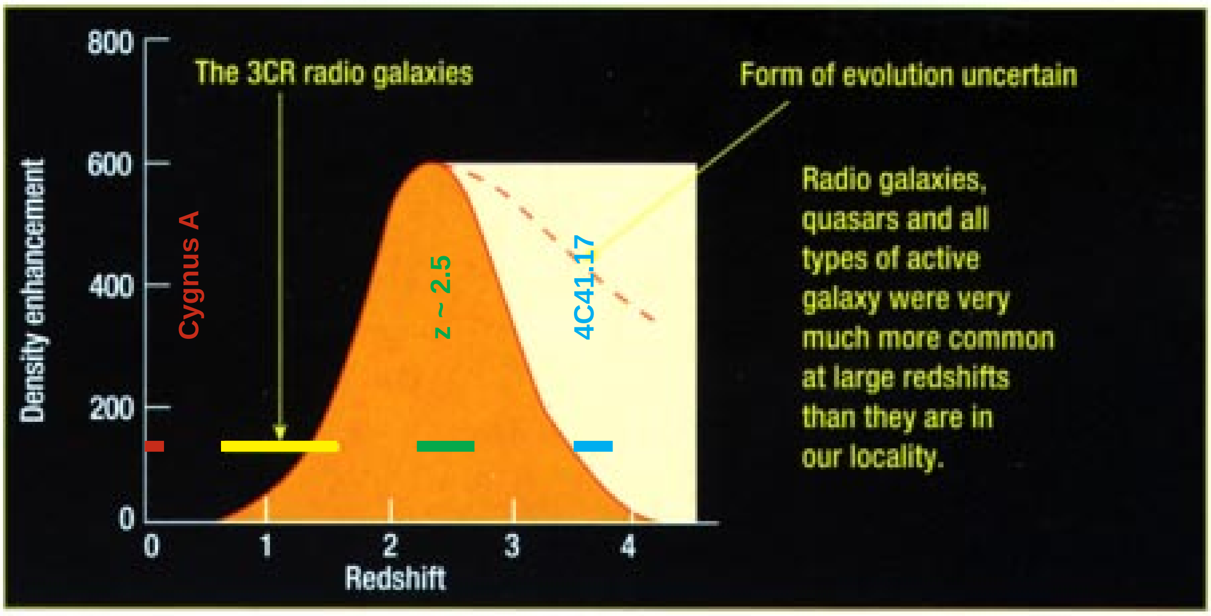
Radio galaxies are readily identified to high redshifts. How can we use them to tell us about galaxy formation and evolution?

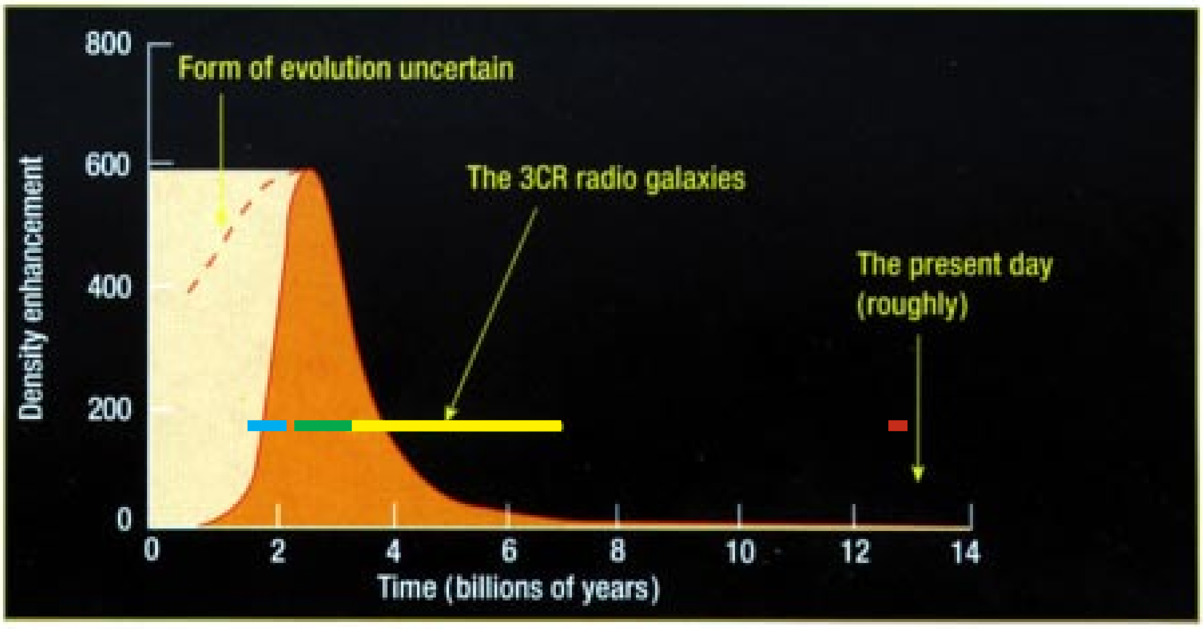
What are the radiation process operating in the UV - optical - NIR spectral bands and how can we disentangle the different components?

Should we be comfortable with the Quasar – Radio Galaxy orientation-based unification?

Summary of talk

- Review of the redshift ~1 radio galaxies and the nature of the 'alignment effect'
- What happens at higher redshifts?
  Keck (spectro)-polarimetry
- Do we understand the low redshift sources?
  Taking Cygnus A apart



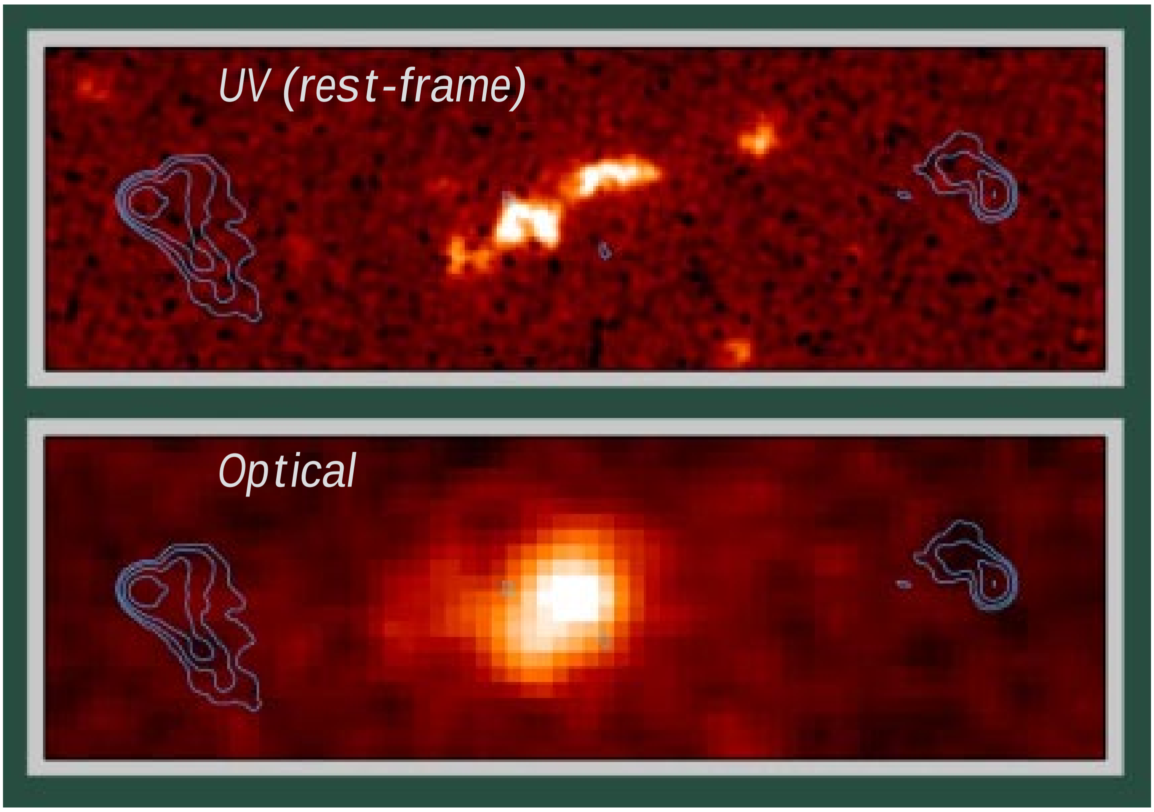


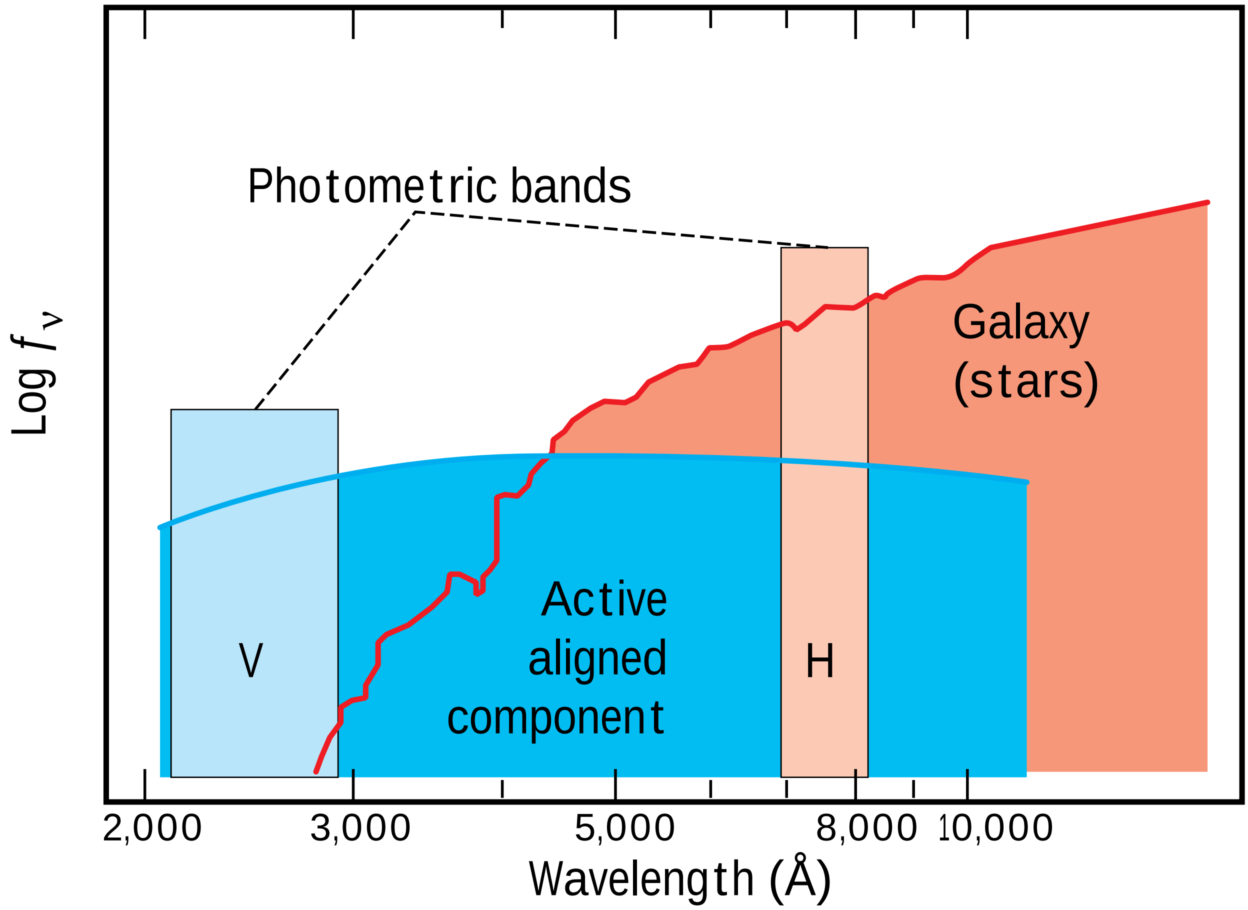
From Longair (1997, A&G, 38, 10)

Redshift one — the *Alignment Effect*

(McCarthy et al. 1987, Chambers et al. 1987)

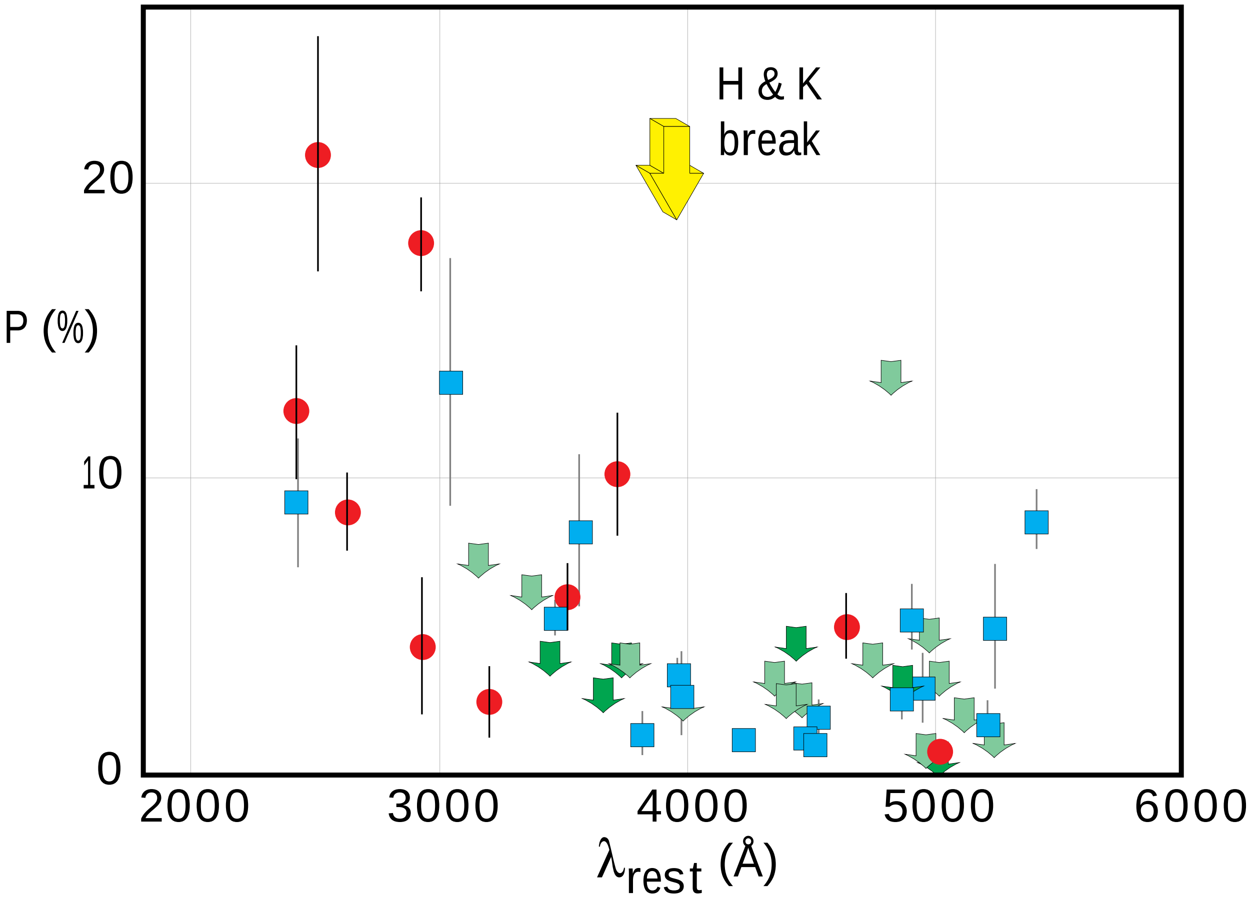
3C 324, z = 1.206
Best et al. (1996)





Polarization behaviour

Measured in the rest-frame, the polarization increases below the 4000Å break. (data from Cimatti et al. 1993)



This suggests that the blue, aligned light contains a polarized component which, since its E-vector is always perpendicular to the alignment axis, we identify with scattered light from a hidden AGN. Above the 4000Å break, this component is diluted by the old stellar population.

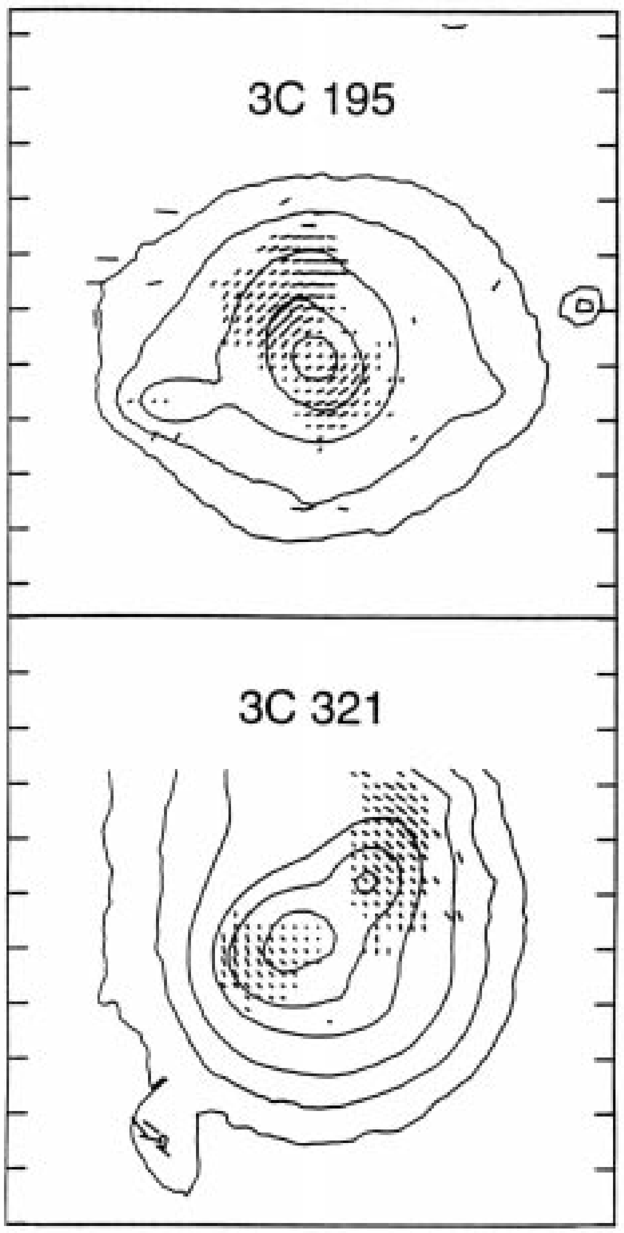
Although this polarized component is seen at low redshift, it appears that the alignment effect really 'switches-on' above redshifts of around 0.7 (McCarthy et al. 1987, Chambers et al. 1987)

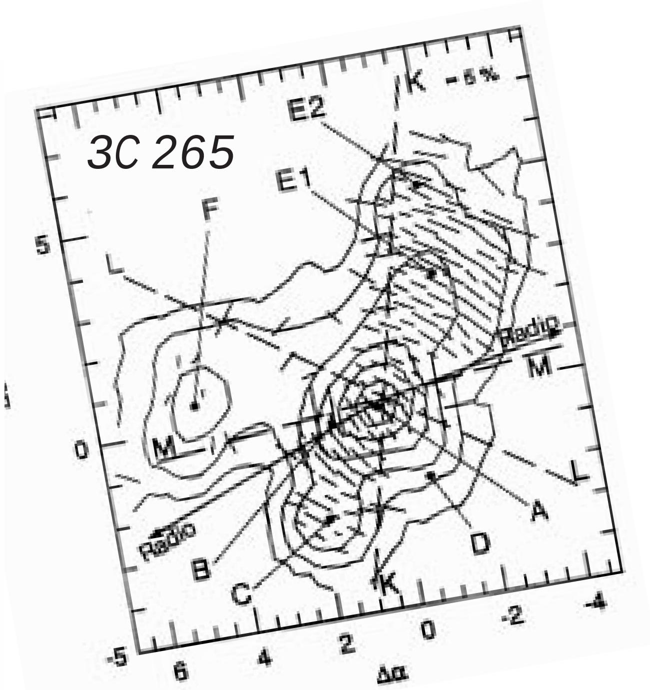
Optical polarization maps

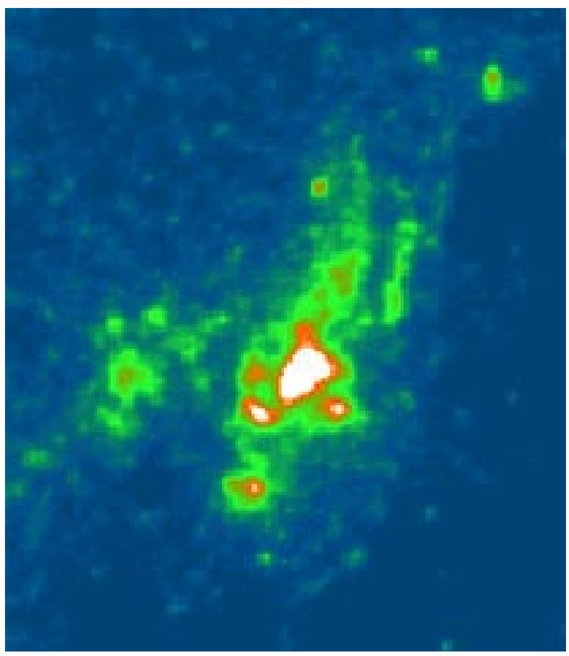
Keck LRIS (Cohen et al.)

These show the characteristic ‘polarization-cones’ indicating scattering from the AGN

3C 265 illustrates a misalignment between the extended light and the radio axis — the E-vectors remain perpendicular





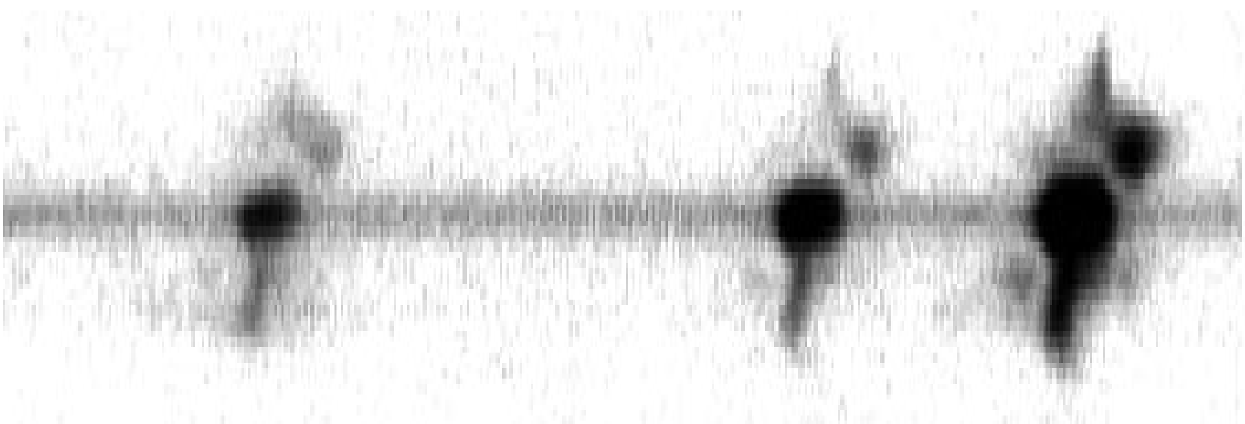


Contributors to the extended light

- ❑ Starlight (seen above the 4000Å break)
- ❑ Nebular continuum
- ❑ Extended emission lines (ionized by a hard continuum) with kinematically disturbed components (see 3C 171 below - Tadhunter et al.)
- ❑ A young stellar population
- ❑ Scattered quasar continuum
- ❑ Scattered quasar broad lines, eg. Mg II, Balmer lines
- ❑ Scattered quasar (high critical density) narrow lines, cf. the [OIII] vs. the [OII] Jackson-Browne test

Extranuclear physical processes

- ❑ Photoionization of the ISM by the AGN
- ❑ Synchrotron components (rare)
- ❑ Scattering of the AGN radiation by dust and electrons
- ❑ Jet/cloud interactions and associated shocks
- ❑ Star formation — triggered by the AGN or by the process which forms/fuels the AGN?

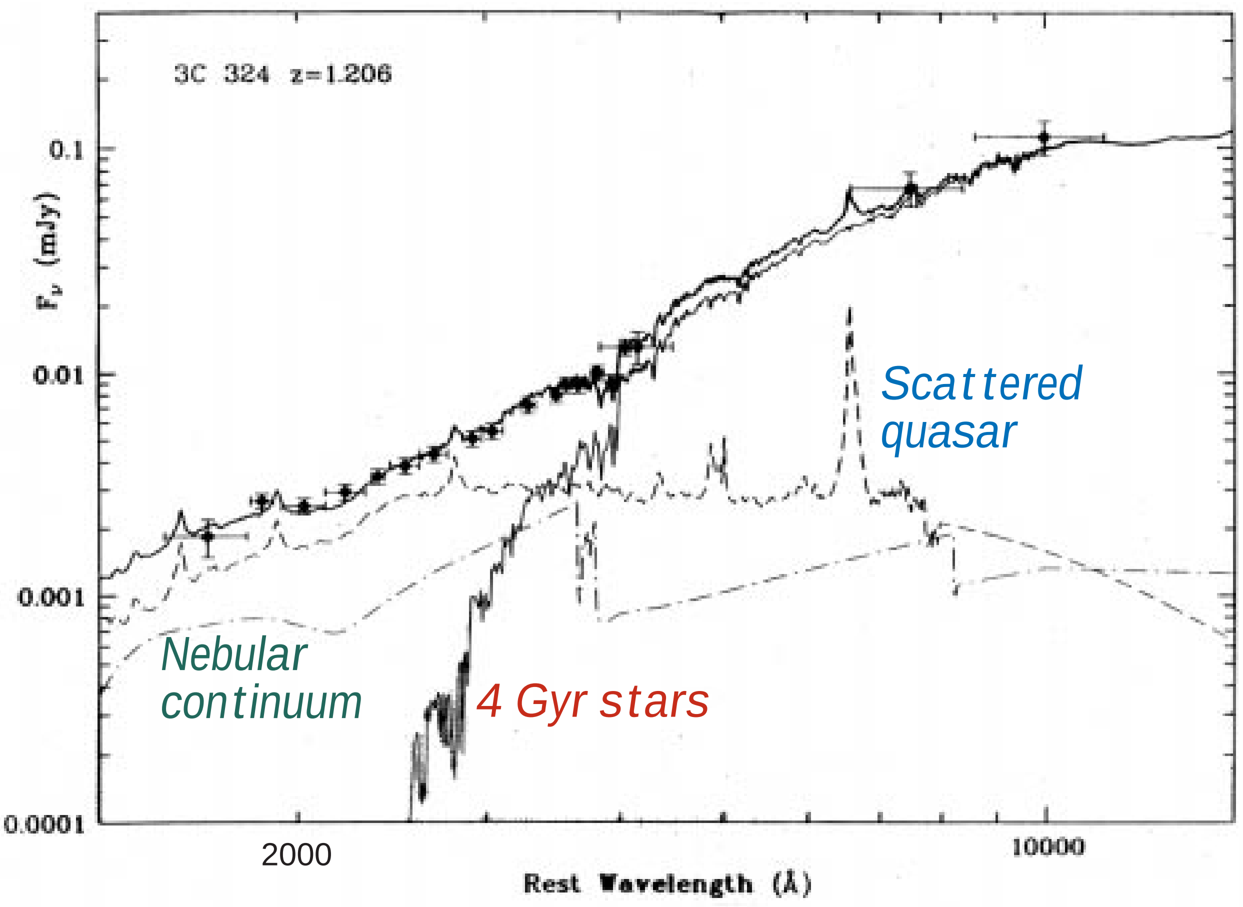


Continuum fitting

(from Cimatti)

The example of 3C 324

- ❑ 4 Gyr stellar population
- ❑ Dust scattered quasar
- ❑ Nebular continuum
- ❑ $E_{B-V} = 0.13$



Colour is a poor diagnostic of the scattering mechanism — cf. the twilight sky!

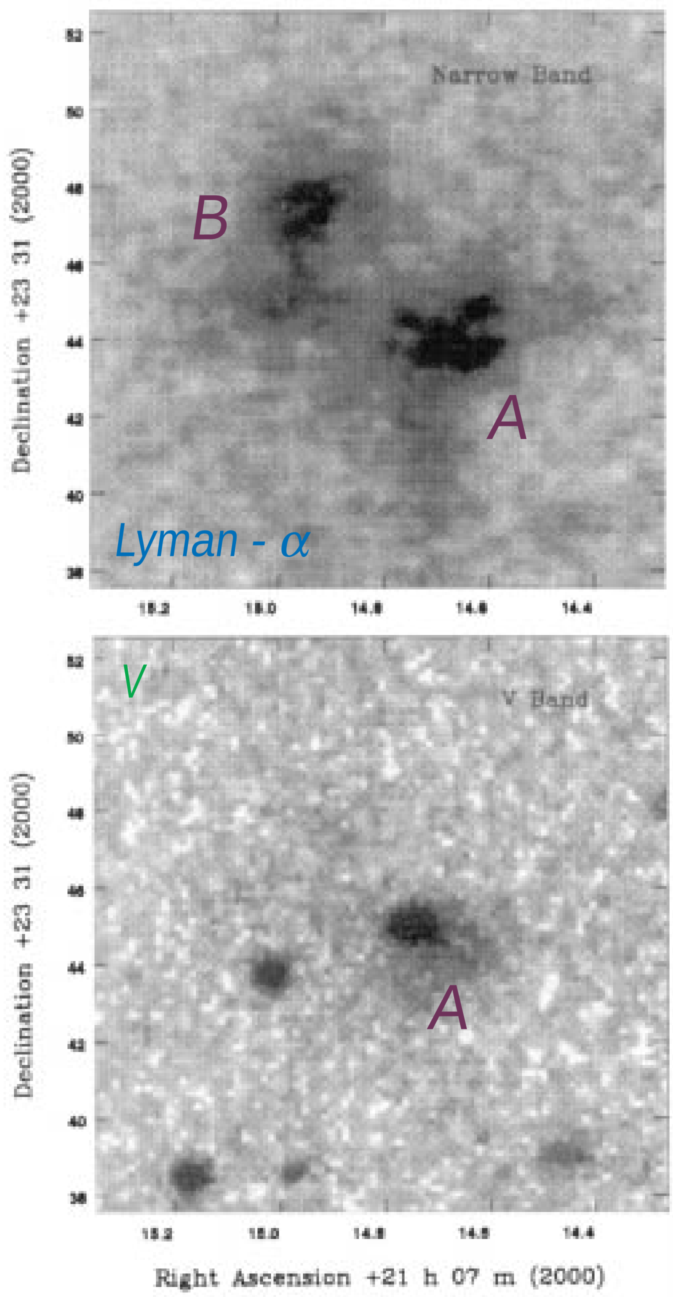
Redshift two and a half

A Keck spectropolarimetry programme to look for stellar and interstellar lines and identify scattering diagnostics around 2000Å in the rest-frame

So far, we have observed:

4C 23.56, z = 2.479, V = 22.4

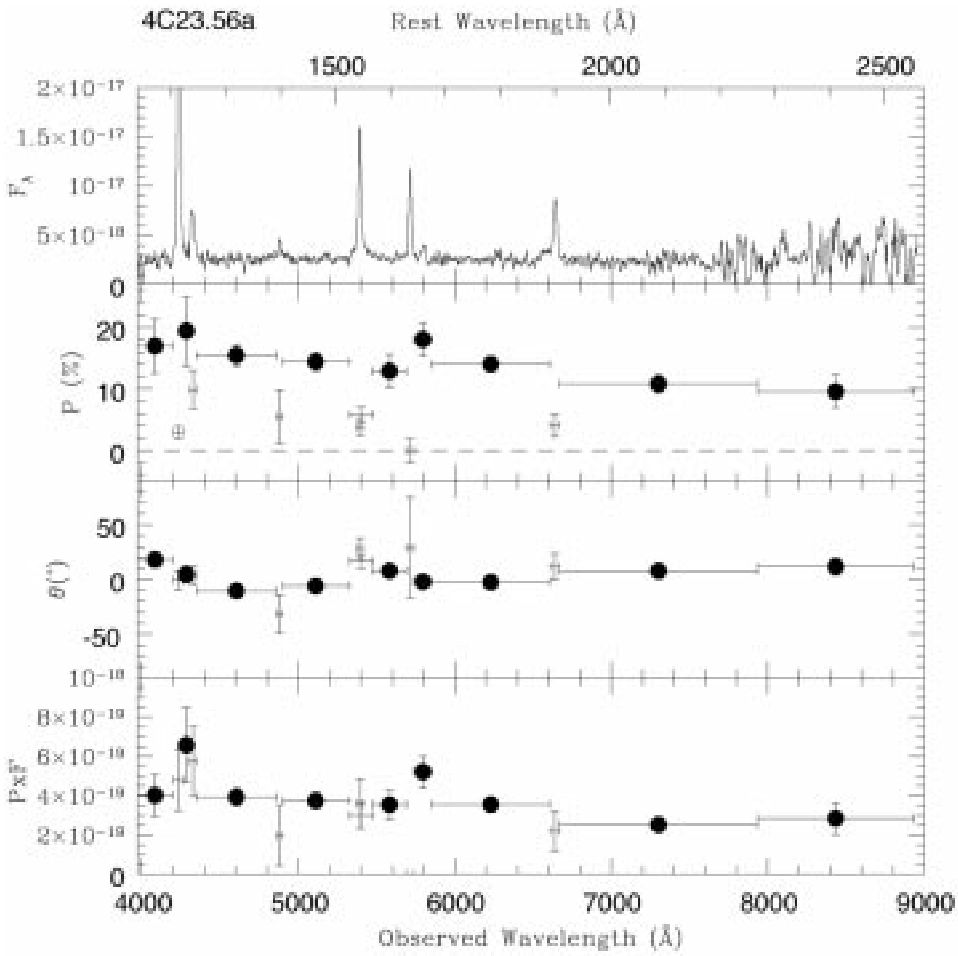
4C 00.54, z = 2.359, R = 22.6



4C 23.56, Knopp & Chambers 1997

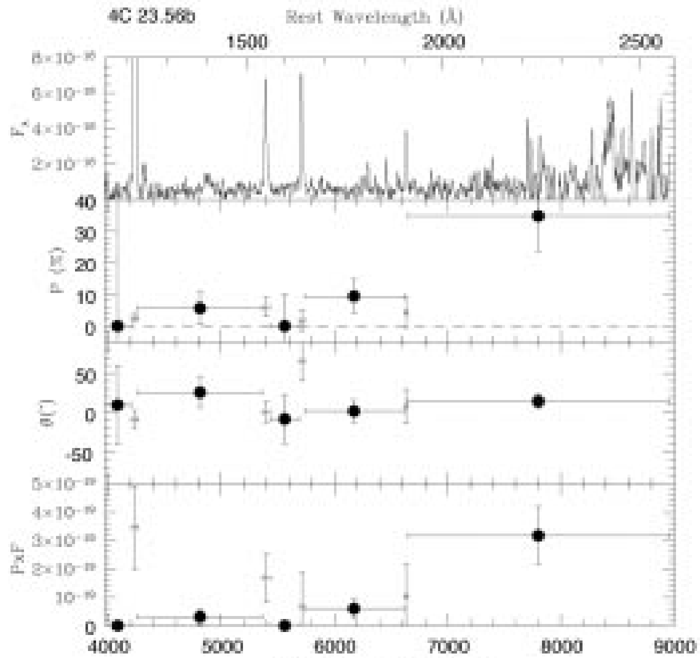
Biconical structure in Ly-α with component A having the brighter continuum.

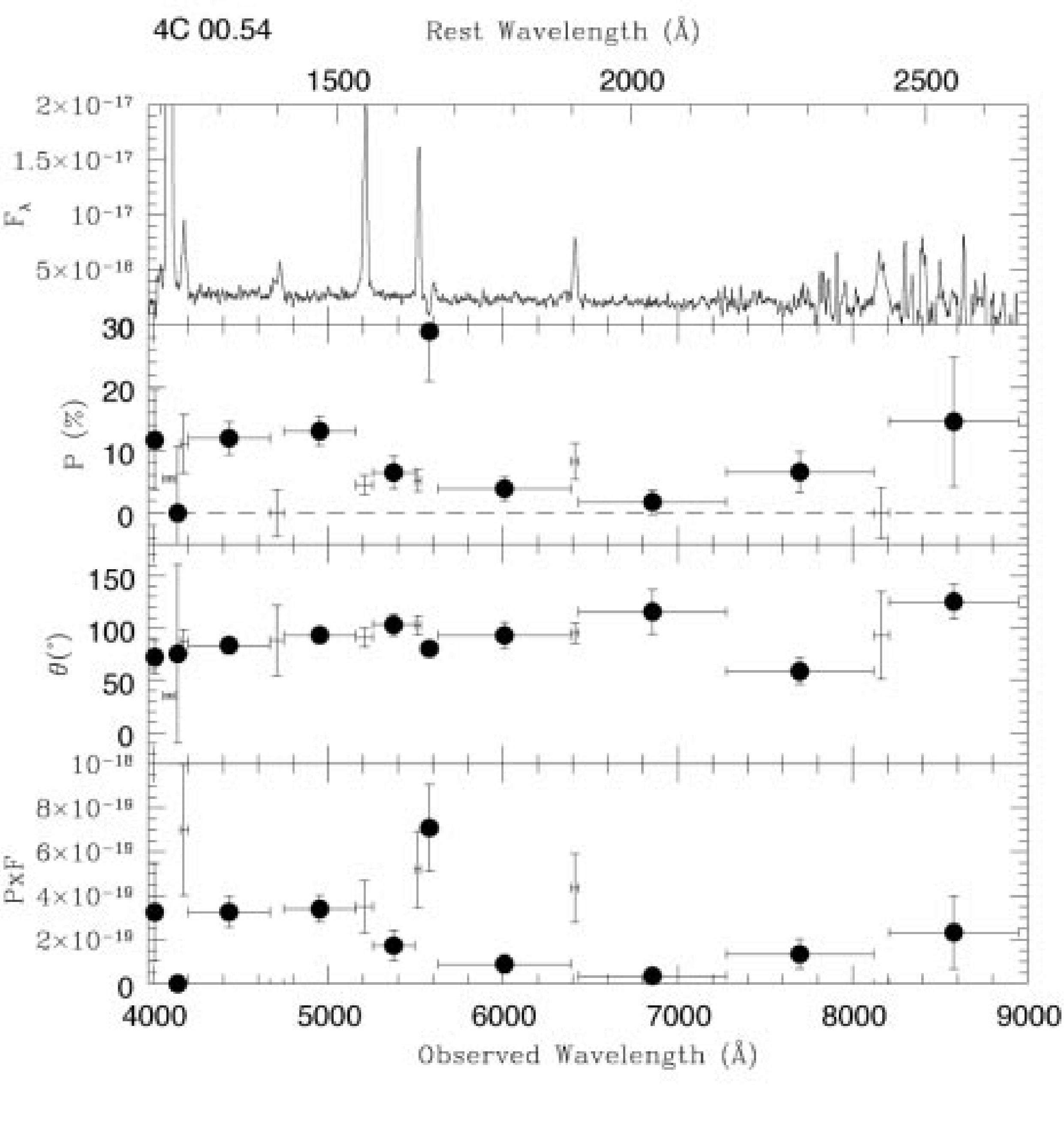
In addition to the polarimetry, we have developed emission line diagnostics (Villar-Martin et al. 1996, 1997) which tell us about the ionization mechanism, dust distribution, illumination geometry and chemical composition.



Polarization rising from 10% in the red to nearly 20% in the blue (around Ly-α) in component A

Component B is too faint to get a good measure of continuum polarization





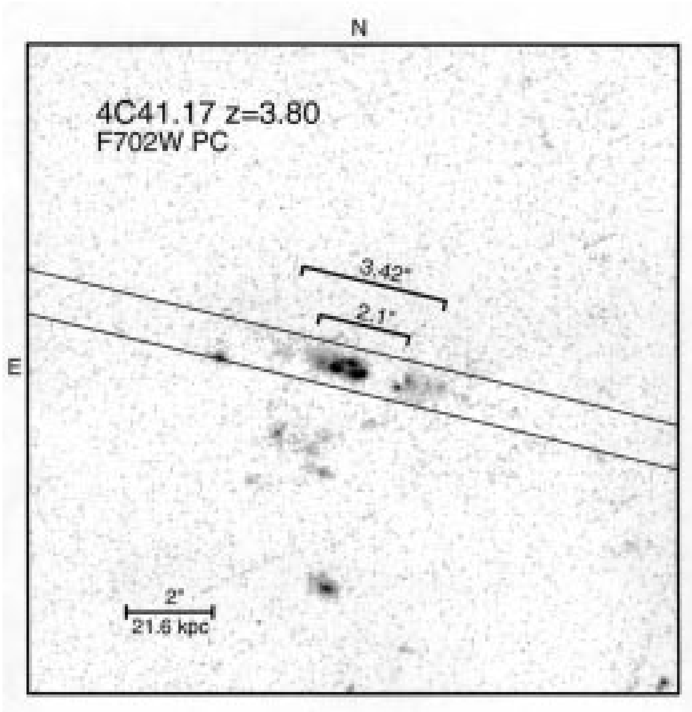
4C 00.54

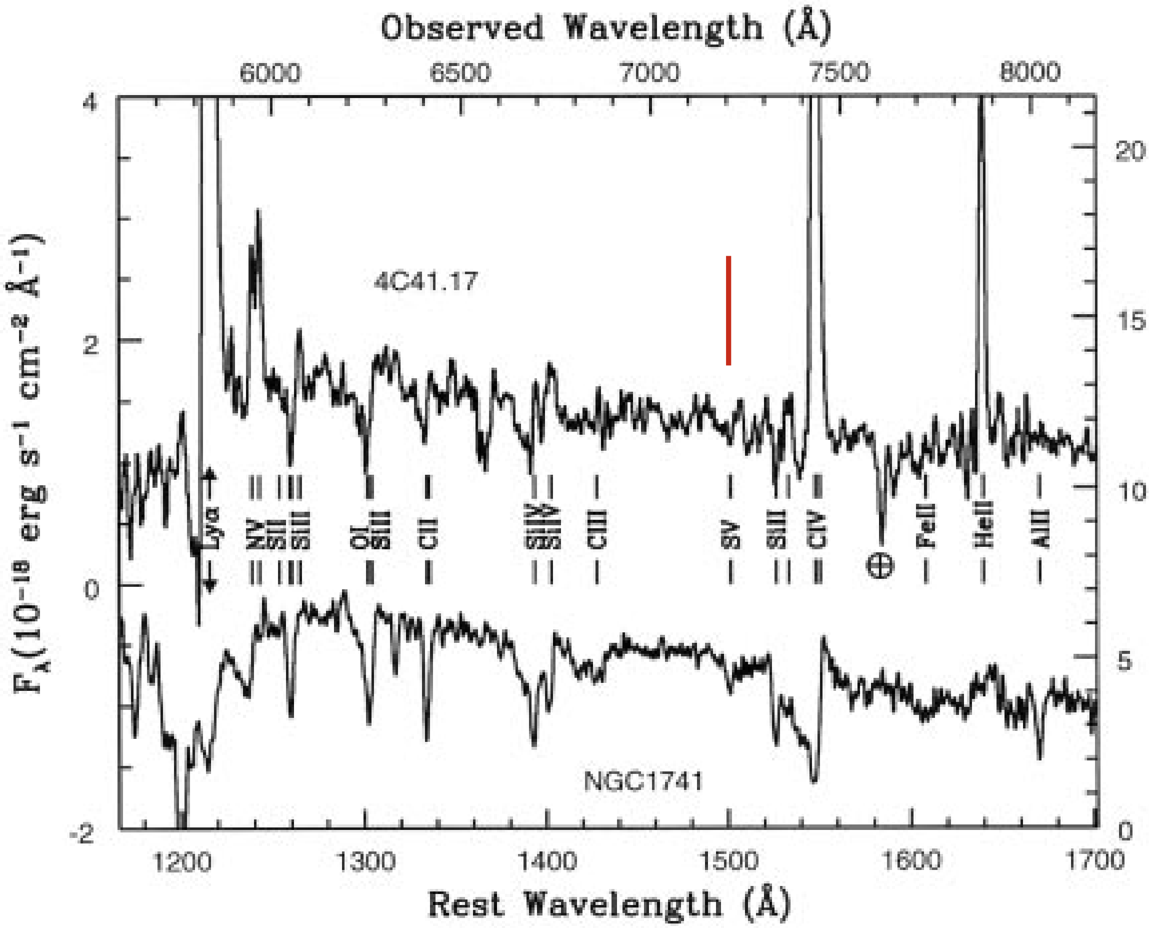
Polarization rising to 10% in the blue (around Ly-α)

Redshift four

The case of 4C 41.17 (Dey et al. 1997)

No detectable polarization ($P_{2\sigma}$ < 2.4%) but detection of a stellar photospheric line from OB stars. If all UV emission is from stars, the implied formation rate is 140–1100 h^{-2}_{50} M_o yr^{-1}





Summary so far

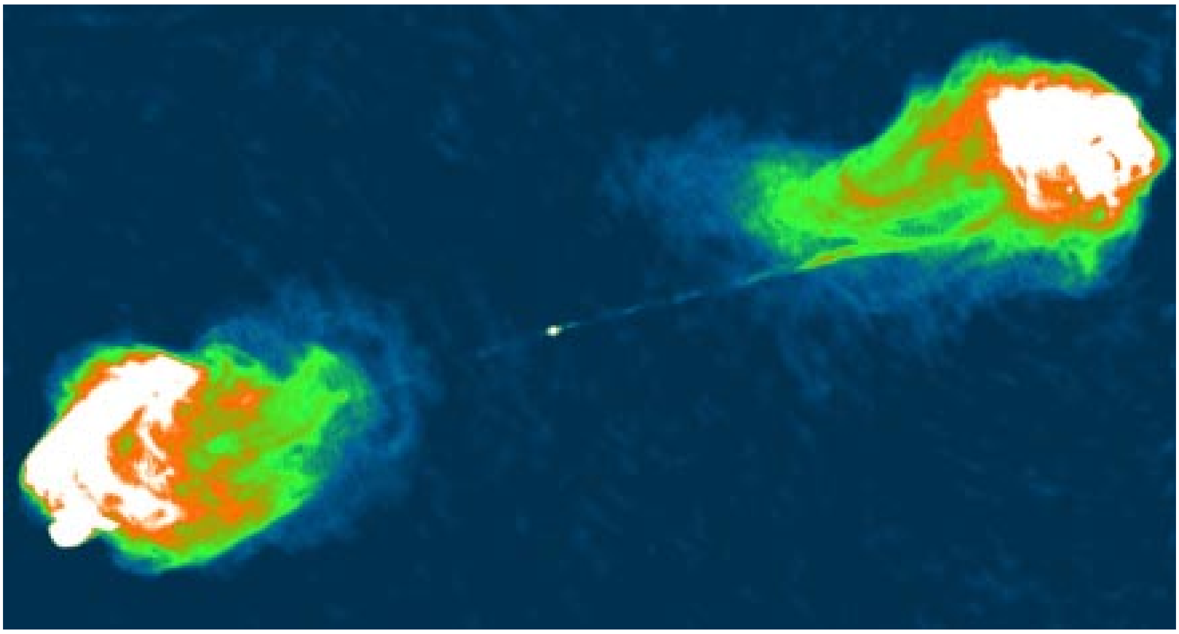
Below the H & K break, there are several contributors to the extended blue light in radio galaxies. A scattered AGN is often, but not always, revealed by polarization.

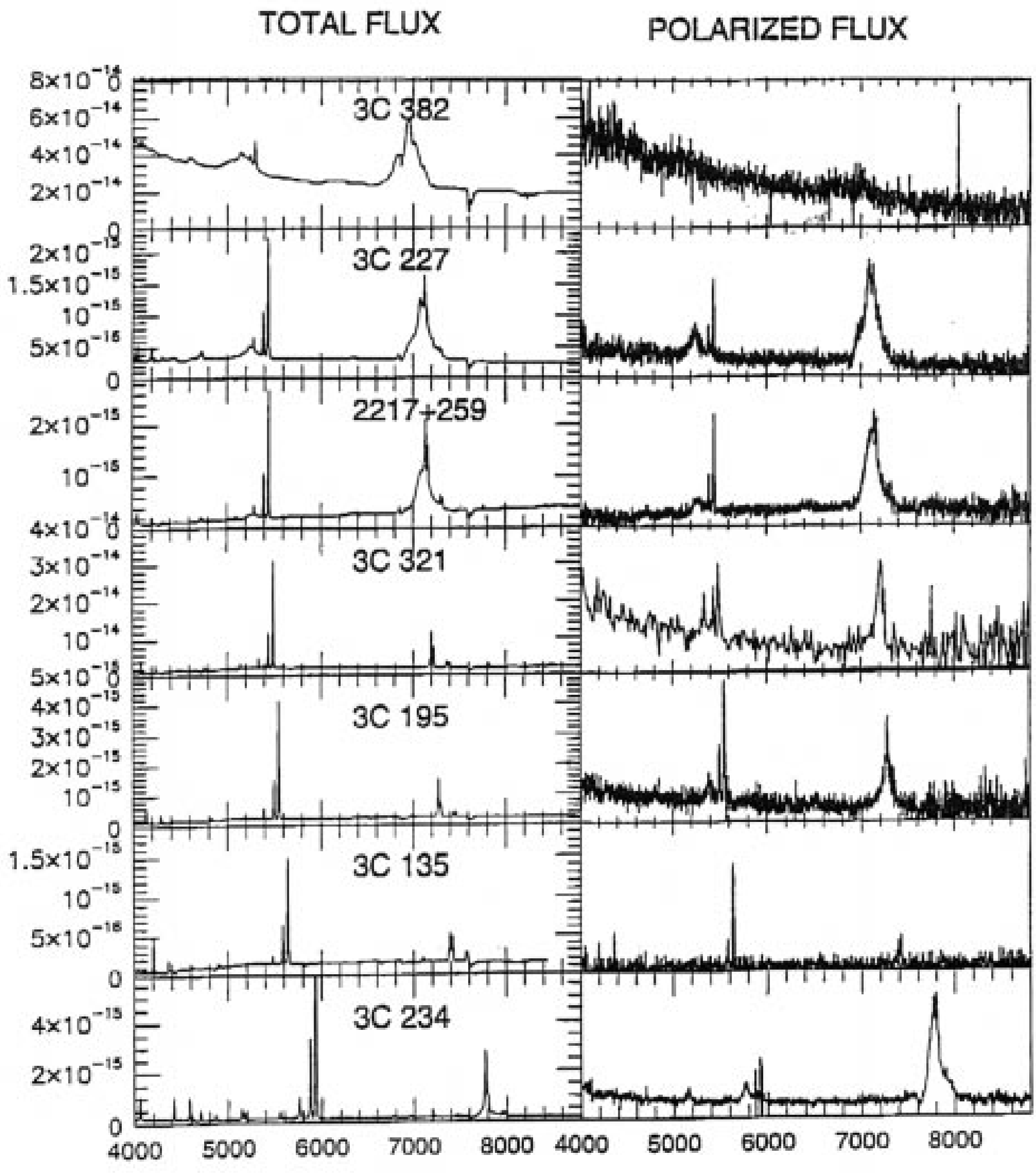
The redshift 2.5 objects seem to be similar to the redshift 1 galaxies but the one object observed at redshift 4 is aligned but unpolarized and most of the UV continuum appears to come from hot stars. It looks like the starbursting galaxies found recently at redshifts 2-3.

It is too early to build a picture from so few objects but we may be seeing the epoch of vigorous star formation in these massive galaxies above z ~ 3.5. As the blue stellar light fades, the AGN reveals itself by scattering from the dust produced by these early stars.

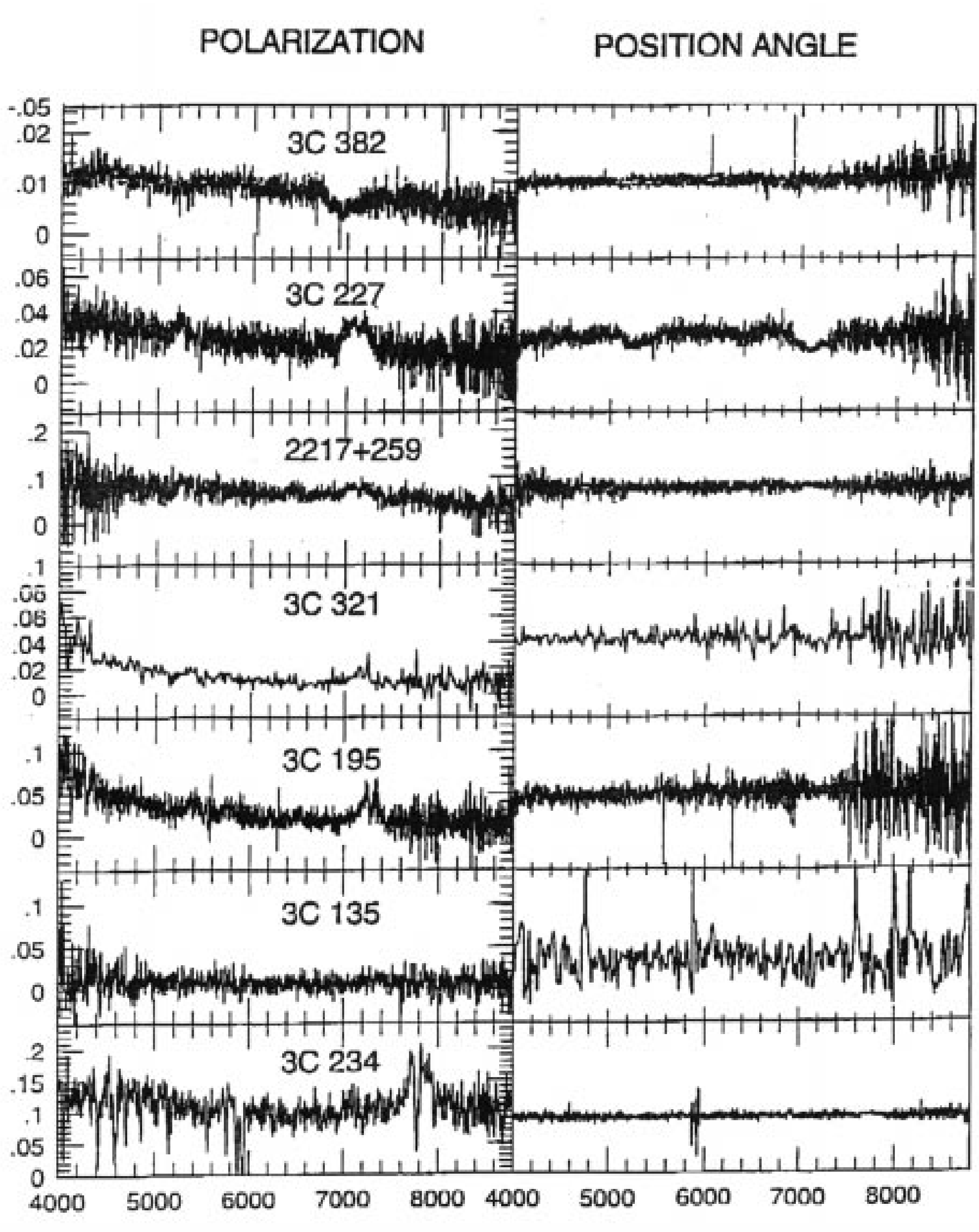
Below z ~ 0.7, the FR II radio galaxies are generally not found in rich cluster environments and the alignment effect is less obvious — as well as being harder to detect at rest-frame optical wavelengths (McCarthy priv. comm.)

With this picture of the distant, powerful radio galaxies, we can take a fresh look at our near neighbour, Cygnus A and see if the picture holds up in detail.

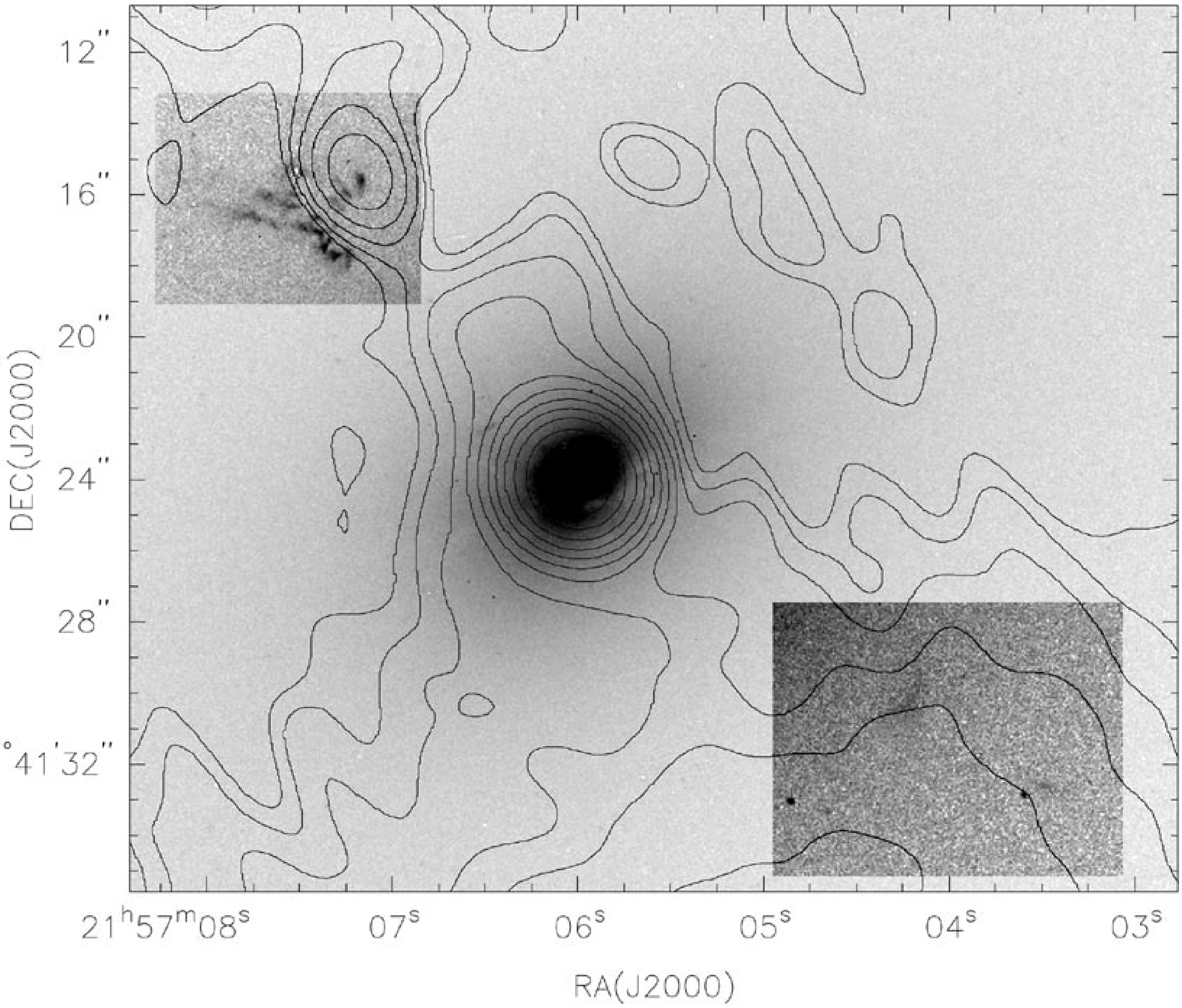




Keck spectropolarimetry of low z RG. Cohen et al.



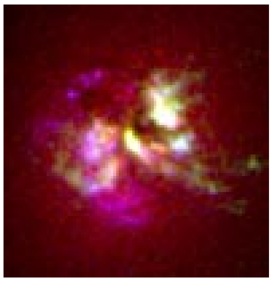
Keck spectropolarimetry of low z RG. Cohen et al.



Jet-cloud interaction in PKS 2152-699, HST (PC 2, F606W) and ATCA (6cm) data.

Fosbury et al. 1998

Reverse engineering Cygnus A



Bob Fosbury, Joel Vernet, Montse Villar-Martin, Patrick Ogle, Marshall Cohen, Joseph Miller, Hien Tran & Bob Goodrich

(with thanks to Richard Hook)

We use Keck imaging- and spectro-polarimetry interpreted with the help of HST WFPC 2 filter imaging (from the public archive).

The purpose is to dissemble Cygnus A into its (optical) component parts and see how the pieces can be used to build high redshift radio galaxies.

Observations

Imaging polarimetry with LRIS on Keck II in October 1996 (Ap J, 482, L37) B-band, 1hr.

Also LRIS spectropolarimetry, 1 arcsec slit in PA 101°, 3600 – 9000Å, 2.2hr.

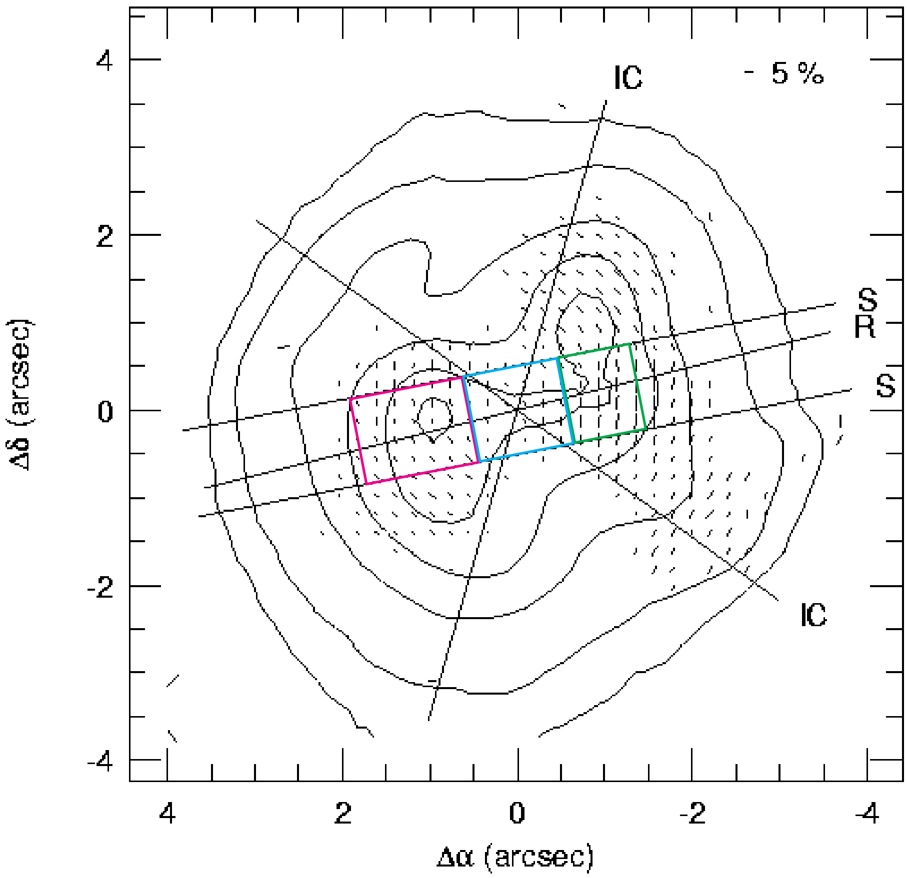
HST, WFPC 2 images in 450W, 550W, 622W, 814W and narrow [OIII], Hα and [OI] (from a program by Neal Jackson — data now in the public archive).

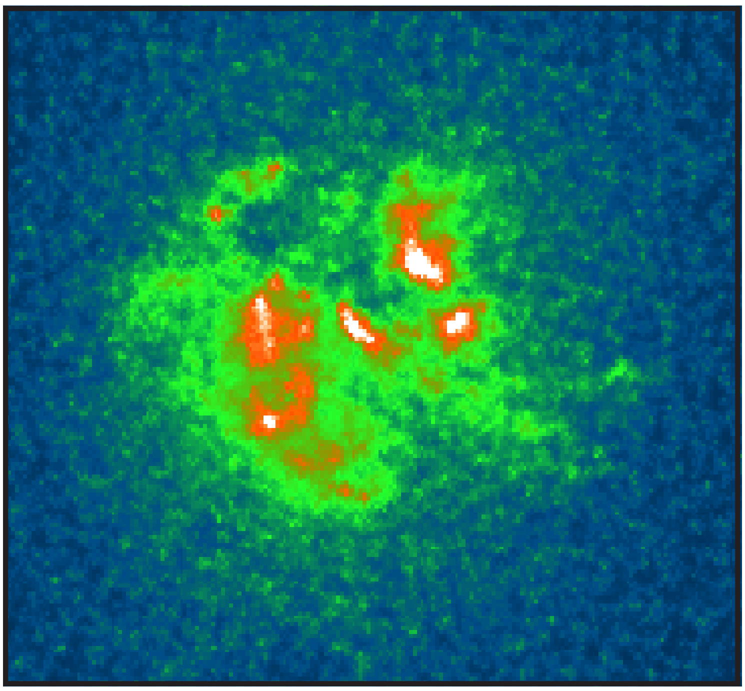
The HST 450W and Keck B-band images were combined using the Lucy-Hook iterative coaddition code to give a high s/n, high resolution B image. This extra signal adds significantly to the value of the HST imaging.

Imaging polarimetry

Peak polarization 10.8 ± 0.8% in the west.

Centro-symmetric pattern following the 55° half-angle bicone seen in the HST images.





Lucy-Hook coaddition of HST 450W and Keck B images (Tran & Hook, 1996)

Spectropolarimetry

Spectra corrected for Galactic reddening with E(B-V) = 0.5

Elliptical galaxy template (NGC 821) subtracted (70% of the observed flux at 5500Å in a 7.6 arcsec slit length).

Component separations (1.3 E, 0.8 W, 1.1 Nuc (x 1 arcsec)).

subtracted Galaxy fraction (5500Å) = 64% ± 3% (east)
62% ± 3% (west)

Broad lines

Hα seen in total flux

FWHM = 26,000 km s^{-1}, 5 x 10^{-15} erg cm^{-2} s^{-1} (Gal. Ext. corr.)

Seen in east and west, weaker in Nucleus.

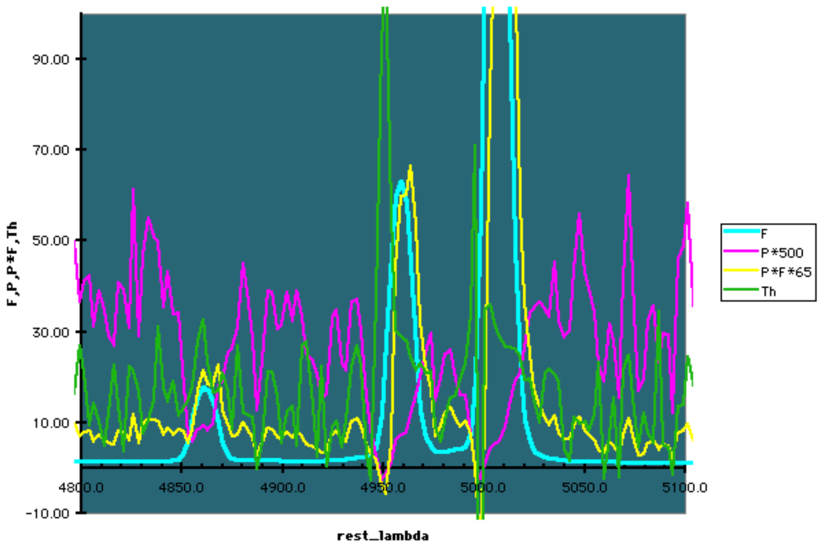
Hβ seen in polarized flux in west.

Narrow lines

P = 1.3% in PA 32° (total flux).

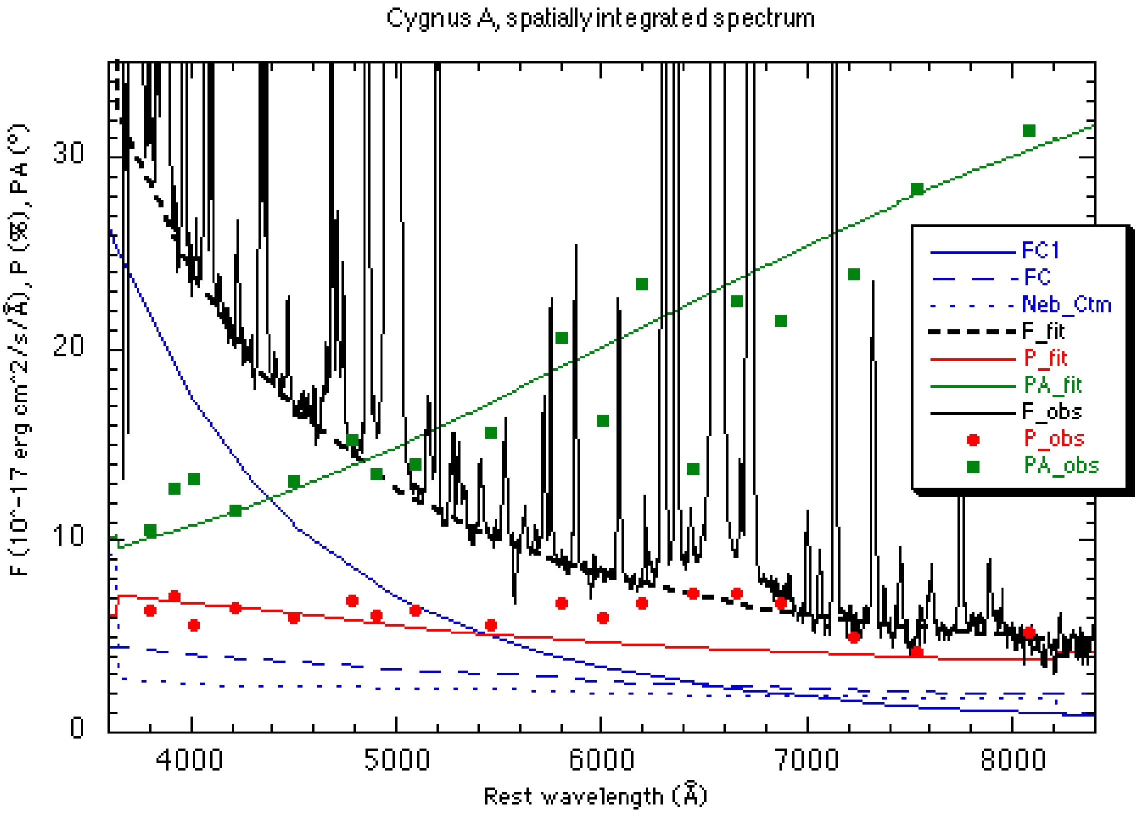
The narrow lines in polarized flux are redshifted by up to 230 km s^{-1} – greatest in the higher ionization lines.

Line spectra similar in east and west except for [Fe VII] and [Fe XI] which are stronger in the east. There is more line reddening in the east (where there is also a Balmer decrement anomaly — see later).



Continuum components

Analysis of the spatially integrated spectropolarimetry (slit length 7.6 arcsec, Ogle et al. 1997) suggests the presence of scattered AGN light (FC1), a second polarized continuum with a different E-vector PA (FC) and a nebular continuum.



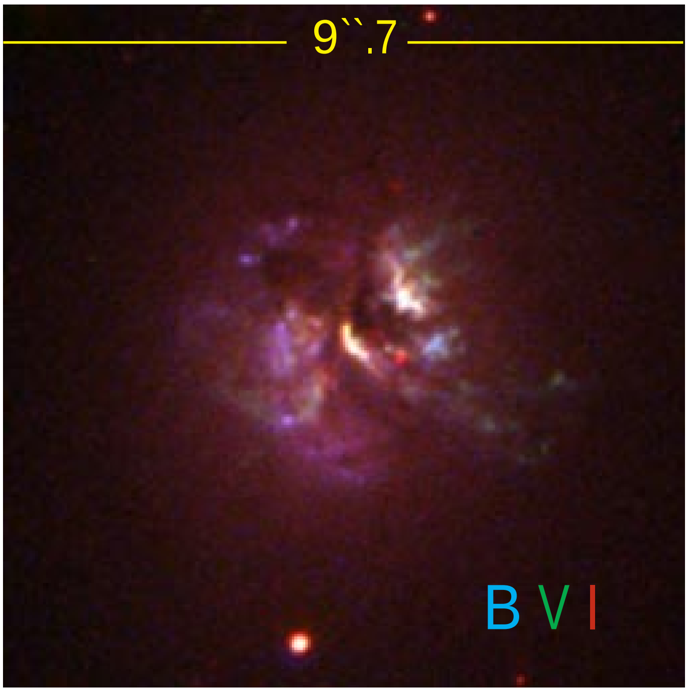
FC1 is relatively stronger in the west (forward scattering) while the continuum in the east is bluer and less polarized. This is consistent with the radio data which suggest that the western jet is closest to us.

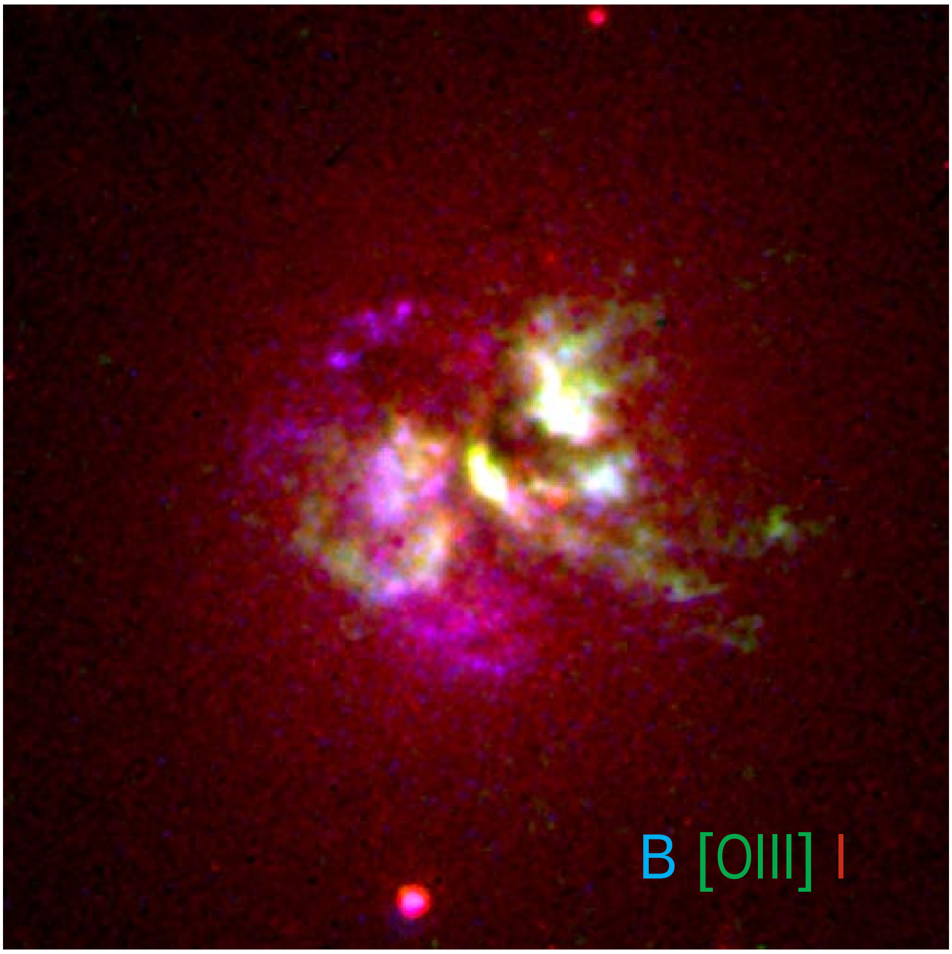
Fitting the eastern and western spectra

We have now attempted to build consistent fits to the eastern and western spectropolarimetry using the three continuum components used above. The key is provided by the HST images — which allow us to identify the spectral components with spatially distinct structures.

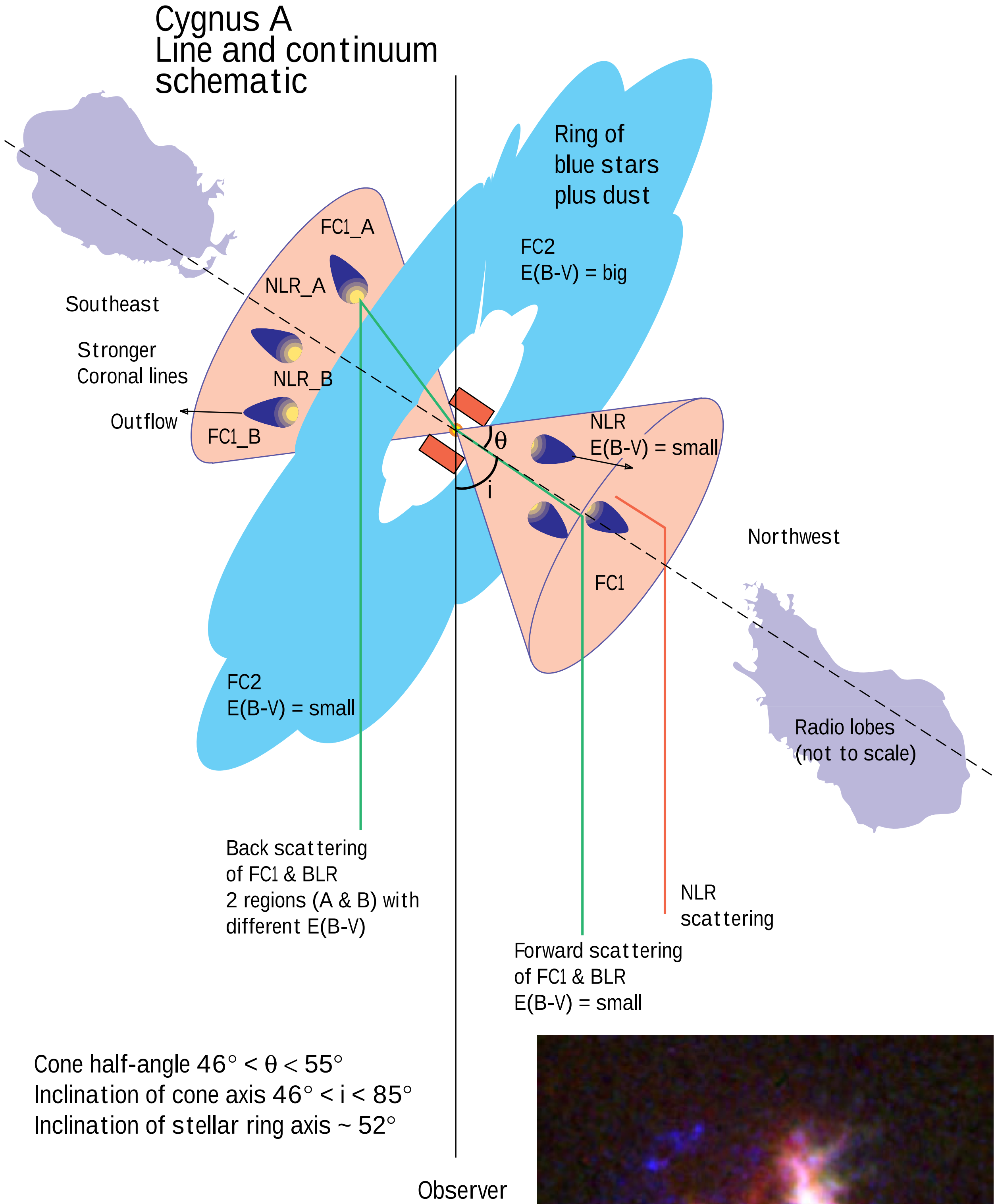
Which are the most informative HST images?

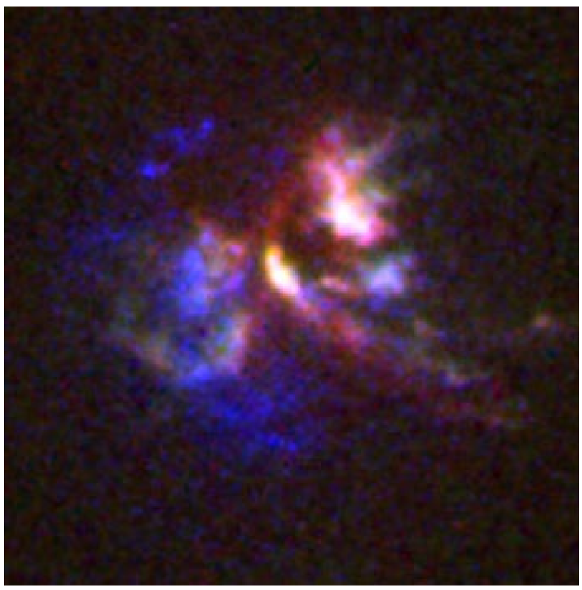
The broadband BVI or BRI images give a hint of what is going on — but the most interesting view is made by combining the B-band continuum (sensitive to young stars), the [OIII] line image (delineating the AGN-ionized gas) and the I-band continuum (which shows the elliptical component)





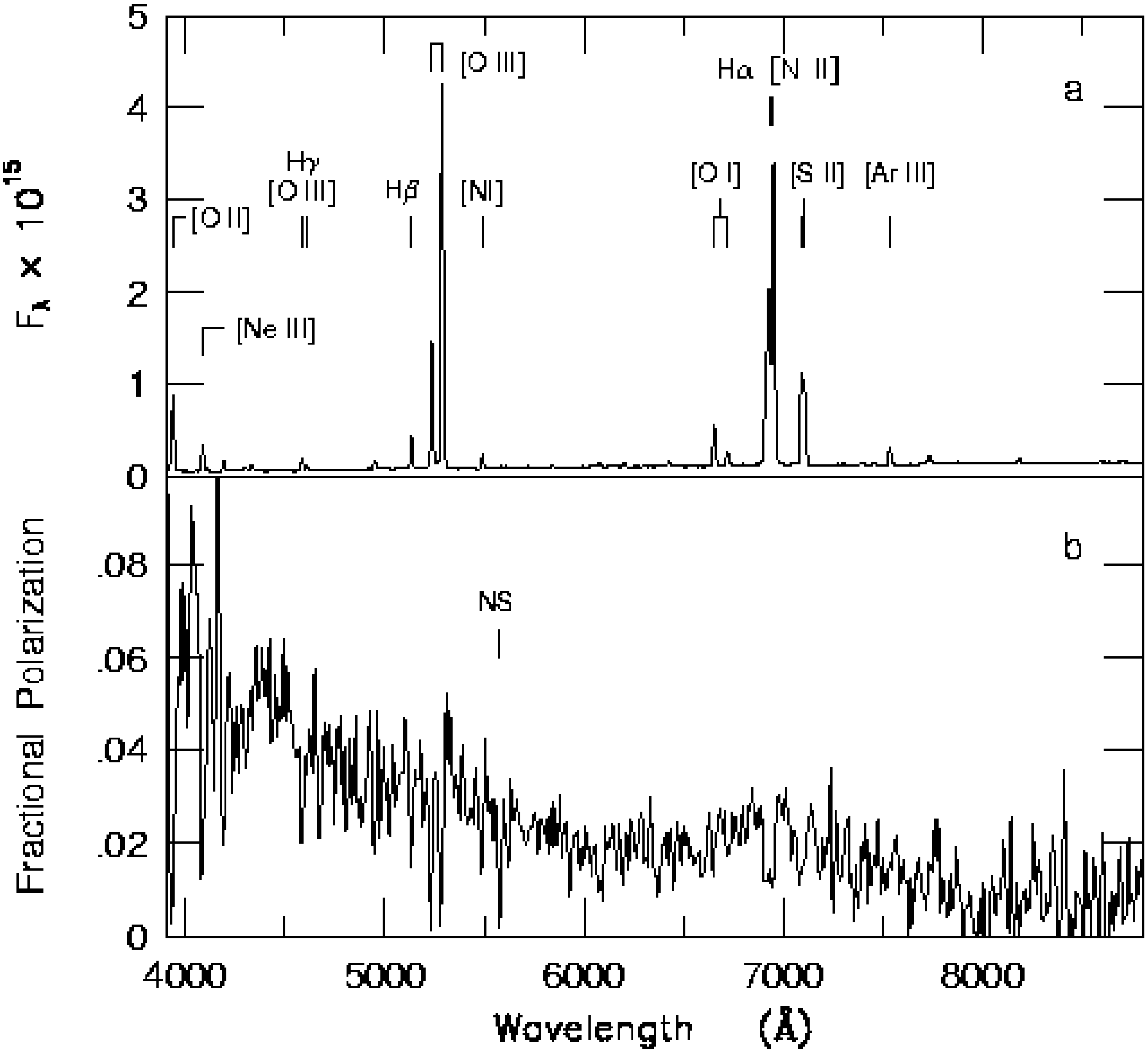
It is clear that the blue continuum in the east is not restricted to the ionization bicone. This suggests that it is blue starlight (as favoured by Stockton & Ridgway)





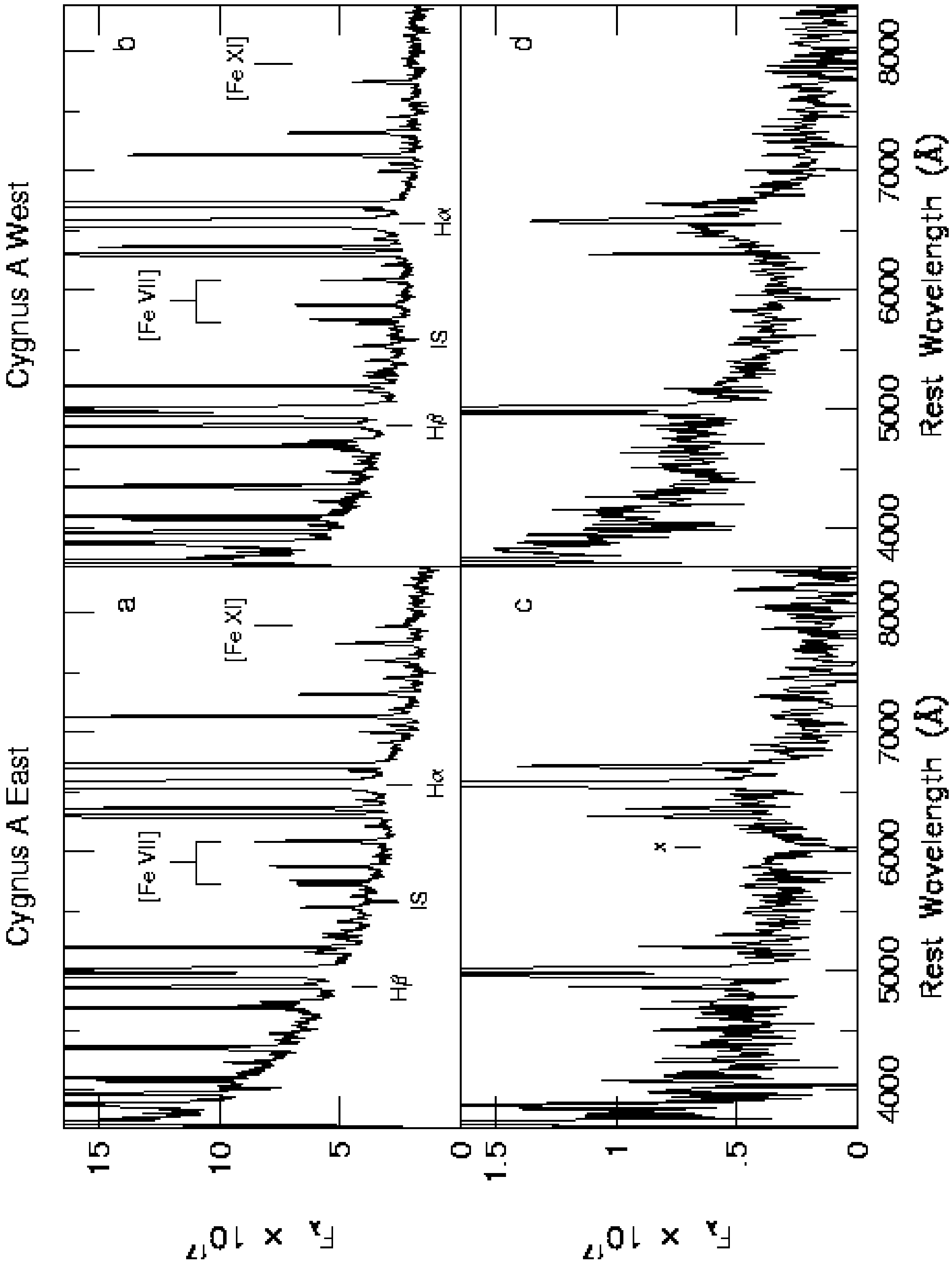
Bob Fosbury ST–ECF

Spatially integrated spectrum (1 x 7``.6)



Total flux and fractional polarization spectra *<u>before</u>* *subtraction of elliptical template.*

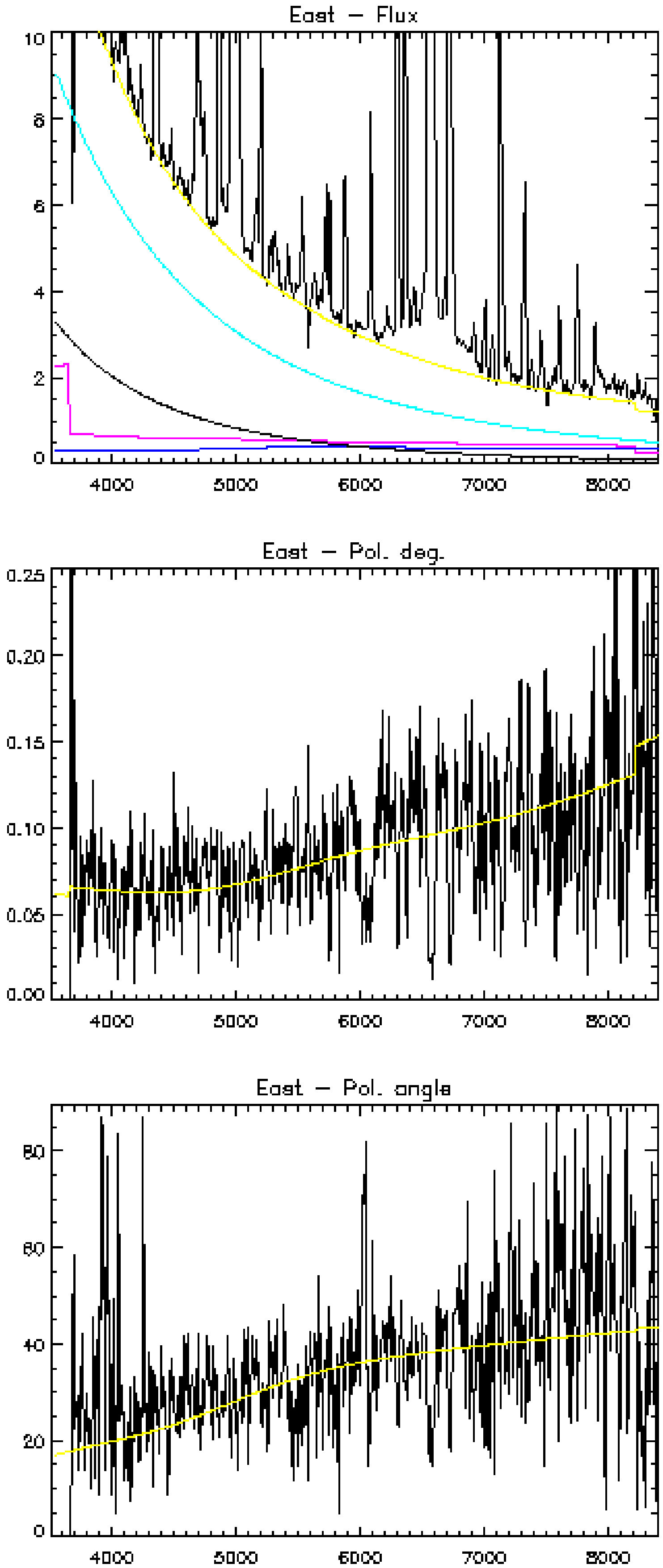
Eastern and western spectra



Continuum fitting — east

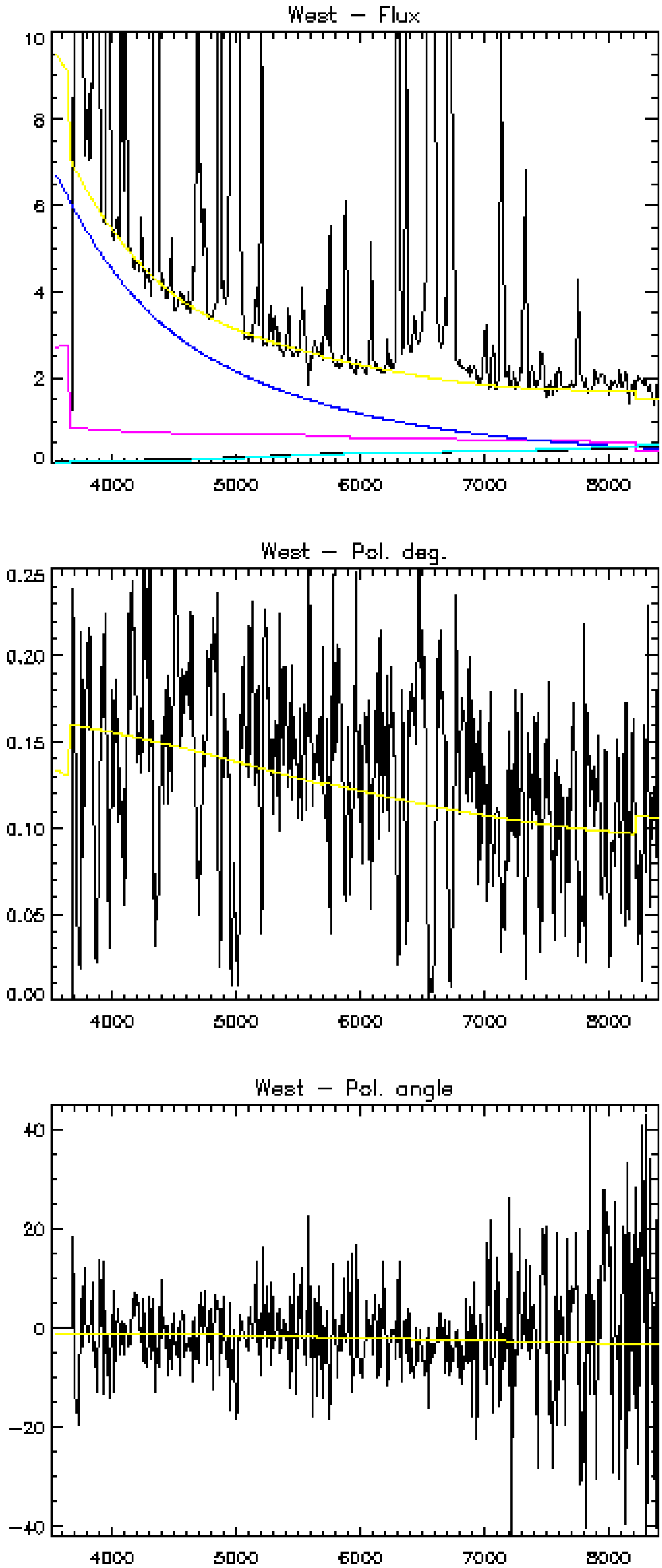
FC2 -> BB @ 25,000K

FC1 -> Power law, ν^{+2}



Comp.	P(%)	PA(°)	$F/F_{tot\_H\alpha}$	E_{B-V}
$FC1_A$	50	48	0.20	1.2
$FC1_B$	25	12	0.15	0
FC2	0	-	0.65	0

Continuum fitting — west

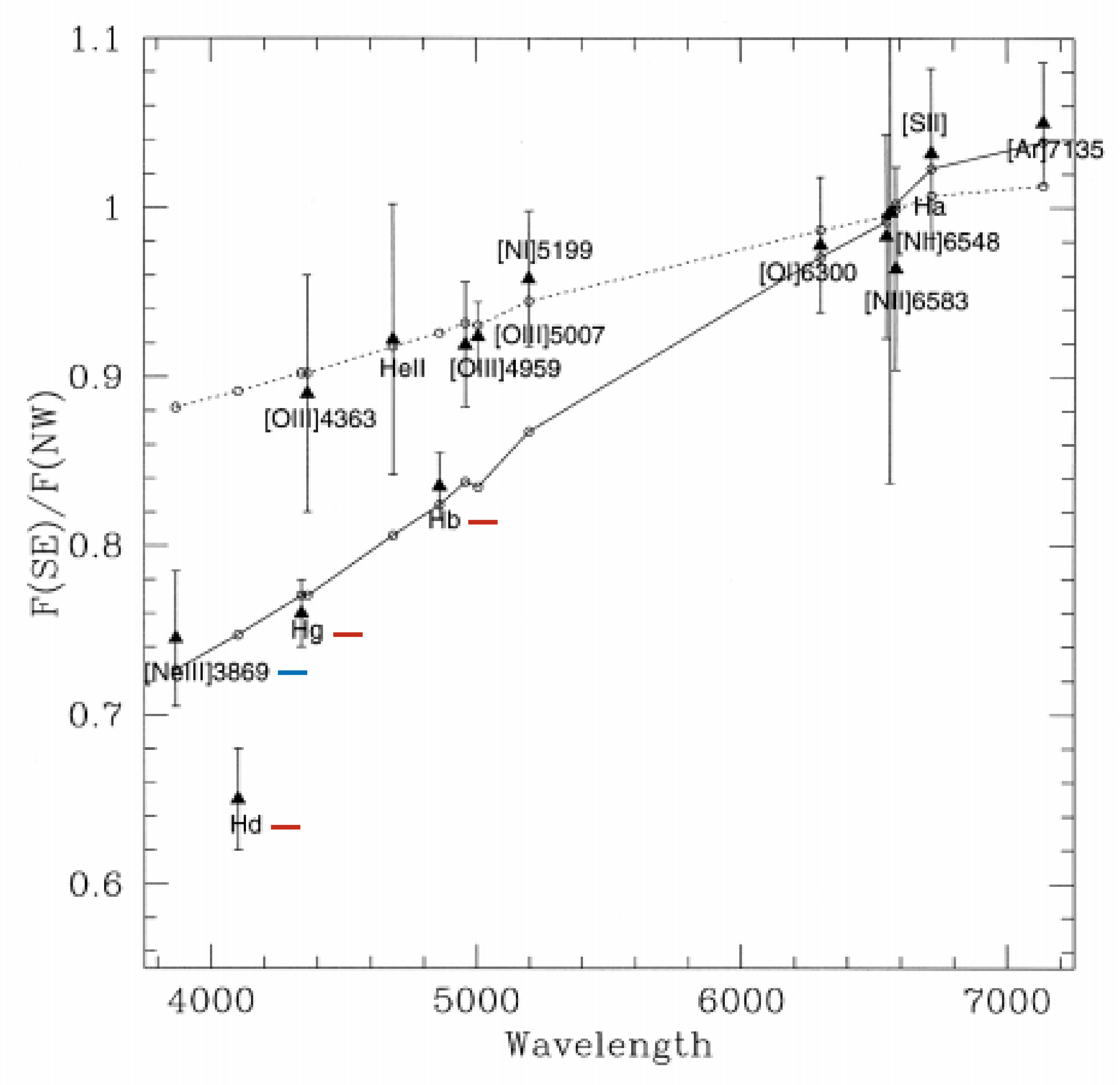


FC2 -> BB @ 25,000K

FC1 -> Power law, ν^{+2}

Comp.	P(%)	PA(°)	$F/F_{tot\_H\alpha}$	E_{B-V}
$FC1_A$	18	-1	0.60	0.18
$FC1_B$	20	-5	0.20	1.8
FC2	2	0	0.20	1.8

Emission line reddening



Most line ratios are very similar in the eastern and western regions.

A plot of the ratio of E/W intensities shows, however, the extra line reddening in the east. The Balmer lines and the blue [NeIII] lines do not follow the trend shown by the other lines ($\Delta E(B-V) = 0.07$). The Balmer anomaly can be due to the underlying Balmer absorption in the stars responsible for FC2 in the east.

Conclusions (Cygnus A)

The optically emitting components of Cygnus A comprise:

A dust-scattered AGN continuum from a quasar (BLRG) of modest luminosity and confined to an ionization bicone. This FC1 is highly polarized (locally up to P~50%) with the E-vector perpendicular to the line connecting it to the nucleus. Its spectral index $\alpha \sim +2$. Reddening differences suggest that the western cone is on the nearside.

Blue stellar continuum ('FC2') from a population of young stars (represented by $T_{eff.} = 25,000$K in our fits) with a low or zero polarization. This is unreddened in the east and significantly obscured in the west. This, together with the HST images, suggests the stars reside in a dusty equatorial ring with a diameter of around 5kpc and an axis coinciding with the radio and ionization cone axes. The starlight avoids the region of the radio jets — they are orthogonal.

Nebular continuum associated with the regions emitting the NLR

Polarized (dust scattered) broad permitted lines — Hα and Hβ in our data, Mg II in the HST spectroscopy of Antonucci, Hurt & Kinney (1994).

Narrow emission lines emitted mostly within the ionization cones (some low ionization lines associated with the extended dust). These are more reddened in the east and are weakly polarized in a manner suggestive of scattering in an outflowing wind.

We see all of these components in HzRG. How common is this geometrical configuration with an equatorial stellar ring? It seems to be common amongst the low z Seyferts. The balance between the FC1 and FC2 luminosity clearly varies from object to object and might be expected to evolve in a particular object.