



Universiteit
Leiden
The Netherlands

High redshift radio galaxies and the alignment effect

Chambers, K.C.; Miley, G.K.

Citation

Chambers, K. C., & Miley, G. K. (1990). High redshift radio galaxies and the alignment effect. Retrieved from <https://hdl.handle.net/1887/6584>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/6584>

Note: To cite this publication please use the final published version (if applicable).

HIGH REDSHIFT RADIO GALAXIES AND THE ALIGNMENT EFFECT

K.C. Chambers

The Space Telescope Science Institute and The Johns Hopkins University, 3700
San Martin Dr., Baltimore, MD, 21218

G. K. Miley

Sterrewacht, Postbus 9513, 2300RA, Leiden, The Netherlands

ABSTRACT We have identified a portion of a sample of 4C radio sources selected for their ultra-steep radio spectrum. Most are at high redshift, including the most distant galaxy known, 4C41.17 at $z = 3.8$. The extended optical/infrared continuum of high redshift radio galaxies is generally aligned along the radio axis. The spectral energy distributions can be nearly flat (f_ν) in the rest frame ultraviolet, but rise significantly into the red. While the nature of the optical/infrared continuum is controversial, it is likely that aligned radio galaxies are dominated by starlight, and that at early epochs powerful radio sources were capable of stimulating vast amounts of star formation.

INTRODUCTION

To our eyes, the few hundred brightest objects in the night sky are all nearby stars. At radio frequencies, the few hundred brightest objects in the sky include objects so distant that we are observing them when the universe was a fraction of its present age. In a classic conspiracy of nature, the luminosity function of radio sources falls off with a slope nearly equal to the rise in volume sampled in a Euclidian universe. So, contrary to intuition, the observed radio flux of an object tells us almost nothing about its distance. A source of 1 or 2 Jy's at 178 MHz can be anywhere in the universe. This is a measure of both the power and the handicap of radio surveys for finding distant galaxies. Therefore it is desirable to develop techniques for pre-selecting the best candidates from the large number of radio sources which become available as we push to fainter and fainter flux limits.

We have developed such a method based on the observed correlation between the radio spectra and luminosities of radio sources. Many authors have remarked on such a possible correlation (e.g. Heeschen, 1960, Veron *et al.* 1972, Macleod and Doherty, 1972, Bridle *et al.* 1972), but the most striking manifestation of this correlation was found as the byproduct of an investigation of a sample of 4C radio sources having ultra-steep spectra (Tielens *et al.* 1978). It was found that the fraction of radio sources which had counterparts on the Palomar Sky Survey was a strong function of the radio spectral index, with almost no identifications for the steepest spectrum sources (Blumenthal and Miley 1979). See Figure 1. On the reasonable assumption that the unidentified ultra-steep spectrum radio sources were distant

galaxies, fainter than the Survey limits, we began a multi-spectral investigation (Chambers, Miley, and van Breugel, 1987, Chambers, 1989) with the most sensitive instrumentation now available, of the ultra-steep spectrum radio source sample of Tielens et al. This comprised 4C sources known to have spectral indices of $\alpha < -1$, between 178 and 5000 MHz, where $S_\nu = k\nu^\alpha$.

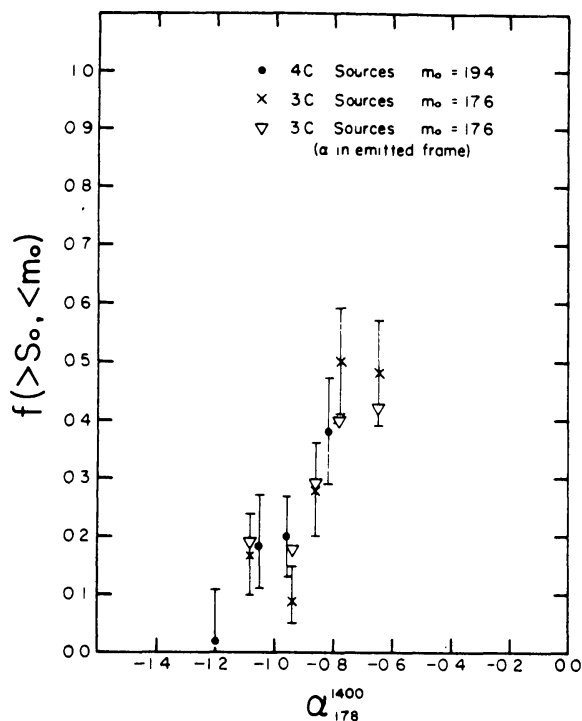


Figure 1: The fraction of radio sources optically identified on the Palomar Sky Survey plotted against the observed metre-wave radio spectral index (from Blumenthal and Miley, 1979).

BACKGROUND

The study of high redshift radio galaxies is currently undergoing a dramatic growth, due in part to new technologies and new techniques which have led to surprising discoveries. With the advent of CCDs in the optical, InSb arrays in the infrared, the high sensitivity and dynamic range of the VLA in the radio region of the spectrum, as well as the software to obtain the optimum performance of these instruments, our ability to identify and study these distant stellar systems has increased dramatically. Previous work on distant radio galaxies has centered on various complete samples from flux-limited surveys, e.g. the 3CR sample of sources with $S_{178} > 10Jy$ (Laing, Riley and Longair, 1983) the "1 Jy" sample (Allington-Smith 1982, Lilly 1988a, 1989, this conference), and the LBDS sub-millijansky sources (Windhorst *et al.* 1985, this conference). Reviews on identifications and optical/infrared properties of high redshift radio galaxies prior to use of the ultra-steep spectrum technique and before the discovery of the alignment effect are given by Spinrad (1986), and Longair and Lilly (1985). Begelman, Blandford, and Rees (1984) reviewed the theory of extragalactic radio sources, Miley (1980) has reviewed the radio observations, and Bridle and Perley (1984) reviewed the situation for radio jets.

The 3CR sample is unique in that it is now nearly completely identified, and the years of investigation of these objects by Spinrad and collaborators has resulted in the discovery of ~ 30 radio galaxies with redshifts larger than one (Spinrad *et al.* 1985; Spinrad 1987; Djorgovski *et al.* 1988; McCarthy 1989; Spinrad 1989, van Breugel, this conference). The most distant 3CR galaxy is the recently identified source 3C257 at $z = 2.474$ (Spinrad, private communication), the most distant "1 Jy" galaxy is 0902+34 at $z = 3.395$ (Lilly, 1988b), and the LBDS has discovered at one galaxy Herc 202 with $z = 2.39$ (Windhorst, this conference).

With the discovery of 4C41.17 and 0902+34 the infrared Hubble diagram has now been extended out to very high redshifts (Lilly, this conference). However, it must be emphasized that one should not discuss high redshift radio galaxies (or plot their infrared K magnitudes) without mentioning their most remarkable property: the alignment between their optical/infrared continua and their radio axes (Chambers *et al.* 1987, 1988b; McCarthy *et al.* 1987b). (See Figures 3, 4, and 5.) This phenomena has recently stimulated a number of observers and theorists to explain it, and we will review some of that work here. The alignment effect is important not only because of its intrinsic interest as new astrophysical phenomena, but also because understanding the alignment effect is crucial to any attempt to use radio galaxies for measuring cosmological constants. Previously, it could be assumed that the host galaxies were otherwise normal giant ellipticals whose properties were divorced from the powerful radio sources by which they were selected. And while there is surprisingly little evidence for a correlation between radio power and infrared luminosity (Lilly 1988a), an intimate relationship between the optical/infrared properties and the radio properties such as the alignment effect is an important clue to some sort of physical interaction.

ULTRA-STEEP SPECTRUM SURVEY

The current status of our 4C ultra-steep spectrum survey is encouraging. Out of 33 4C ultra-steep spectrum sources, we have obtained 31 optical identifications,

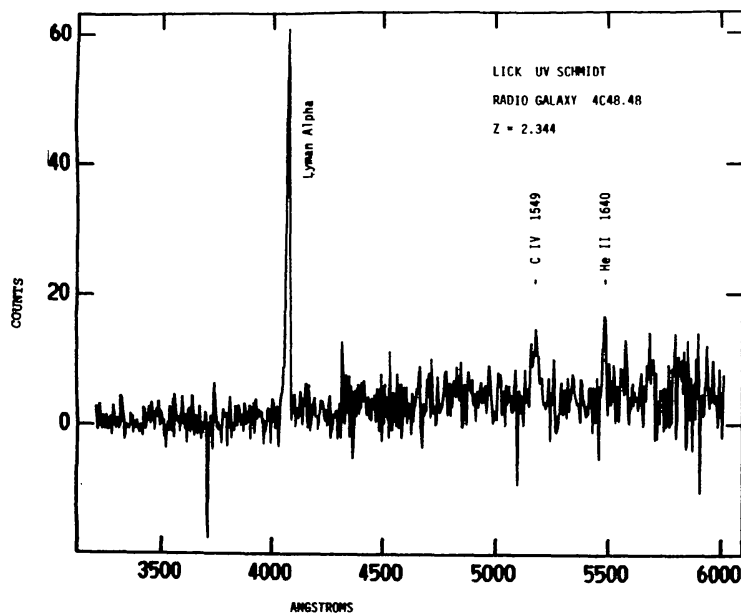


Figure 2. Spectrum of 4C48.48 at $z=2.344$

attempted optical spectroscopy of 32, have found 16 with strong emission lines and with $z > 0.5$, 8 of these with $z > 2$ including 4C40.36 at $z = 2.267$ (Chambers *et al.* 1988a) and 4C41.17, currently the most distant galaxy known, at $z = 3.800$ (Chambers *et al.*, 1989). In Figure 2 we present a spectrum of 4C48.48 at a redshift of 2.371. It has a strong Lyman α emission extended along the radio axis, CIV 1549, and HeII 1640, typical of the high redshift radio galaxies.

We are also currently extending our ultra-steep spectrum survey to fainter flux levels using sources from the Parkes, Texas, Molonglo, 6C, and 8C surveys (Miley *et al.* 1989).

THE ALIGNMENT EFFECT

There are several observational aspects of the alignment effect (Chambers *et al.* 1987, 1988b; McCarthy *et al.* 1987b) which need to be emphasized. First, we prefer to call the phenomena the "alignment effect" rather than a morphological correlation because the optical/infrared emission in general is *not* coincident with the radio lobes. Often the radio source is larger, sometimes much larger, than the optical/infrared continuum, but there are examples, e.g. 4C41.17, where the aligned continuum and/or emission line gas extends beyond the radio lobes. The failure to make this distinction has resulted in untenable explanations which require spatial coincidence between the radio emission and the optical/infrared emission. While the radio emitting regions and the optical/infrared emitting regions occasionally overlap, the crucial characteristic is that they have a common axis. (See Figure 3.) Second, although a

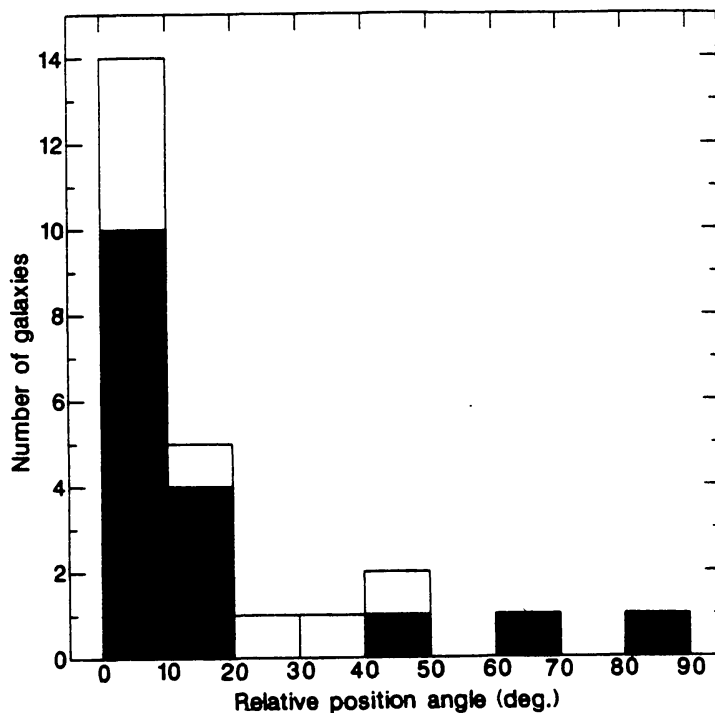


Figure 3. Histogram of the angle between the optical and radio axes in high redshift radio galaxies. From Chambers *et al.* 1987.

statistically significant phenomena, there are exceptions to the alignment effect. Some systems, even though they are reasonably elongated, are not well aligned with the

radio axis. This is worth keeping in mind, since some explanations would seemingly require no exceptions. Third, the alignment is seen both in the continuum and in strong extended emission lines, but the detailed morphology of the emission lines and the continuum often differ. Fourth, there appear to be small color gradients in the continuum of some objects, although contamination of the continuum by emission lines and different ways of displaying low signal-to-noise images can exaggerate these. But it is important to note that the infrared alignments (Chambers *et al.* 1988b, Eisenhardt and Chokshi 1989) have now been detected in enough objects that it is reasonable to conclude that in general the infrared morphologies resemble the optical morphologies. There are *no* observed counter-examples which support a popular conjecture that these objects are really nice round ellipticals in the red, and only aligned in the ultraviolet. Fifth, while there are exceptions, (e.g. 0902+34 van Breugel, this conference) the radio sources generally do not have peculiar morphology or polarization structure. In general they have the Fanaroff-Riley type II edge-brightened double morphology of normal powerful radio sources.

ALIGNED RADIO GALAXIES 3C368 AND 4C41.17

There is danger in assigning a prototype to any particular class of object, particularly if it is really an archetype, having certain characteristics to an extreme degree. Nonetheless, 3C368 has become the classic aligned radio galaxy (Djorgovski *et al.* 1987, Chambers *et al.* 1988b, LeFevre *et al.* 1988). It is worth noting however that because of its extreme elongation and relatively low redshift ($z = 1.132$) that it is not typical of aligned radio galaxies. In Figure 4 we show a VLA radio image overlaid with a 2.2 micron image to demonstrate the infrared alignment. This infrared image was one of the first deep images obtained with an InSb array and was not deep enough to detect the southern component that is visible in optical images. Techniques have improved dramatically in the last year, and deeper images are now possible.

The most distant stellar system known today is 4C41.17 at a redshift of $z = 3.800$ (Chambers, Miley, van Breugel, 1989). The radio source was mapped with the VLA as part of our ultra-steep spectrum survey, and identified with a faint extended optical object, whose spectrum showed two emission lines corresponding to Lyman α and CIV 1549 redshifted by $z = 3.800$. The Lyman alpha emission is elongated along the radio axis and includes an elliptical halo that extends more than 100 kpc, considerably beyond the radio source. It is clumpy and has a velocity dispersion of ~ 500 km/s, but with some gas in regions well correlated with the radio source having velocities at least as great as ~ 2000 km/s. The Lyman α has a rest frame equivalent width of (~ 270 Å). The optical and infrared continua have similar properties to those of other high-redshift radio galaxies, i.e. extended along the same axis as the radio source. In 4C41.17 however the continuum extends beyond the eastern radio lobe, although subsequent deep radio imaging has detected a diffuse very steep spectrum component to the northeast. In Figure 5 we show a radio image overlaid with the 2.2 micron image. In the rest frame this is roughly equivalent to a V band image, i.e., sampling the continuum longward of the 4000 Å break. The rest frame spectral energy distribution is roughly flat in the ultraviolet and exhibits a "red bump" longwards of 4000 Å (see Figure 6.) For more images of other aligned radio galaxies see McCarthy (1989), Lefevre *et al.* (1988a, 1988b, 1988c), and for infrared images, Eisenhardt and Chokshi (1989).

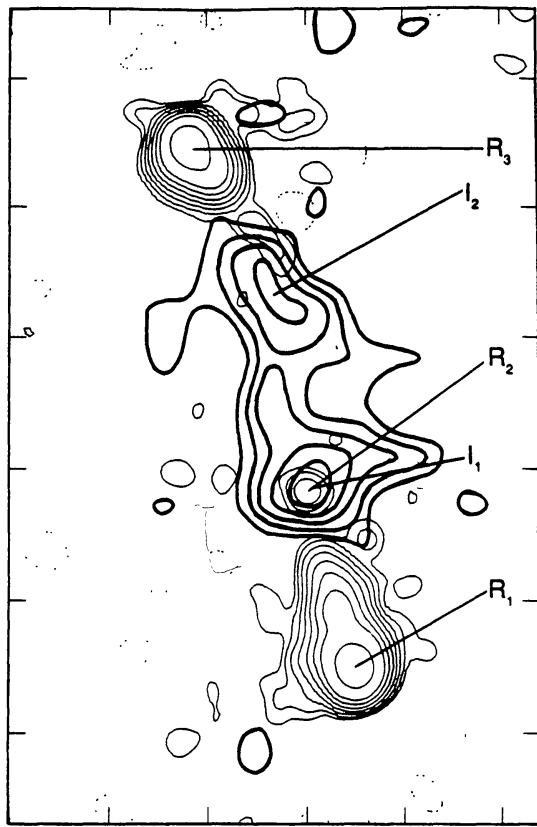


Figure 4. 3C368 K band image (dark contour) and VLA radio image (light contour). Adapted from Chambers et al. 1988b.

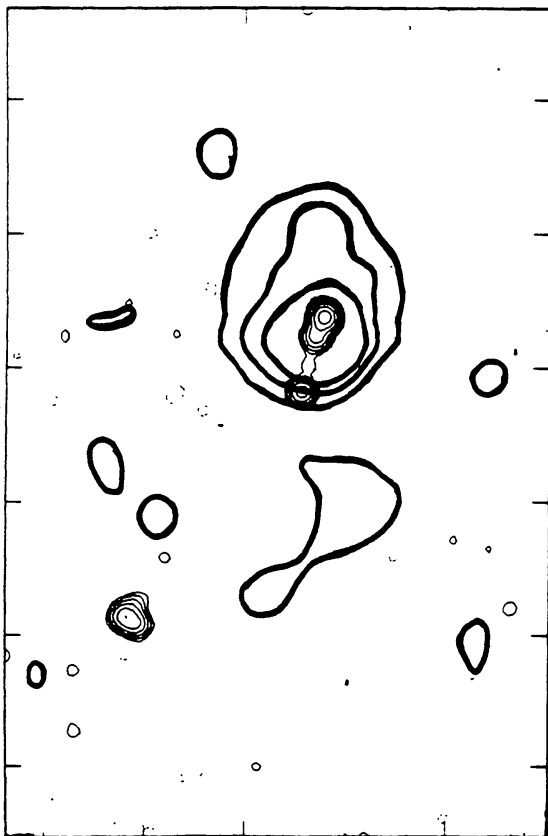


Figure 5. 4C41.17 K band image (dark contour) and VLA radio image (light contour). Adapted from Chambers et al. 1989.

THE NATURE OF OPTICAL/IR CONTINUUM

Is the optical and infrared emission from aligned radio galaxies dominated by starlight? The best evidence that the extended optical/IR continuum emission in such objects is produced by stars is the existence of stellar absorption features recently found in the summed ultraviolet spectra of high redshift radio galaxies by Chambers and McCarthy (1989). However over the past two years other mechanisms for producing the optical/ir continuum have been discussed in the literature (e.g. Chambers *et al.* 1987, 1988b, McCarthy 1987, LeFevre 1988, Fabian 1989, Rawlings and Eales 1989, di Serego Alighieri *et al.* 1989, Tadhunter 1989), and currently there is no consensus. In light of the recent work advocating various alternative explanations for the optical/ir continuum from distant radio galaxies we will discuss the various ideas and arguments. The ability of each scenario to explain various observations is summarized in Table 1. This table is meant as guide to where both the observations and the simple models need additional work.

(a) Gravitational Lensing.

In a series of papers Le Fevre, Hammer, and collaborators (1988a, 1988b, 1988c) have discussed the role of gravitational lensing (both multiple imaging and amplification) in contributing to the luminosity and morphology of high redshift radio galaxies. It is unlikely that the observed morphology is due to multiple gravitational images. Some of these sources have radio cores, yet no multiple images of the radio cores have been observed. Furthermore the lens hypothesis cannot account for the alignment effect since the often very large and extended radio lobes cannot be multiply imaged, and there is no reason to prefer multiple images along the background radio axis. Since these sources are dominated in the radio by such large extended radio structure, it is implausible that gravitational amplification has significantly biased the radio selection of these objects. In addition some optical spectral lines have been shown to have spatially distributed velocity gradients, and different gradients in different lines (e.g. Djorgovski *et al.* 1987). This is difficult to account for since a gravitational lens is achromatic. There are however aligned radio galaxies with obvious foreground galaxies near the line of sight. These might provide some optical luminosity amplification, as opposed to multiple imaging. And while such an explanation is neither necessary nor sufficient to account for the morphology and high luminosity of the aligned radio galaxies, some contribution to their luminosity from gravitational lenses can not be ruled out.

(b) Nonthermal Mechanisms.

The high energy tail of the radio synchrotron spectrum in some nearby radio sources has been observed in the infrared, optical, and X-rays (e.g. M87, 3C273, 3C66, see Miley 1980) However such extrapolations are too faint by several orders of magnitude to account for the optical/ir emission from the high redshift aligned radio galaxies which have the luminosities surface brightnesses greater than or equal to that of the largest giant ellipticals. Moreover, the rest frame spectral energy distributions (SEDs) show large departures from a nonthermal power law.

Inverse Compton radiation from scattering of the microwave background by the radio-emitting relativistic electrons would require extreme departures from equipartition.

Finally explanations involving mechanisms related directly to the radio synchrotron photons suffer from the inability to account for the extreme differences in the radio and optical morphologies.

(c) *Electron Scattering.*

Fabian (1989) has proposed electron scattering of an obscured QSO nucleus as the mechanism for the alignment effect and Rawlings and Eales (1989) have favored this explanation for their data. Polarized emission has been detected from 3C368 (di Serego Alighieri *et al.* 1989), but their data favor dust scattering and will be discussed below. Electron scattering would not modify the overall SED of the nucleus, but the observed SEDs of aligned radio galaxies (e.g. Lilly 1988a, 1988b, Chambers and Charlot 1989) are very different from the power-law continuum of QSO's. Furthermore, while such a scenario has been adjusted to fit a particular geometry (i.e. 3C356) as a general explanation of the alignment effect it would require either an extreme mass in ionized hydrogen, or QSO (blazar) luminosities far above what is observed directly. For example, for an extended region 10 kpc across, Thompson scattering requires a mass of ionized hydrogen $M \sim \tau A / \sigma \sim 10^{16} M_{\odot} \tau (R/10\text{kpc})^2$, where $A = R^2$ is the apparent area of the emitting region, τ is the optical depth, and $\sigma = 0.4\text{cm}^2/\text{gram}$ is the Thompson cross section for fully ionized hydrogen. The optical depth τ must be greater than 0.01 to produce absolute magnitudes of $M_v \sim -25$ for an extended region or the central (obscured) quasar would be much brighter than the brightest known qso's. This requires a minimum mass of $10^{14} M_{\odot}$ in ionized hydrogen, which is much too extreme for the extended gas kinematics. The alternative is that there is a central blazar in all these objects which is several magnitudes brighter than any object observed. Two additional arguments against electron scattering come from the high densities required. Rawlings and Eales put a lower limit of $n_e = 5\text{cm}^{-3}$ for the thermal plasma in their electron scattering model, but for a typical equipartition magnetic field ($\sim 10^{-4}$ gauss) this would preclude the detection of any polarized radio emission from a lobe spatially coincident with aligned optical flux (e.g. the southern lobe in 3C368 or the eastern lobe in 4C41.17). Furthermore, cool emission-line clouds in pressure balance with such a hot dense phase would require densities far greater than what is derived from emission line ratios of the extended narrow line emission (McCarthy 1989).

(d) *Dust Scattering.*

Because of their very high Lyman α luminosities, aligned radio galaxies are not expected to be dusty objects. However, if the the emission line gas is clumped in a substantially different way from the dust, then dust scattering of light from a hidden nucleus is another mechanism for producing aligned blue flux. Some evidence that dust scattering may play a role is provided by the recent observation of polarized blue light from 3C368 (di Serego Alighieri *et al.* 1989). However, because of its inefficiency in scattering red light, dust scattering cannot explain the infrared alignments (Chambers *et al.* 1988b and Eisenhardt and Chokshi 1989) and thus one must propose two carefully tuned alignment processes acting in concert: one for the blue component and one for red. An alternative single explanation is preferable.

There are additional arguments against dust scattering dominating the extended emission. For example, typical qso broad line lyman alpha equivalent widths are $\sim 100\text{\AA}$ with ~ 0.8 in the broad component (Kinney, 1987,1989). Therefore if the

TABLE 1
Are proposed scenarios consistent with the observed properties of Aligned Radio Galaxies ?

Observed Properties	Young Stellar Population			Old Stars	Obscured AGN (consequence of orient.)		Nonthermal		Gray. Lens
	Young	Reddened Burst	Massive Stars		Old + Burst	Electron Scattering	Dust Scattering	Synchro- tron	
Optical Alignment Effect	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Infrared Alignment Effect	Yes	Yes	Yes	No	Yes	No	No	No	No
SEDs	Yes	Maybe	Maybe	Yes	No	No	No	No	Yes
Stellar Absorption Features	Yes	Yes	Yes	Yes	No	No	No	No	Yes
High Surface Brightness	Yes	Yes	Yes	Yes	Yes	Maybe	No	No	Yes
$L\gamma$ Eq. Width	Yes	Maybe	Yes	Yes	Yes	Maybe	Yes	Yes	Maybe
Continuity of Hubble diagram	Yes	Yes	No	Yes	No	No	No	No	No
Low Dispersion of Hubble dia.	Yes	Yes	No	Yes	No	No	No	No	No
Kinematics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Extended Polarization	Maybe	Maybe	Maybe	Maybe	λ ind.	λ dep.	Yes	Yes	No
Nuclear Polarization	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Low Limit on Broad $L\gamma$	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Faint Radio Cores	Yes	Yes	Yes	Yes	Maybe	Maybe	Yes	Yes	Yes
Inferred Properties									
z_F	1 - 5			7 - 30					
IMF	Normal	1 - 5 Normal	$M_* > 5M_\odot$	Normal					
Mass					No $M_* < -30$	No $M_* < -30$	No	No	No
Radio Source Induced Star Form.	Yes	Yes	Yes	Yes					
AGN anisotropic abs. Mag.									No

continuum is dominated by dust scattering of a typical QSO nucleus, broad Lyman alpha components with an equivalent width of $\sim 80\text{\AA}$ ($\sim (1+z)80\text{\AA}$ in observed frame) should have been detected. Such a feature should be even more apparent when one considers that the broad component should be enhanced in a dusty environment due to the resonant destruction of Lyman α in the core of the line.

This last argument can only be avoided if the central object has no broad lines (a high redshift BL Lac or featureless blazar) and effectively stays that way for $\sim 10^5$ years. Under optimistic conditions (e.g. Tadhunter, 1989) the dust scattering of a blazar can produce enough blue (but not red) surface brightness if the blazar has an absolute magnitude of $M_v \sim -30$, i.e. marginally above the brightest blazar known.

Finally, all scenarios which endeavor to explain the alignment effect as a manifestation of the orientation of radio loud quasars (e.g. Barthel 1989), including all scattering scenarios (e.g. Fabian, 1989; Rawlings and Eales, 1989; di Serego Alighieri *et al.*, 1989; Tadhunter, 1989) suffer from the inability to explain the observed continuity and low dispersion of the infrared Hubble diagram for radio galaxies (Lilly, 1988a and this conference). As emphasized by Lilly (1988b), the continuity argument is quite powerful; it is difficult to imagine why alternative scenarios would happen to give just the right luminosities at just the right redshifts to join smoothly on to the Hubble diagram (both in amplitude and in slope) with intermediate redshift giant ellipticals. A corollary to this argument is that the high redshift counterparts to intermediate redshift radio galaxies must exist somewhere, if they are not the aligned radio galaxies, where are they? Although the low dispersion of the Hubble diagram for radio galaxies is curious, it is certainly clear that intrinsic quasar luminosities show far greater dispersion (e.g. Hewitt and Burbidge, 1987). Presumably any scattering mechanism could only add to the quasar dispersion; hence in the context of the scattering scenarios it is hard to understand how the radio galaxies could be drawn from the same population as the quasars. On the other hand, if the alignment effect is not due to scattering effects, then there is at present no inconsistency with the Barthel (1988) hypothesis.

(e) *Massive Stars.*

One early explanation for the alignment effect was that the radio source was somehow triggering star formation along its axis (Chambers *et al.* 1987, McCarthy *et al.* 1987). Mechanisms of this kind will be discussed below; here we consider whether consistent stellar population models can account for the observed SED's of the aligned continuum. The models have been constructed using an updated version of Bruzual's code (1983). (See Chambers, Miley, van Breugel 1989, and Chambers and Charlot 1989 for details of the models.) Figure 5 shows how four of these models are fit to the observations of 4C41.17. These models are not unique, and are meant only to investigate various possibilities.

First we examine an IMF restricted to massive stars as an efficient way to produce a large luminosity with relatively few stars. This works well in the ultraviolet, but the challenge is to explain the alignment of the observed red and near infrared continuum (the "red bump" ~ 4000 to 10000\AA in the rest frame). Chambers *et al.* (1988b, 1989) and Bithell and Rees (1989) investigated the possibility that the infrared continuum in aligned radio galaxies is due to a large population of red supergiants. The idea acquired new motivation with the discovery of objects like 0902+34 and 4C41.17 at very high redshift as a mechanism to avoid the large cosmic age suggested by Lilly (1988b).

However, our present modelling (Chambers, Miley, van Breugel 1989) indicates that it is difficult to produce a plausible massive star scenario that fits the spectral energy distributions for the simple reason that massive stars spend more time being blue than red. The situation is a bit complicated, since the proportion of time that a massive star spends being blue to the time spent being red depends crucially on the details of evolution models for massive stars (e.g. mass loss and convective overshooting) and even the current models are not well matched by the galactic star counts. There is a large and rich literature on the topic which is presently advancing rapidly, not the least because of SN 1987a (e.g. Woosley 1988.) However, with any currently envisioned blue to red supergiant ratio, the simplest model, constant (steady state) massive star formation, is too blue to fit the red bump in the SED of aligned radio galaxies.

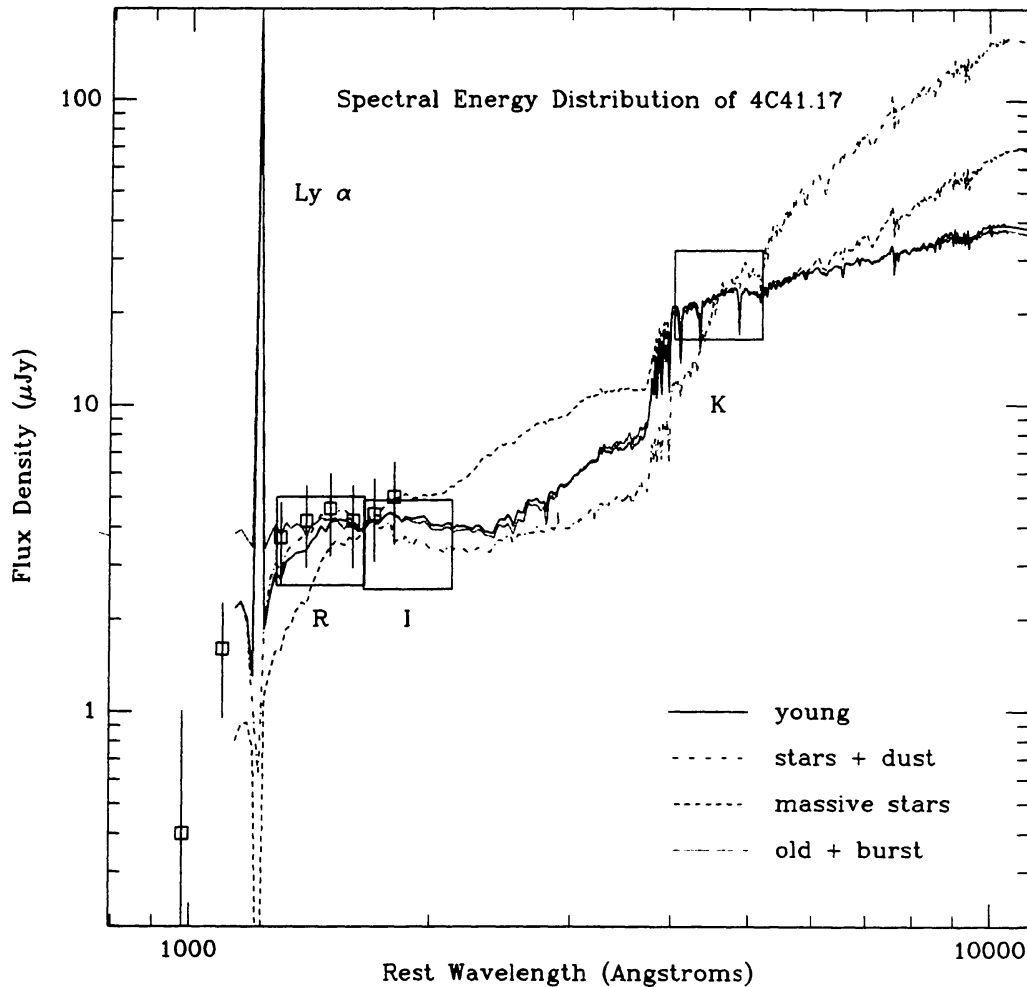


Figure 6. SED of 4C41.17 adapted from Chambers *et al.* 1989.

A plausible attempt to get around this problem is to use an evolving model, since a burst of massive star formation is eventually dominated by red supergiants with a very red SED. Various evolving massive star models with different star formation rates have been studied (Chambers *et al.* 1989, Bithell and Rees 1989), with similar results. Since the smallest of the high mass stars lives the longest the evolution of the SED at late times is controlled totally by the assumed low mass cutoff. This causes two fundamental difficulties for massive star models. First, the model SEDs fit the data only for a very small percentage of its luminous phase, spending a much

greater fraction of its lifetime ($\sim 90\%$) with a very blue SED, which has never been observed, or being extremely red ($\sim 5\%$ of its luminous lifetime). Second, while it has an extremely low M/L, and is thus very efficient, the luminosity has dropped by a factor of > 100 from its burst luminosity by the time it fits the observed SED's. Since aligned radio galaxies are already very luminous, such a model would predict extreme luminosities for their burst phase.

Finally, as with the scattering models, a massive star scenario is incapable of explaining the continuity and low dispersion of the infrared Hubble diagram.

(f) Old Population plus Small Burst.

Lilly (1988b, this conference) has argued that the red bump in the SED is due to an old stellar component. Figure 5 shows a similar model where it is assumed that the bulk of the stars are formed in a continuous burst lasting 1 Gyr. Then the star formation halts and the population evolves. At some later epoch (the epoch of observation) a second star burst is assumed to occur, perhaps associated with the radio activity. This second burst is responsible for the flat ultraviolet component, and its high star formation rate need only last for a short period of time. The young starburst is taken to last 0.1 Gyr and a mass fraction of 0.04 is great enough to produce the observed ultraviolet if the burst happens this fast. Using the stellar population models we find that the older generation had to be at least 1.3 Gyrs old (or 0.3 Gyrs after the end of the 1 Gyr constant burst) in order to match the red bump. Clearly an even older population would fit as well, but 1.3 Gyr was taken as the youngest possible age in this scenario which will give an acceptable fit to the SED of 4C41.17.

There are two major difficulties with the old stellar population model. First, the large ages asserted for the highest redshift objects become a powerful constraint on the epoch of formation of these galaxies, and on cosmological models as well. If Lilly is correct, and 4C41.17 is older than $\sim 1.3 \times 10^9$ years, then this excludes an $H_0 = 50, q_0 = 0.5$ cosmology where the universe is only 1.25×10^9 years old. While the problem is not as extreme for low q_0 cosmologies, large ages for the highest redshift radio galaxies imply very high redshifts of formation $z_F \sim 10 - 30$. Second, the most crucial objection, is that old stellar population model can not explain the infrared alignments. The ages of the galaxies in this model are far larger than than is reasonable for the radio source. Thus one must assert that the radio jet (which must be moving much faster than escape velocity) is sensitive to the mass distribution, a difficult proposition to believe. One might argue that the infrared alignments are due to selection effects, i.e. we only find the radio objects whose luminosity has significantly brightened because the radio jet happened to hit a nearby companion galaxy. However, if the radio luminosity were so dramatically effected by such an interaction, then it is difficult to understand why an enormous asymmetry in the radio luminosity (or spectral index) is not observed along with the size asymmetry which is observed and is due to a density asymmetry (McCarthy 1989).

(g) Young Stellar Population.

Chambers and Charlot (1989) have shown that the observed SED's of high redshift radio galaxies (0902+34 and 4C41.17 in particular) can be produced with a normal (Scalo, 1986) IMF in less than $\sim 3 \times 10^8$ yr if the galaxies formed the bulk of their stars on slightly shorter timescales ($\lesssim 1 \times 10^8$ yr). In this connection, it is

interesting to note that the star formation timescales are comparable to the probable free-fall times of the galaxies. This suggests that these objects may be relatively young and that we are observing them (at least the ones with the flat UV) near the time in which they formed most of their stars. The “epoch” of this type of galaxy formation would have extended over a fairly wide range of redshifts, from $z \sim 1$ to $z \sim 5$. Therefore they do not require the large ages suggested by Lilly (1988b). This is primarily due to the short timescale of formation, although the addition of an observationally derived AGB contribution contributes $\gtrsim 20\%$ of the red light on the timescales considered.

The ability to obtain “flat UV plus red bump” SED’s on short timescales and maintain a roughly constant red luminosity during the first Gyr makes the Chambers and Charlot (1989) scenario the only model so far capable of explaining both the infrared alignments while at the same time maintaining the observed small dispersion and continuity of the Hubble diagram. Such a scenario is also consistent with both the observed ultraviolet stellar absorption features recently discovered in the summed spectra of aligned radio galaxies by Chambers and McCarthy (1989), and their suggestion that the overall shape of the ultraviolet continuum indicates that the star formation was substantially greater in the immediate past.

The only difficulty with the young stellar population scenario seems to be relatively minor. The coherent extended polarization in 3C368 reported by di Serego Alighieri *et al.* is large; however it does presuppose substantial dust, and therefore star formation extended ~ 50 kpc along radio source anyway. Hence a small contribution to extended emission by dust scattering would be consistent with the young stellar population model, whereas scattering alone cannot explain the infrared alignments.

(h) Stars plus Dust.

Aligned radio galaxies are not expected to contain much dust because of their large Lyman α surface brightnesses. Even a small amount of dust can extinguish most resonance line photons such as Lyman α . However, the inferred star formation rates are large ($\gtrsim 100M_{\odot}/\text{yr}$) and the dust could be clumped differently from the emission line gas. Figure 5 shows a burst SED (roughly flat) reddened by an extinction curve derived from the Small Magellanic Clouds. A similar result could be obtained using the Galactic extinction curve, except that it would exhibit the pronounced feature at 2000 \AA . Dust would mainly affect the rest-frame “flat UV” part of the spectrum, but hardly affect the red or near infrared emission. Thus it would not change the conclusions of the young galaxy picture discussed above. The greatest affect of ignoring reddening would be to *over-estimate* the ages derived from the observed SED’s.

RADIO SOURCE INDUCED STAR FORMATION

Can a radio source trigger vast amounts of star formation at early epochs? At low redshift slight amounts of star formation associated with the jet of Cen A were suggested by Osmer (1978) and DeYoung (1981). The ability of radio jets to interact with, entrain, and accelerate ambient media was demonstrated by Miley and collaborators in a series of papers (e.g. Miley *et al.* 1981, Heckman *et al.* 1982, 1984 van Breugel *et al.* 1984, 1985a, 1986). Then Minkowski’s Object (van Breugel 1985b, Brodie 1985) was investigated, and it appears to be the best nearby example of a

starburst triggered by a radio source. With the discovery of the alignment effect at high redshift, Chambers *et al.* 1987 and McCarthy *et al.* 1987 suggested that the effect might be due to star formation stimulated by the associated radio sources.

Recently, Rees (1989) and Begelman and Cioffi (1989) have independently proposed a specific mechanism for efficient radio source induced star formation at early epochs. (See also DeYoung 1989 and Daly 1989). While galaxies are in the process of forming, the development of a two phase structure is a nearly inevitable consequence of inhomogenities (Fall and Rees, 1985). Infalling material is heated to the virial temperature, $10^6 - 10^7$ K; embedded in it are clouds or filaments at $\lesssim 10^4$ K. If then the cocoons of shocked gas that are expected to surround powerful radio sources (Scheuer, 1974) engulf and compress the circumgalactic clouds, this can drive them over the Jeans limit and trigger star formation. Rees (1989) estimates that the star formation rate can be enhanced by the radio source over what one would otherwise expect from normal gas dynamical considerations (e.g. Fall and Rees, 1985) by an amount comparable to the Mach number of the radio jet, i.e. by a factor of $10 \sim 100$. This suggests a dramatic star formation rate during the expansion of the radio source through the galactic environment. Begelman and Cioffi (1989) give a prescription for the evolution of the radio cocoon and derive a comparable star formation rate.

Can the timescale of the passage of the radio source be associated with a reasonable prescription for the star formation rate? First, in the Scheuer "Dentist's Drill" model the radio hot spots track the instantaneous point of impact of the jet, and not the time averaged bow shock of the entire cocoon. The observed speed of a hot spot, or jet material (e.g. Cygnus A) may not reflect the true speed of the advance of the cocoon. Hence it may be difficult to estimate in practice the crossing time of the cocoon. Spectral index age estimates are unreliable, particularly in the ultra-steep spectrum sources where other mechanisms for steepening the radio spectrum are probably at work (Chambers *et al.* 1989). Secondary star formation processes may also be at work. For instance the passage of the radio source could be identified with the fast rise-time of the star formation rate of Chambers and Charlot (1989) and the tail of star formation could then be due to effects stemming from the starburst, e.g. supernovae driven shocks. The results of Chambers and McCarthy (1989) suggest that the high radio luminosity sources (3C and 4C) do not achieve their maximum radio luminosity until somewhat after the bulk of the star formation has occurred.

SUMMARY

Selecting radio sources for study on the basis of their ultra-steep radio spectrum has proven to be an extremely successful technique for locating very high redshift galaxies. This in turn has helped discover a remarkable property of high redshift radio galaxies, that their optical/infrared continua are generally aligned with their radio axes. The extended optical and infrared continuum of high redshift radio galaxies is probably dominated by starlight, and radio source induced star formation is the most plausible explanation for the alignment effect. The young galaxy model discussed is the only idea so far that explains all the observations, especially the infrared alignments. Powerful radio sources appear to be stimulating substantial star formation at early epochs.

Much work remains to be done, including addressing the question of how much of a role radio sources may have played in the formation of ordinary galaxies.

ACKNOWLEDGEMENTS

We would like to thank Hy Spinrad and Wil van Breugel for organizing the Berkeley conference "Radio Galaxies at High Redshift, a Multi-Spectral Synthesis" which provided a great deal of stimulating discussion amongst all the participants.

REFERENCES

- Allington-Smith, J. R. 1982, *M.N.R.A.S.*, 199, 611
 Barthel, P.D., 1989, *Ap. J.*, 336, 606
 Begelman, M.C., and Cioffi, D.F., 1989 *Ap. J. (Letters)*, 345, L21
 Begelman, M. C., Blandford, R.D., Rees, M.J., 1984, *Reviews of Modern Physics*, 56, 255
 Bithell, M., and Rees, M., 1989 *preprint*
 Blumenthal, G., Miley, G.K., 1979, *Astr. Ap.*, 80, 13
 Bridle, A.H, Perley, R.A., 1984, *Annual Reviews of Astronomy and Astrophysics*, 22, 319
 Bridle, A.H., Kesteven, M.J.L. Guindon, B., 1972, *Ap. J. (Letters)*, 11,27
 Brodie, J.P., Bowyer, S., McCarthy, P.J., 1985, *Ap. J. (Letters)*, 293, L59
 Bruzual, G. 1983 *Ap. J.*, 273, 105.
 Chambers, K.C., 1989, Ph.D. Thesis
 Chambers, K.C., and Charlot, S., 1989, *Ap. J. Letters, in press*
 Chambers, K.C., and McCarthy, P.J., 1989, *Ap. J. Letters, in press*
 Chambers, K.C., Miley, G.K., and Joyce, R. R. 1988b, *Ap. J.*, 329, L75
 Chambers, K.C., Miley, G.K., and van Breugel, W. 1987 *Nature* , 329, 604.
 Chambers, K.C., Miley, G.K., and van Breugel, W. 1988a, *Ap. J.*, 327, L47
 Chambers, K.C., Miley, G.K., and van Breugel, W. 1989, *Ap. J.* submitted
 Daly, R., 1989, *Ap. J. in press*
 DeYoung, D., 1981 *Nature* , 293, 43
 DeYoung, D., 1989 *Ap. J. (Letters)*, 342, L59
 Djorgovski, S., 1986, in *Starbursts and Galaxy Evolution*, ed. T. Montmerle, p. 401.
 Djorgovski, S., Spinrad, H., Pedelty, J., Rudnick, L., Stockton, A., 1987, *A. J.*, 93, 1307
 Djorgovski, S., Spinrad, H., McCarthy, P., Dickinson, M., van Breugel, W., Strom, R., 1988, *A. J.*, 96, 836
 Eisenhardt, P., Chokshi, A., 1989, *Ap.J. Letters*, submitted
 Fabian, A.C., 1989, *M.N.R.A.S.*, 238, 41p
 Fall, S.M., and Rees, M.J. 1985, *Ap. J.*, 298, 18.
 Heckman, T.M., Miley, G.K., Balick, B., van Breugel, W.J.M., and Butcher, H.R., 1982, *Ap. J.*, 262, 529
 Heckman, T.M., van Breugel, W.J.M., and Miley, G.K., 1984, *Ap. J.*, 286, 509
 Heesch, D., 1960, *Pub. A.S.P.*, 72, 368
 Hewitt, A., Burbidge, G., 1987, *Ap. J. Suppl.*, 63,1
 Kinney, A., Huggins, P.J., Glassgold, A.E., Bregman, J.N., 1987, *Ap. J.*, 314,145
 Kinney, A., 1989 *private communication*
 Laing, R.A., Riley, J.M., Longair, M.S., 1983, *M.N.R.A.S.*, 204, 151
 Le Fevre, O., Hammer, F., Nottale, L., Mazure, A, Christian, C., 1988a, *Ap. J. (Letters)*, 324, L1
 Le Fevre, O., Hammer, F., Jones, J., 1988b, *Ap. J. (Letters)*, 331, L73

- Le Fevre, O., Hammer, F., 1988c, *Ap. J. (Letters)*, 333, L37
- Lilly, S. J. 1988a, *Ap. J.*, 340, 77.
- Lilly, S. J. 1988b, *Ap. J.*, 333, 161.
- Lilly, S. J., Longair, M. S. 1984, *M.N.R.A.S.*, 211, 833
- Longair, M. S., Lilly, S. J., 1984, *Journal of Astrophysics and Astronomy*, 5, 349
- McCarthy, P. J., Van Breugel, W., Spinrad, H., and Djorgovski, S. 1987, *Ap. J. (Letters)*, 321, L29
- McCarthy, P. J., Spinrad, H., Djorgovski, S., Strauss, M. A., van Breugel, W. J. M., and Liebert, J. 1987a *Ap. J. (Letters)*, 319, L39
- McCarthy, P.J., 1989, Ph.D. Thesis
- Macleod, J.M., Doherty, L.H., 1972, *Nature*, 238, 88
- Miley, G.K., 1980, *Annual Reviews of Astronomy and Astrophysics*, 18, 165
- Miley, G.K., Heckman, T.M., Butcher, H.R., and van Breugel, W.J.M., 1981, *Ap. J.*, 247, L5
- Miley, G.K., Chambers, K.C., Hunstead, R., Macchetto, F., Roland, J., Rottgering, H., Schilizzi, R., 1989, *ESO Messenger*, 56, 16.
- Osmer, P.S. 1978, *Ap. J. (Letters)*, 226, L79
- Rawlings, S. and Eales, S., 1989a, Second Wyoming Conference, *The Interstellar Medium in External Galaxies*, in press.
- Rees, M.J. 1989, *M.N.R.A.S.*, 239, 1p.
- Scalo, J.M., 1986, *Fundamentals of Cosmic Physics*, 11, 1.
- Scheuer, P.A.G., 1974, *M.N.R.A.S.*, 166, 513
- di Serego Alighieri, S., Fosbury, R., Tadhunter, C., 1989, *Nature*, in press
- Spinrad, H. and Djorgovski, S. 1984, *Ap. J. (Letters)*, 285, L49
- Spinrad, H. Djorgovski, S., Marr, J., Aguilar, L. 1985a, *Pub. A.S.P.*, 97, 932
- Spinrad, H., *et al.* 1985b, *Ap. J. (Letters)*, 299, L7
- Spinrad, H. 1986 *Pub. A.S.P.*, 98, 269
- Spinrad, H., Djorgovski, S. 1987 IAU Symposium 123, *Observational Cosmology*, ed. G. Burbidge, (Dordrecht:Reidel), P. 129
- Tadhunter, C.N., Fosbury, R.A.E, di Serego Alighieri, *Proceedings of the Como Conference on BL Lac Objects: 10 Years After*, ed. L. Maraschi, in press
- Tielens, S., Miley, G., Willis, A., 1979, *Astr. Ap. Suppl.*, 35, 153
- van Breugel, W.J.M., Heckman, T.M., Butcher, H.R., and Miley, G.K., 1984, *Ap. J.*, 276, 79
- van Breugel, W.J.M., Miley, G.K., Heckman, T.M., Butcher, H.R., and Bridle, A., 1985a, *Ap. J.*, 290, 496
- van Breugel, W.J.M., Filippenko, A.V., Heckman, T.M., Miley, G.K., 1985b, *Ap. J.*, 293, 83
- van Breugel, W.J.M., Heckman, T.M., Miley, G.K., Filippenko, A.V. 1986, *Ap. J.*, 311, 58
- Veron, M.P., Beron, P., Witzel, A., 1972, *Astr. Ap.*, 18, 82
- Windhorst, R.A. Miley, G.K., Owen, F.N., Kron, R.G., Koo, D.C., 1985, *Ap. J.*, 289, 494
- Woolsey, J., 1988, *Ap. J.*, 330, 218