Chapter 7

Near-IR imaging II: radio source evolution

Abstract

Using KPNO 2.1 m J, H, and K-band data on samples of Gigahertz Peaked Spectrum (GPS, radio size < 1 kpc), Compact Steep Spectrum (CSS, 1–20 kpc), and 3CR classical doubles (> 20 kpc), we have constructed mean broadband spectral energy distributions (SEDs) for each of the object classes and compared these with synthetic SEDs. The host galaxies of the compact and extended radio sources appear to have similar near-IR broadband SEDs, implying similar stellar populations and AGN. These SEDs are best fit with a mean metallicity of ~solar and fairly old stellar populations implying formation redshifts of ≥ 5. Redshift evolution of the sources is consistent with a passive evolutionary model. In addition, an extra IR component is needed which can be modeled by emission from dust at a temperature of 900–1300 K, perhaps produced by the putative obscuring torus. All of our results are consistent with the hypothesis that the GPS and CSS are the progenitors of the large-scale 3CR radio galaxies.

7.1 Introduction

In this second paper on near-IR imaging of radio galaxies, we present an interpretation of results found in the first paper (de Vries et al. 1998, Chapter 6), as well as a comparison with stellar synthesis model predictions. The radio galaxies studied here are among the most powerful radio emitters in the universe. The sources range in size from the very compact Gigahertz Peaked Spectrum (GPS, < 1 kpc \(^2\), O'Dea et al. 1991), via the intermediate Compact Steep Spectrum (CSS, 1–20 kpc, Fanti et al. 1990), to the large-scale classical double radio galaxies (FRII, > 20 kpc, Fanaroff & Riley 1974). Even though strictly speaking, the small double sources satisfy the FRII condition, we will use the term FRII for the large-scale classical double sources to distinguish them from the GPS and CSS sources in our discussion.

As has been discussed in Chapter 6, an evolutionary scenario has been proposed where the radio source is “born” in the GPS phase and subsequently expands outwards to the CSS and finally the FR II stage (e.g., Carvalho 1985, Hodges & Mutel 1987, De Young 1993, Fanti et al. 1995, Begelman 1996, Readhead et al. 1996a, 1996b, Bicknell et al. 1997, O'Dea & Baum 1997). Unfortunately, this idea is not compatible with the observed number densities of GPS, CSS, and FRII's (O'Dea & Baum 1997), assuming a constant radio luminosity and lobe advancement speed. This constant expansion speed (\(\sim 0.02 \, c\), Readhead et al. 1996a, 1996b) implies a linear relation between the source age and its size, GPS sources being \(\sim 10^{3–4}\) times as young as the FRII sources. Consequently, GPS sources should be \(\sim 10^{3–4}\) less numerous. However, GPS constitute about 10% of the powerful radio source population, two orders of magnitude too high. Two scenarios seek to explain this GPS overdensity.

In the first scenario (Fanti et al. 1995, Begelman 1996, O'Dea & Baum 1997), the GPS sources do expand, but do not evolve into the most powerful FRII sources. Instead, they decrease significantly in radio power due to adiabatic expansion losses. The GPS sources then form the progenitors of radio sources with intermediate FR I / FR II type luminosities (\(\sim 10^{24–25}\) W Hz\(^{-1}\) at 178 MHz). The actual FRII progenitors would have to be very powerful indeed, with radio powers on the order of \(\sim 10^{28}\) W Hz\(^{-1}\) at 178 MHz. And, as a consequence of the size evolution, they are very short lived and rare, on the order of \(\sim 1\) in the whole sky.

The second scenario implies a large fraction of the GPS sources are not expanding (i.e., evolving), but remain confined to their small sizes by an unusually dense ISM (e.g., van Breugel et al. 1984, Wilkinson et al. 1984, Fanti et al. 1990, O'Dea et al. 1991, Carvalho 1994, 1998). Obtaining direct evidence for this confining medium is difficult, and the results are mixed (see O'Dea 1998 for a review). Evidence that GPS and CSS quasars have higher obscuring columns than non GPS/CSS quasars has been found by e.g., Baker \& Hunstead (1995) in optical spectra of CSS quasars, and by Elvis et al. (1994,1996) in X-ray spectral cut-offs in GPS quasars. On the other hand, similarities in optical line fluxes (e.g., Morganti et al. 1997), similar spectral indices for the optically thin radio emission (de Vries et al. 1997b, Chapter 3) and absence of high rotation measures across the lobes in GPS sources (e.g., Udomprasert et al. 1997) suggest otherwise.

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\(^2\)Throughout this chapter we adopt: \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\), and \(q_0 = 0.5\)
7.2. **THE SAMPLE**

In either scenario, the radio source environment (i.e., its host galaxy) determines the time evolution of the radio structure. Similarities in host galaxy properties over a range of radio source types and sizes imply a single evolutionary scenario. On the other hand, differences in ambient nuclear density might indicate that either the GPS source remains small, or does not evolve along the GPS–CSS–FRI / FRII sequence. By comparing host galaxy properties over the range of radio source sizes, one can get a handle on the possible radio source evolution. In this chapter we focus on the near-IR part of our ongoing multi-wavelength campaign. The near-IR is particularly well suited for our comparison purposes. First of all, the Galactic absorption towards the sources is rather small, even at low Galactic latitudes, so uncertainties in the correction are as a consequence also small. Furthermore, the unknown source intrinsic extinction is also at a minimum. At somewhat higher redshifts ($z \approx 1$) the restframe $J$ band is probed in $K$, instead of restframe UV. As discussed in a subsequent section, another advantage of the near-IR is the smooth nature of the spectral energy distribution, making K-corrections across this part of the spectrum much more reliable than corrections across the Balmer decrement.

Averaging host galaxy properties over the size subclasses will not only minimize source peculiarities, but also enable us to investigate correlations between mean host galaxy properties and radio source size. For example, the inferred higher ambient nuclear densities in GPS sources might result in a source which becomes more nucleated at longer wavelengths and more so than the large-scale radio sources, either through a larger extinction (obscuring more of the AGN light at shorter wavelengths) or through a higher level of thermal dust emission, peaking longward of $K$. No evidence for this effect has been found, however (cf. Chapter 6).

We present our results on detailed comparisons of radio source host galaxies, in combination with predictions made by stellar synthesis models (Bruzual & Charlot 1993, 1999). In Section 2 we introduce the sample, Section 3 discusses the use of stellar synthesis models and its implications for the next sections. The results are presented in Sections 4 and 5, which includes the color-redshift plots, color evolution diagrams, and the broadband spectral energy distributions with their model fits.

### 7.2 The Sample

The original sample consisted of 20 GPS, 20 CSS, and 20 FRII radio galaxies, matched in redshift and radio flux density (selected analogously to Heckman et al. 1994). In this way the effects of intrinsic radio luminosity will be limited, since the log of the radio power scales with the log of the redshift at fixed flux density. Also, in the galaxy–quasar viewing angle paradigm, the radio emission of galaxies is from the unbeamed component and therefore a direct measurement of the power of the central engine. Induction of quasars in our sample might result in inclusion of intrinsically low luminosity sources, due to relativistic boosting of emission towards the line of sight. This in turn might introduce unknown radio luminosity effects. By focusing on the galaxies we feel confident we are comparing radio sources of intrinsically similar radio luminosities.

During two observing runs in April 1994 and December 1995, $JHK$ images were
obtained for 16 GPS, 5 CSS, and 9 FRII sources. Since sources were initially selected mainly on radio flux density and size, and infrared fluxes were largely unknown, this partial sample is still representative of the radio source hosts, albeit with smaller numbers. The observational data, reduction process, and photometry results are presented in Chapter 6. Statistics for the intermediate CSS class are somewhat scant, but the extremes of the evolutionary sequence are better sampled. In looking for evolutionary effects we will focus on the average properties of the GPS and FRII galaxies. The redshift and radio power distributions can be found in Fig. 7.1, and some mean properties are listed in Table 7.1. In the bottom part of Fig. 7.1, the monochromatic power at 5 GHz (restframe) is plotted. Since GPS sources are close to their peak radio emission and 3CR FRII sources generally decline with a spectral index of \( \alpha \sim 0.75 \) \((S \propto v^{-\alpha})\) from their high 178 MHz fluxes (> 9 Jy, Bennett 1962), GPS sources are somewhat brighter at this frequency than FRII's at similar redshifts.

We added \( R \) band magnitudes for our sample from the literature, mainly from O'Dea et al. (1996), our ongoing \( BVR \) imaging program, and NED\(^3\). All \( R \) band magnitudes were converted into Cousins \( R_c \), as described in O'Dea et al. (1996).

\(^{3}\) The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration
7.3 Stellar Synthesis Models

Comparison of the sources at the same restframe wavelength implies a redshift correction (K-correction). Besides the effect of reduced bandwidth with a \((1 + z)\) factor, sources are imaged at \((1 + z)\) times higher intrinsic frequency, and thus at a different part of their spectra. It is this spectral correction that is highly uncertain if one does not have actual spectra for the sources, as is the case with our sample. We will rely on model (restframe) spectra, created by stellar synthesis models. We use the latest model code (GISSEL 1997) by Bruzual & Charlot using the Salpeter (1955) IMF. Both mean age and metallicity are input parameters of the model, with 5 discrete metallicities: \(Z=0.001\) (0.5% solar), \(Z=0.004\), \(Z=0.008\), \(Z=0.02\), and \(Z=0.05\) (250% solar), and mean ages \((A)\) ranging from \(10^4\) up to \(2 \times 10^{10}\) yr.

The K-correction is defined as:

\[
K_{\text{corr}}(z, Z, A) = 2.5 \times \log(1 + z) + \\
2.5 \times \log \left( \frac{\int_0^\infty R(\nu) S(\nu, Z, A) d\nu}{\int_0^\infty R(\nu) S(\nu(1 + z), Z, A) d\nu} \right) \tag{7.1}
\]

with \(R(\nu)\) being the filter response function, and \(S(\nu, Z, A)\) the restframe spectrum for a metallicity \(Z\) and mean age \(A\). The K-correction is then subtracted from the observed magnitude, i.e. \(m_{\text{obs}} = m_{\text{obs}} - K_{\text{corr}}(z, Z, A)\). To appreciate the effect metallicity and age have on the spectra, and therefore on the K-correction, model spectra spanning the range of both parameters are plotted in Fig. 7.2. Two effects are apparent: a) below 4000Å flux declines significantly, and b) age differences predominantly show at \(\lambda \lesssim 7000\)Å because, unlike the 10 Gyr curve, the 1 Gyr spectrum is still affected by the initial burst of star-formation with its associated blue / UV emission. The increase in K-correction with increasing redshift for the \(R\) band is mainly due to the flux decrease shortwards of the Balmer break. The \(R\) band K-correction spread with \(Z\) can be understood in terms of the large variation in UV emission. Note the more regular nature of the \(K\) band corrections, a consequence of the smooth source spectra beyond 1 micron.

Another effect that has to be eliminated before the sources can be compared to the models is extinction. This extinction is made up of contributions by our own Galaxy, intervening matter, and by the source itself. Of these components only the Galactic contribution can be estimated by using \(H\) column densities towards the sources (cf. Burstein & Heiles 1982, 1984). In Chapter 6 we corrected the \(JHK\) magnitudes for this Galactic absorption, and found that in almost all cases this correction is small \((\lesssim 0.05 \text{ mag in } J\) band). The extinction through the ISM of the (gas-poor elliptical) host galaxy is also likely to be small and should have little effect on the derived colors of the stellar population. However, the circumnuclear region may be very obscured and may strongly affect the derived AGN colors.

7.4 Color Plots and Evolution

Under the hypothesis that GPS sources are confined, frustrated sources, the high nuclear gas densities required may produce near-IR color differences between GPS and
3CR sources, as argued in the introduction. One direct way of comparing color gradients, without invoking K-corrections, is the color-redshift diagram. Here sources are compared at their respective redshift, and so sources with similar redshifts have similar bandwidth effects and spectral shifts. Fig. 7.3 plots the $R - K$ color against the 5 GHz radio luminosity, and, as can be seen, the color is more or less independent of radio power. Thus, if one assumes the radio emission to be nuclear in origin, these colors seem to be independent of AGN output. In fact $R$ and $K$ band magnitudes for these radio galaxies have been found to correlate with redshift (the Hubble diagram, e.g., Snellen et al. 1996, O'Dea et al. 1996), indicating that the emission is dominated by the host stellar population. Also, none of the sources were found to be dominated by a point source in the near-IR (Chapter 6), which is expected for an obscured AGN, and the surface brightness profiles all indicated the sources were resolved. Therefore, we feel confident that the $R - K$ (and $J - K$) colors are due to the underlying host stellar population, and that comparison between observations and stellar synthesis models is meaningful.

Figs. 7.4 and 7.5 plot the $R - K$ and $J - K$ colors against redshift. All colors are
correction for foreground Galactic extinction. Although these corrections are small in the $J$ and $K$ bands, they become appreciably large in the shorter wavelength $R$ band. If uncorrected, most sources will appear to have anomalously large $R - K$ colors, obscuring both source stellar population colors and extinction properties.

There are a few points to be made looking at Fig. 7.4. First, except for a few outlier sources, both GPS and 3CR sources seem to populate the same strip in the plot. The two 3CR sources 3C 208.1 and 3C 226 most likely have an aligned blue component, lowering the $R - K$ color. Some evidence for an aligned component has been presented by McCarthy et al. (1995) for the latter source, using 3m Lick emission line imaging. The GPS source 0500+019 has a very high optical spectral index of $\alpha_{R-K} \approx 7$ ($S \propto \nu^{-\alpha}$), which, combined with an unidentified spectral line in their spectrum, led Stickel et al. (1996) to the conclusion that 0500+019 is a background quasar severely reddened through a foreground galaxy. Since most of the argument hinges on the spectral feature, the lack of the same line in other published spectra (Kollgaard et al. 1995; de Vries et al. 1995, Chapter 2) places their conclusion on unsure footing. The fact remains, however, that 0500+019 does have a very red nucleus. GPS 0428+205 seems to have similar intrinsic absorption properties. If we ignore 1404+286, which has a Seyfert I nucleus and atypical colors, only 0500+019 still stands out a little in the $J - K$ color plot, 0428+205 is much closer to the model track now (compare Figs. 7.4 and 7.5). Second, two of the CSS sources (3C 258 and 3C 67) display the same anomalously low $R - K$ value as the two 3CR sources
Figure 7.4: Plot of the $R - K$ colors vs. redshift for our sample. All magnitudes have been corrected for Galactic foreground extinction. The solid line represents the $R - K$ color expected for the given mean metallicity ($Z=0.008$, 40% solar) at that redshift, if the initial burst of star-formation was at $z_f = 5$. Both dashed lines are evolving models, with the mean age fixed at 5 Gyr (lower) and 10 Gyr (upper line) respectively. Note the good correspondence with the model lines, if we exclude some very red GPS sources, and the 2 3CR sources with an $R$ band excess in the lower right.

3C 208.1 and 3C 226. From high resolution *Hubble Space Telescope* Wide Field Planetary Camera (WFPC2) imaging, CSS sources have been found to display the alignment effect as well, and more pronounced than the 3CR sources (de Vries et al. 1997a, Chapters 4 & 5). Therefore the same explanation for the $R - K$ colors applies: the $R$ band magnitude is enhanced by either blue stellar continuum, line-emission or scattered nuclear light from the aligned component.

The last point we would like to make is the fact that compared to the $R - K$ plot (Fig. 7.4), the $J - K$ (Fig. 7.5) displays less scatter in the distribution of colors. This can be understood in terms of two effects working in parallel: 1) the wavelength separation between the $J$ and $K$ bands is smaller than the $R$ and $K$ band, thereby decreasing the color difference; 2) the contribution of nuclear UV and line-emission light (mainly [O III] and Hα) to the $J$ band is negligible at these redshifts, the $J - K$ color is just due to the old stellar population of the host galaxy plus any AGN contribution.

Evidence for higher values of $R - K$ and $J - K$ (i.e. “redder” sources) among the GPS sources compared to the FR II sources, as predicted by the confinement scenario,
is not present in either Fig. 7.4 or 7.5. Some GPS sources (0500+019 and 0428+205) may indeed be more obscured than usual, and some FRII sources may exhibit a blue excess (3C 208.1 and 3C 226); however, on the whole both populations occupy the same regions of the plot. This is especially true for the $J - K$ plot (Fig.7.5), where effects due to extinction or non-stellar contributions are minimized. This leads us to conclude that there are no differences in the integrated near-IR properties of the host stellar population and AGN of GPS and 3CR/FRII galaxies.

7.4.1 Color Evolution

Using the Bruzual & Charlot (1999) code, colors can be predicted for a given redshift. Since there is no significant near-IR color difference observed within our sample, we can fit model tracks to our sample as a whole. The calculated colors for a given redshift are converted into observed colors (i.e. $K$-corrected in the opposite direction), so that they can be compared with the observed values directly. As the mean age of the population enters the model and the individual age of each source is unknown, the assumption is made that the true source color is somewhere in the region outlined by the non-evolving track (i.e., all sources are of similar age, irrespective of $z$), and
the passively evolving track (all sources formed at the same formation redshift $z_f$).

Since the models are metallicity ($Z$) and age ($A$) dependent, a least squares fit to the data will yield best-fit values for these parameters. For the $R - K$ plot, the best fitting tracks have a mean metallicity of 40% solar and a $z_f = 5$, while the $J - K$ plot yields $Z = 250\%$ and $z_f = 5$. The variations in metallicity between individual galaxies using stellar synthesis codes as an estimator may be significant however. In some 3CR FRII sources an excess "blue" (aligned) component is present, mimicking lower metallicity sources. On the other hand, significant internal reddening which may be present in some GPS sources has the exact opposite effect. In assessing the mean age and metallicity of the sample, the $J - K$ plot is somewhat better suited than the $R - K$ plot, mainly because the $J$ band is not nearly as affected by a blue AGN component as is the $R$ band. The highest redshift in our sample is $z = 1.02$ (3C 208.1), and even at this $z$ no blue / UV light enters the $J$ band, however, the $R$ band in this case is severely affected; note the aberrant $R - K$ color for 3C 208.1 in Fig. 7.4. Explaining such blue $R - K$ colors in terms of pure stellar population colors is almost impossible, the inferred mean age would have to be extremely low ($< 10^7$ years), with on top of that a very low population metallicity ($< 0.5\%$ solar). The dispersion in the $R - K$ colors therefore does not necessarily reflect a large scatter in host galaxy age and metallicity properties, but is more an indication of significant presence of non-stellar emission components.

Another major source of uncertainty in age and metallicity estimates is fact that the $R - K$ and $J - K$ colors do not uniquely constrain the SED. Actually, the spectral shape between the end points is a free parameter. The resulting best fitting values are indicative only. So to summarize, and combining both fits:

<table>
<thead>
<tr>
<th>Mean metallicity</th>
<th>$\approx$ solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation redshift</td>
<td>$z_f \approx 5$</td>
</tr>
<tr>
<td>Mean source age</td>
<td>5-10 Gyrs</td>
</tr>
</tbody>
</table>

Our mean source age of 5 Gyrs or more, is similar to values found for local (giant) ellipticals (e.g., Bressan et al. 1996, Vazdekis et al. 1997). Bender et al. (1996) find luminous giant ellipticals (at a redshift of 0.37) probably have formation redshifts of $z_f > 4$. The metallicity derived for our sample as a whole ($\sim$ solar) is consistent with values found for bright (local) ellipticals, using different techniques. For instance, Vazdekis et al. (1997) find extra solar metallicities for the nuclear regions of ellipticals, and Greggio (1997) gives a range of 50%-300% solar.

Thus our estimates of roughly solar metallicity and formation redshifts of 5 or larger are consistent with values from other studies of bright ellipticals.

### 7.4.2 Absolute $K$ Magnitude Evolution

Recently it has been suggested GPS galaxies were possibly less massive at higher redshift, and were gaining mass by mergers as the redshift decreases (Snellen et al. 1996). They were led to this conclusion by plotting absolute $K$ band magnitude (within a 32 kpc aperture) versus redshift, in which they found luminosity increasing
Figure 7.6: Absolute $K$ band magnitude versus redshift. Filled symbols represent our sample of GPS, CSS, and FR II radio sources. Open squares are brightest cluster galaxies (BCG) from the Aragón-Salamanca et al. (1993) sample. The bottom set of 4 tracks are passive evolutionary tracks for $5 \times 10^{11} \, M_\odot$ luminous mass, with a mean metallicity $\sim$ solar and formation redshifts ($z_f$) of 1.5, 2, 5, and 8 (top to bottom) respectively. The top solid track is for $1.5 \times 10^{12} \, M_\odot$ luminous mass, with $z_f = 2$. The dashed track is a best fit to the BCG sample, roughly consistent with the non-evolving case (horizontal lines in this plot). Both indicated sources are overluminous due to a Seyfert I nucleus, and are not at their nominal position in the plot.

with decreasing redshift for their sample, where, in contrast, passively evolving ellipticals decrease in absolute luminosity for a fixed total mass with decreasing $z$. This implies GPS galaxies accrete significant amounts of luminous matter. Since we have a sample of different radio source size classes, we can test whether this effect is present in the later stages of radio source evolution. If the effect in GPS galaxies is real, then as a consequence of the evolutionary scenario, FR II sources should display this effect as well, since they are simply slightly older versions of the GPS sources. The result for our data can be found in Fig. 7.6, where the absolute $K$ band magnitude (not the 32 kpc aperture data) is plotted against the log of $(1 + z)$. Note that the $K$ band magnitude is restframe $K$, K-corrected using a mean solar metallicity and age of 5 Gyr, parameters derived in the previous section.

As can be seen in this plot, the GPS, CSS, and FR II sources occupy the same region in the plot. Both indicated sources, GPS galaxies 1404+286 and 1345+125, have significant AGN contributions in $K$ due to the presence of a Seyfert I nucleus, in the case of 1345+125 actually residing in the companion (Gilmore & Shaw 1986).
These sources are overluminous, and are not at their nominal host galaxy positions in the plot. Whether or not we exclude these points, we find that a) there is no evidence of an increase in GPS absolute $K$ band luminosity with decreasing redshift as found earlier, and b) the larger source size classes have similar absolute magnitudes and evolution with redshift. Using an aperture of 32 kpc, analogous to Snellen et al. (1996), does not change these conclusions. Individual source $K$ band magnitudes may change (to fainter absolute magnitude), but this effect is still much smaller than the source-to-source variation present in this plot (at similar redshifts). The general 'shape' of the point distribution does not change therefore. Actually this also holds true when one significantly deviates from the assumed mean age of 5 Gyrs and the solar metallicity in the applied K-correction. The results of Snellen et al. (1996) probably can be attributed to their limited sample size.

With the luminosity evolution parameterized as:

$$K_{abs}(z) = K_{abs}(0) - 2.5 \gamma \log (1 + z) \quad (7.2)$$

non-evolving sources will fall along horizontal trajectories in Fig. 7.6; where "non-evolving" is in the sense of no mass increase and no luminosity changes. Aragón-Salamanca et al. (1993) compared brightest cluster galaxies (BCG) and 3CR radio galaxies with a horizontal (i.e., non-evolving) scenario. They concluded that the BCG evolution is consistent with the non-evolving case (fitted in the plot by the straight dashed line; $\gamma = 0.6 \pm 0.3$ and $K_{abs}(0) = -26.81 \pm 0.13$ in this case), but that the 3CR sources seem to decrease in luminosity with decreasing redshift. From this they conclude 3CR galaxies are not as homogeneous in their evolutionary behavior as the BCGs. If one, on the other hand, compares the sources to a more realistic passive evolutionary scenario (the solid tracks), another conclusion seems more likely. The top set of four (solid) tracks are passively evolving galaxies with $5 \times 10^{11}$ M$\odot$ luminous mass, and formation redshifts of 8, 5, 2, and 1.5 respectively (top to bottom). Even though the data does not constrain the formation redshift very well, the decrease in absolute $K$ band luminosity with decreasing redshift (for constant mass) is a trend well reflected in the data. Note, for instance, the gradual decline in $K$ band luminosity with decreasing $z$ for the brightest GPS galaxies. For the BCGs, the fact that these sources seem to fall along a more horizontal trajectory compared to the $5 \times 10^{12}$ M$\odot$ track consequently implies these sources would either have to increase in luminous mass (by merging), or have to increase their non-stellar emission component (the AGN must become more luminous at lower redshifts). In either case, the evolution of the radio sources seems to be more consistent with a passively evolving galaxy than is the case for the BCGs.

Another difference between the BCGs and our radio sources is the offset in absolute magnitude of $\sim 1$ magnitude (at least up to $z \sim 0.6$). Since none of the BCGs are radio loud, this result is consistent with the picture that most powerful radio sources seem to favor host galaxies less luminous than BCGs (e.g., Owen & Laing 1989), typically around a few $M_*$, which at $K$ is $-25.2 \pm 0.4$ (Aragón-Salamanca et al. 1993).

To summarize: GPS, CSS, and FRIi radio galaxies seem to have a redshift evolution similar to a passively evolving elliptical. No evidence for significant luminous
mass increase with decreasing redshift is found, in contrast to BCGs, which do seem to increase in luminous mass (or otherwise seem to deviate from a simple passive evolution). Typical radio source hosts are approximately $M_*$ galaxies, with a luminous mass of $\sim 5 \times 10^{11} M_\odot$, and about 1 magnitude fainter in absolute magnitude than the brightest cluster galaxies at similar redshifts.

### 7.5 Broadband Spectra

With the K-corrected $J$, $H$, and $K$ band magnitudes for the sources, and with (corrected) $R$ band magnitudes added from the literature, restframe broadband energy distributions (SEDs) can be constructed for the sources, which can be compared directly to model SEDs. This will give us besides age and metallicity information, a handle on near-IR emission / absorption properties. If hot dust or large obscuring columns are present in a source, its SED will deviate from model SEDs which do not include non-stellar emission and obscuration. In the next sections the same metallicity and mean age are applied to both the K-correction of the sample and to the construction of the model broadband SED.

We are interested in mean sample properties, and want to minimize source peculiarities, which can be achieved by constructing average broadband SEDs for each of our subsamples (i.e. GPS, CSS, and FRII). The mean is weighted by the inverse of the photometry errors on each source in the class. The mean SEDs are shown in Fig. 7.7, top row. Two important effects can be seen in these plots: 1) The FRII sources are significantly bluer than the other types, about 0.7 magnitude in the mean compared to the GPS galaxies; 2) the large errorbars in the $R - K$ colors are indicative of the large intrinsic scatter present in this color. The FRII source class has two very blue
sources (3C 208.1 and 3C 226), the GPS class has two rather red sources (0428+205 and 0500+019), in both cases increasing the dispersion. Excluding these four sources significantly reduces the scatter in the curves. The large $R-K$ color difference between the FR II and GPS sources disappears completely (cf. Fig. 7.7, bottom row). This leads us to the conclusion that all powerful radio sources (in our sample at least) have similar optical to near-IR broadband spectra, if we ignore the few FR II sources with an excess in blue light and the GPS sources which are heavily obscured (four sources in total). This SED similarity implies similar physical conditions in the nuclei of these radio sources.

With this similarity in mind, all the available broadband SEDs can be combined to reduce the errorbars even further, making a detailed model-data comparison possible. In this overall mean all sources but the 4 outliers 0428+205, 0500+019, 3C 208.1, and 3C 266 are included, leaving 26 SEDs to combine. The mean is constructed in the same way as before, and is represented in Fig. 7.8 by the thick solid line. The errorbars are again 1σ errors, the narrow lines represent the various model SEDs with different mean ages (indicated by 1, 2, 5, and 10 Gyrs) and metallicity. None of the models fit the sample mean SED over the range from $R$ to $K$ band, although the $Z=0.050$ (2.5× solar) metallicity fits the SED rather well in the near-IR ($J$ through $K$, cf. rightmost panel in Fig. 7.8).

Since none of the model SEDs fit the observed mean, an extra component to the model is needed. We will examine two options: 1) emission from hot (nuclear) dust, and 2) intrinsic source extinction and/or blue AGN emission.

### 7.5.1 Hot Dust

The first way to make the model SEDs more like the sample mean SED, is adding emission from hot dust. Hot dust emission in AGN has been modeled previously (Pier & Krolik 1992, 1993; for Seyferts) as a circumnuclear dusty torus, heated by the central engine. Barvainsis (1987, 1990) detected near-IR excess emission from radio
quiet quasars, modeled as thermal emission from dust of \(\sim 1500 \text{ K}\). Evidence for large quantities of cooler dust (50–100 K) has been found by Heckman et al. (1994) for a sample of GPS, CSS and FRII radio galaxies, with \(\sim 10^{12}\) solar luminosities in the mid to far infrared. Since an (extended) dust component re-radiating the AGN emission is already present in these sources, a hotter dust component closer to the nucleus is not unlikely.

We assume the emission spectrum of the hot dust is a black body spectrum, modified by an emissivity proportional to \(\lambda^{-2}\) (cf. Pier & Krolik (1992) for calculated spectra). This emissivity effectively shifts the peak of the spectrum towards shorter wavelengths compared to the pure black body emission peak. In this way a significant contribution to the bluer passbands (\(R\) and \(J\)) can be made without invoking unphysically high dust temperatures. As an upper limit to the dust evaporation temperature \(\sim 2000 \text{ K}\) is adopted (Salpeter 1977), so the range of black body temperatures investigated here runs from 700 to 1800K (comparable to Pier & Krolik's temperature range).

Model \(R\), \(J\), \(H\), and \(K\) band fluxes are calculated integrating under the actual model spectrum, after which the magnitudes are normalized by the \(K\) band flux (i.e. one gets \(R - K\), \(J - K\), and \(H - K\) colors). The additional dust component colors are similarly integrated over the modified Planck spectrum: \(F_{\text{hot dust}} = \int_0^\infty R(\lambda)\lambda^{-2}B_\lambda d\lambda / \int_0^\infty R(\lambda)d\lambda\), with \(R(\lambda)\) being the passband's response function, and \(B_\lambda\) the Planck function.

Adding flux to the \(K\) band will inevitably add flux to the other bands as well, according to the \(\lambda^{-2}B_\lambda(T)\) spectrum. The assumption made here, is that any contribution to the \(R\) band made this way is much smaller than the one to the \(K\) band. At \(T = 1500 \text{ K}\) the fraction of flux ending up in \(R\) is always smaller than 2% of the increase in \(K\), rising to \(\sim 15\%\) at \(T = 1800 \text{ K}\), the upper temperature limit in our models. So only at the edge of our temperature range will the model + hot dust SED not precisely match the \(R - K\) color of our data. In all other cases, the model and data SEDs have the same \(R - K\) color (and \(K\) band point of course) as a consequence of the method used.

For the addition of hot dust emission to be meaningful, the \((R - K)_{\text{model}}\) color has to be less (i.e. bluer) than the \((R - K)_{\text{data}}\), otherwise the added component will actually be in absorption, with an unphysical spectral shape. The unphysical regime is denoted in the plots by the dashed region in Figs. 7.9 – 7.11. Plotted here are the rms-values of the model fit, defined as

\[
\text{rms} = \left[ \sum_{i=R,J,H} ((i - K)_{\text{model+dust}} - (i - K)_{\text{data}})^2 \right]^{\frac{1}{2}} \text{ (mag)} \quad (7.3)
\]

and the fractional contribution of the hot dust component to the \(K\) band flux.

We apply as an additional constraint from our profile fitting (Chapter 6) that the upper limit to a contribution from a point source component at \(K\) band is roughly 35\%. Then the following solutions are obtained:
Figure 7.9: Confidence contours of the model + hot dust fit to the mean SED of the data. The mean age of the sample is assumed to be 2 Gyrs in this plot. Contours increase from the white area around (Z=0.0001, T=1400K) of rms < 0.1 magnitude exponentially outwards (< 0.2, < 0.4, < 0.8, and < 1.6 mags respectively). The lower part of the figure plots the fractional contribution of the hot dust emission to the K band flux. The dashed area to the right indicates "negative emission", i.e. unphysical absorption with the same spectral shape as the emission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean stellar metallicity</td>
<td>40% - 100% solar</td>
</tr>
<tr>
<td>Mean population age</td>
<td>2-5 Gyrs</td>
</tr>
<tr>
<td>Fraction of hot dust emission</td>
<td>~30%</td>
</tr>
<tr>
<td>Black body temperature</td>
<td>900-1300 K</td>
</tr>
</tbody>
</table>

These parameters are roughly consistent with the metallicity and mean age inferred in Sect. 7.4.1.

7.5.2 Intrinsic Extinction

Instead of adding red flux to the model, we can also remove blue light by introducing extinction intrinsic to the source. In the extra solar metallicity case, blue light is actually added to the model, but since the emission and absorption spectra are similar, both cases are considered at the same time. The extinction law adopted here is proportional to λ⁻², as argued by Cardelli et al. (1989), and we assume an \( R_V = A(V)/E(B-V) \) of ~3.1, i.e. the standard value for the diffuse ISM. With
Figure 7.10: Similar plot as in Fig. 9, but with a mean age of 5 Gyrs.

This $R_V$ value and the $A(\lambda)/A(V)$ values from Cardelli et al. (1989, Table 3), the appropriate $J$, $H$, and $K$ band extinctions can be calculated.

Again, the rms-es of the fits are defined by Eqn. 7.3, and are presented in Fig. 7.12. The solid line demarcates the region of extinction (to the left of the line) and emission (to the right). As can be seen in the plot, the only region of reasonably small rms-es is in the extreme right hand corner, implying a stellar population with a 250% solar metallicity and a mean age less than 1 Gyr. However, this also corresponds to a very small contribution of such a component, the rms-es are in fact consistent with no extra component at all. Also a mean age of less than 1 Gyr is hard to reconcile with the broadband colors which are similar to well evolved, old stellar populations (cf. earlier sections and e.g., O’Dea et al. 1996, using $r - i$ data on GPS sources).

Keeping all this in mind, we conclude that explaining the observed mean SED with a model which incorporates extinction of the stellar light does not seem to work. Also, adding blue light to the model (without altering the near-IR part) yields in our opinion unrealistically low ages. The deviation in the near-IR of our mean sample SED from the models is best explained by adding near-IR emission to the model (i.e., the hot dust component), and not by invoking extremes of the model.

### 7.6 Summary and Conclusions

Based on our $JHK$ imaging and stellar synthesis modeling results, we conclude the following:
1. GPS, CSS, and large-scale FR II sources have similar near-IR colors. This implies that these sources have similar host stellar populations, AGN luminosities, and amounts of gas and dust in the near nuclear environment. Also, there is no indication of a higher nuclear density with associated higher extinction in the most compact sources (the GPS galaxies).

2. Fits to color evolution (in $R - K$ and $J - K$) of the sample as a whole yield a mean stellar age of $\sim 5$ Gyrs, and a metallicity of $\sim$ solar. Both values are not very well constrained by these fits, and should be treated as indicative only.

3. Host stellar populations of GPS, CSS, and FR II sources have a redshift evolution consistent with a passively evolving elliptical galaxy. No differences in absolute $K$ band magnitude between the size classes were found, and on average sources seem to be $\sim 1$ magnitude fainter than brightest duster galaxies at similar redshifts.

4. The observed IR-excess compared to the models can be adequately fitted by emission from $\sim 1000$ K hot dust, which may originate in a circumnuclear dusty torus. This emission accounts for $\sim 30\%$ of the flux in $K$ band. The temperature ranges from 900 to about 1300 K, and is significantly hotter than other dust components, like the infrared emission from H II regions with dust temperatures in the range of 50–150 K (e.g., Spitzer 1978).
7.6. SUMMARY AND CONCLUSIONS

Figure 7.12: Confidence contours of the model + absorption fit to the mean SED of the data. Contours increase from the light area in the right hand corner ($0.2 < \text{rms} < 0.3$ magnitude) towards the left as: $< 0.4$, $< 0.5$, $\cdots$ mag. The solid line separates the absorption from the (blue) emission case.

The consistency in near-IR colors between the sources from different size classes argue in favor of the evolution of the radio source along the GPS–CSS–FR I / FR II sequence. No differences in host stellar population and / or different nuclear obscuration properties have been found to indicate possible different evolutionary paths for our size subsamples. The lack of significant differences in the obscuration of the AGN does not support the postulated large amounts of gas needed to confine the radio sources to the sub-kpc scales. However, observations at longer wavelengths are needed to constrain the presence of cooler dust on larger scales. Thus, our results are consistent with the idea that the GPS sources are the progenitors of large-scale powerful radio sources. As such they may provide the key to understanding radio galaxy origin and evolution.

Acknowledgments

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Table 7.1: Mean observational values

<table>
<thead>
<tr>
<th>Mean quantity</th>
<th>GPS</th>
<th>CSS</th>
<th>3CR FRII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift</td>
<td>0.39±0.18</td>
<td>0.30±0.15</td>
<td>0.49±0.25</td>
</tr>
<tr>
<td>J band</td>
<td>16.7±1.4</td>
<td>16.5±0.8</td>
<td>17.3±0.8</td>
</tr>
<tr>
<td>H band</td>
<td>15.7±1.4</td>
<td>15.7±0.9</td>
<td>16.5±0.7</td>
</tr>
<tr>
<td>K band</td>
<td>15.3±1.4</td>
<td>15.1±0.8</td>
<td>15.8±0.7</td>
</tr>
<tr>
<td>J – K\text{ext}</td>
<td>1.43±0.07</td>
<td>1.29±0.10</td>
<td>1.46±0.05</td>
</tr>
<tr>
<td>J – K\text{nuc}</td>
<td>1.61±0.13</td>
<td>1.65±0.14</td>
<td>1.68±0.09</td>
</tr>
<tr>
<td>J – K\text{tot}</td>
<td>1.61±0.08</td>
<td>1.36±0.08</td>
<td>1.56±0.05</td>
</tr>
</tbody>
</table>

Note – All magnitudes are corrected for Galactic extinction