The nuclear spectrum of the radio galaxy NGC 5128
(Centaurus A)

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ABSTRACT

We present near-infrared spectra of the nuclear disk in the nearby radio
galaxy NGC 5128 (Centaurus A). On the basis of the observed strengths of
the [S III] λ0.9532 μm and [Fe II] λ1.2567 μm lines, we classify NGC 5128 as a
LINER. Modeling of the strengths of these and additional lines suggests that
the nuclear region is powered by shocks rather than photoionization.

Subject headings: galaxies: active — galaxies: individual (NGC 5128,
Centaurus A) — galaxies: nuclei — infrared: galaxies

1. Introduction

The galaxy NGC 5128 hosts the extragalactic radio source Centaurus A. It is our
nearest radio galaxy, and has been the subject of intense study which has revealed a jet
seen at radio, near-infrared, and X-ray wavelengths (Meier et al. 1989; Joy et al. 1991;
Schreier et al. 1979), and an unresolved nucleus which appears longward of 2 μm (Turner et
al. 1992). Perhaps the most obvious feature of NGC 5128, however, is the dust lane which
straddles the galaxy. Such prominent and well-ordered dust obscuration is more commonly
associated with spirals, and is unusual for an early-type galaxy (although perhaps not for a
radio galaxy: de Koff et al. 1996). It is widely believed that the dust lane was formed from
material stripped from a dusty disk galaxy (Baade & Minkowski 1954; Thomson 1992), and
a natural consequence of this merger would be substantial star formation, which is indeed
inferred (Quillen, Graham & Frogel 1993; Storchi-Bergmann et al. 1997).

The type of spectroscopic study normally performed on the nuclei of active galaxies,
however, has yet to be undertaken on NGC 5128. Since the nucleus is not visible in

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ground-based optical images, no astrometry has been performed to allow it to be acquired for spectroscopy. Phillips (1982) assumed the nucleus was located at the near-infrared ‘hot spot’ of Kunkel & Bradt (1971), a feature which can now be identified with the infrared jet, and Storchi-Bergmann et al. (1997) used a wide (10′′) slit which contained a significant contribution from material excited by the young stars in the larger-scale disk. Recently, Schreier et al. (1998) have shown that there is a physically distinct Paα-emitting region at the nucleus approximately 2″ in size, which they interpret as a disk. As similar, albeit larger, disks have been seen in a number of FRI radio galaxies, a nuclear spectrum might reveal whether this smaller-scale disk shares their properties.

The only spectrum of the nucleus alone is that of Meadows & Allen (1992, MA92), who used the Infrared Imaging Spectrometer on the 3.9-m Anglo-Australian Telescope, IRIS (Allen et al. 1993), which has the capability to image a field before inserting the dispersing element. In this paper, we present further spectra taken with IRIS, covering the wavelength range 0.9 µm < λ < 2.5 µm, and use them to investigate the excitation mechanism operating at the nucleus of NGC 5128.

Throughout this paper, we adopt a distance of 3.6 Mpc to NGC 5128 (Soria et al. 1996), corresponding to a projected linear scale of 17 pc arcsec⁻¹.

2. Observations and reduction

Data were taken with both narrow (1″4) and wide (5″8) slits at a spatial resolution of 0″8 pixel⁻¹. IRIS was configured to use the IJ (0.9–1.5 µm) and HK (1.4–2.5 µm) echelles and provided a spectral resolution of λ/∆λ ∼ 400 (narrow slit) or ∼ 100 (wide slit). The true nucleus of NGC 5128 was acquired by locating the continuum peak at K′, and spectra were taken at either end of the 13″ slit and differenced to remove the sky and underlying galaxy. All data were taken with the slit oriented east–west in approximately 2″ seeing. Narrow slit HK echelle data were taken on the nights of UT 1991 April 26/27 and 1991 June 25/26 for a total integration time of 7400 s, and were presented in MA92. Narrow slit IJ data totaling 2000 s were taken on UT 1992 April 14. Wide slit data were taken on UT 1992 September 13, with an exposure time of 1200 s in each echelle.

Standard spectral reduction techniques were applied to remove the spatial and spectral response of the detector, the curvature of the echelle orders, and the apparent rotation of the slit, which changes across the orders, before one-dimensional spectra were extracted. The narrow slit spectra, which were taken in non-photometric conditions, have been flux calibrated by scaling the continuum fluxes so that they matched photometry from the
images of MA92, which in turn were calibrated using the aperture photometry of Turner et al. (1992). We estimate that the systematic uncertainties introduced by this method are less than 20%; the ratios derived from line pairs within the $IJ$ or $HK$ echelles are, of course, unaffected. Observations of standard stars were used to calibrate the wide slit data.

3. Results and analysis

The narrow slit spectrum is shown in Figure 1. We present the extracted line fluxes from both the wide and narrow slit spectra in Table 1. These fluxes were obtained by measuring the signal above a linear continuum level which was determined by eye. The placement of this continuum is the dominant source of uncertainty in the measurements, and so several measurements with different ‘reasonable’ continuum levels were made to estimate the possible errors. The measurement uncertainties from the narrow slit data are much smaller than those from the wide slit spectra, due to the lower sky noise, which allows more accurate continuum determination.

Given the poor seeing conditions of our observations, we would expect the line fluxes from the wide slit spectra to be $\sim 40\%$ higher than those from the narrow slit spectra due to slit losses, even if the line emission were unresolved. Coupled with the uncertainty in the flux calibration of the narrow slit data, we are unable to find any evidence for significant spatial extension in any of the emission lines. It therefore seems likely that all the emission lines share the morphology of Pa$\alpha$ seen by Schreier et al. (1998).

3.1. Reddening to the emission line region

The most reliable estimate of the reddening to the emission line region comes from the near-infrared [Fe II] lines, whose intrinsic intensity ratio is fixed (Nussbaumber & Storey 1988). The observed ratio in the narrow slit data suggest $A_V = 3$ mag, although it is also consistent with zero reddening, and provides a formal $3\sigma$ upper limit of $A_V < 8$. In the wide slit data, the 1.6435 $\mu$m line is strongly affected by poor sky subtraction and so no useful ratio can be obtained.

The only reliable H I line ratio we have from the wide slit data is Pa$\beta$/Br$\gamma = 1.25 \pm 0.25$. Compared to the Case B ratio of 5.88, this implies an extinction of $A_V = 10.9 \pm 2.2$. Although the Pa$\beta$/Br$\gamma$ and Pa$\gamma$/Br$\gamma$ ratios from the narrow slit data are less reliable due to the method of flux calibration, they too support a value for the extinction of about ten magnitudes. However, the observed narrow slit Pa$\beta$/Pa$\gamma = 1.83 \pm 0.35$ is consistent with
the Case B value of 1.81, implying negligible reddening, whereas if $A_V \approx 10$, it should be twice as large. A formal $3\sigma$ upper limit to the extinction based on this ratio (which is not affected by flux calibration uncertainties) is $A_V < 7.7 \text{ mag}$. We therefore conclude that the $\text{Br}\gamma$ flux is enhanced by an additional component which, presumably by virtue of being heavily reddened, does not contribute to the Paschen lines. This component could arise from a putative broad line region. Assuming the broad line region suffers the $A_V \approx 30 \text{ mag}$ of extinction which obscures the nuclear continuum (Giles 1986; MA92) then any broad $\text{Br}\gamma$ will be reduced in flux by a factor of about 20. If the broad line is intrinsically 40 times brighter than the narrow line (e.g. Jackson & Eracleous 1995), then the ratio of narrow $\text{Pa}\beta/\text{Br}\gamma \approx 4$, corresponding to $A_V \approx 3$, in line with that derived from the [Fe II] ratio. This extinction is also consistent with obscuration from the dust lane alone, based on the observed nuclear $J - H$ color if we assume that approximately half the nuclear $H$ band emission is non-stellar (MA92), and so we adopt $A_V = 3 \text{ mag}$ for the extinction to the emission line region. This value is somewhat lower than that derived by Schreier et al. (1996), but by failing to correct for the presence of the heavily-reddened nucleus these authors are likely to have overestimated the extinction to the NLR.

### 3.2. Excitation mechanism

MA92 suggested a starburst origin for the emission lines on the basis of their $HK$ spectrum, and in particular the $H_2 v=1–0 \text{ S}(1)/\text{Br}\gamma$ ratio. However, the low dissociation temperature of $H_2$ means the $H_2$ line emission is not produced cospatially with the other emission lines, and this line ratio is therefore not ideal for determining the excitation mechanism. The observed ratio of 0.6 is equally consistent with starburst, Seyfert, and LINER galaxies (Moorwood & Oliva 1988; Larkin et al. 1998). A starburst can, however, be excluded on the basis of the luminosity of the [Fe II] emission. Following the discussion of van der Werf et al. (1993), the radius of an individual SNR at the beginning of the radiative phase is $\sim 6 \text{ pc}$, and our spectroscopic observations indicate that the [Fe II] emission is at best barely resolved. Even making the generous assumption that the line-emitting region is spherical with a diameter of 20 pc, there is only room for at most 5 SNRs but, adopting $L_{\text{[FeII]}} = 10^3 L_\odot$ for a single remnant, about 20 are needed to provide the extinction-corrected luminosity.

Of the emission lines we observe, those of [Fe II] and [S III] have been the most well-studied, and we present a line ratio diagram in Figure 2. Although few objects have been observed in both emission lines, resulting in a sparsely populated plot, many more have fluxes for one or other of the two lines, and different classes of object are fairly well-separated
in each of the ratios, although there are regions of overlap. We can therefore subdivide the parameter space as illustrated. We also plot the theoretical line ratios as determined using the photoionization code CLOUDY V90.04 (Ferland 1996) for a plane-parallel slab with densities in the range $n_H = 10^3$–$10^6$ cm$^{-3}$ illuminated by a power law spectrum extending from 10 $\mu$m to 50 keV with $S_\nu \propto \nu^{-1.4}$, a range of ionization parameter $U = 10^{-2}$–$10^{-5}$ and a gas phase iron abundance one-twentieth of solar. The observed ratios can be explained by an ionization parameter $U \sim 10^{-4}$, typical of LINERs, (e.g. Ferland & Netzer 1983), and a density $n_H \sim 10^{4.5}$ cm$^{-3}$. This relatively high density is required to produce the H I line emission, since the extinction-corrected H$\alpha$ luminosity is $L_{H\alpha} = (2.2 \pm 0.3) \times 10^{32}$ W (under Case B), which is larger than the luminosity in the nuclear disk of M 87 (Ford et al. 1994), yet the emission in NGC 5128 comes from a much smaller region.

We observe He I $\lambda$1.0830 $\mu$m/Pa$\gamma \approx 4$. This compares with typical values of $\sim 2$ (from Case B recombination and the observed He I $\lambda$0.4471 $\mu$m/H$\beta$ ratio) in both H II regions (Doyon, Puxley & Joseph 1992) and AGN (Ferland & Osterbrock 1986), although larger ratios of 6.2 and 6.7 have been observed in Orion and NGC 4151, respectively (Osterbrock, Shaw & Veilleux 1990), and a ratio of 5.8 is predicted for the starburst galaxy NGC 3256 based on the observed He I $\lambda$2.06 $\mu$m/Br$\gamma$ ratio (Doyon, Joseph & Wright 1994). This ratio is therefore unable to tell us anything about the excitation mechanism.

We have also detected the [C I] $\lambda\lambda$0.9840,0.9850 $\mu$m and [S II] $\lambda$1.0330 $\mu$m blends. They have also been seen in NGC 4151, where their fluxes relative to [S III] $\lambda$0.9532 $\mu$m were 0.01 and 0.05, respectively (Osterbrock et al. 1990). We would expect stronger emission from these low-ionization lines in a source with a lower ionization parameter, but there are no data from such sources with which to make comparisons, so we must compare our data with model predictions. We again use CLOUDY for the photoionization models and MAPPINGS II (Sutherland & Dopita 1993) to investigate the effects of shock excitation, performing the same self-consistent iterative process as Dopita & Sutherland (1996). We used a solar iron abundance for the shock models, since grains would be destroyed by the shocks, liberating iron into the gas phase (Greenhouse et al. 1991). A high preshock density is required, since the scaling relation for H$\beta$ luminosity of Dopita & Sutherland (1996) for a planar shock with speed $V$ covering an area $d^2$, requires

$$n \sim 1.1 \times 10^5 \left( \frac{V}{100 \text{ km s}^{-1}} \right)^{-2.41} \left( \frac{d}{10 \text{ pc}} \right)^{-2} \text{ cm}^{-3},$$

to explain the inferred H$\beta$ luminosity.

Table 2 presents the dereddened line fluxes and model results (relative to Pa$\beta$). As MAPPINGS II does not provide the strength of the He I $\lambda$1.0830 $\mu$m line in its output, we are unable to compare the observed value with its prediction. Instead we present a lower limit
to the strength of this line, from Case B ratios and the strength of He I $\lambda 0.4471 \mu m$. The relatively high density required will result in a somewhat larger flux, since He I $\lambda 1.0830 \mu m$ is readily enhanced by collisional excitation. Since all the emission lines we are studying arise from a fairly small wavelength region, the line ratios are not strongly affected by reddening. Even if the true extinction were as high as $A_V = 5$ mag, the most strongly affected line ratio, $[S III]/Pa\beta$, would only increase by 40%, not altering the conclusions we draw.

Although we have not investigated all the parameter space for the shock models, due to the computational effort involved, it is clear that shocks provide a rather better fit to the observed line ratios than do the photoionization models. In particular, photoionization fails to produce the observed line ratios over the range of ionization observed (C$^0$, S$^+$, S$^{2+}$), as has often been seen in the ultraviolet (e.g. Dopita et al. 1997). We therefore favor shocks over photoionization, although ideally we would like some empirical evidence to support this conclusion, from observations of the same emission lines in objects where shocks are known to be the dominant excitation mechanism.

4. Discussion

The above arguments support the classification of NGC 5128 as a LINER, even though the emission lines which define this class (Heckman 1980) are not observable. While Storchi-Bergmann et al. (1997) also made such a classification, their much larger aperture was dominated by emission lines originating in the starburst disk, and so did not directly inform on the nuclear properties. The fact that we see a shock-excited LINER spectrum in the nuclear disk is perhaps not surprising, since the same is seen in M 87 (Virgo A; Harms et al. 1994; Dopita et al. 1997) and the similarities in the radio properties of NGC 5128 and M 87 are quite extensive (Tingay et al. 1998). Whether shock-excited nuclear disks are a common feature of FR I radio galaxies is a question that requires further study.

Spectroscopic observations in the ultraviolet might also confirm our claim that the emission lines are powered by shocks, since the predictions of shock excitation and photoionization for lines such as C IV $\lambda 0.1550 \mu m$ and [Ne V] $\lambda 0.3426 \mu m$ can differ by factors of $10^4$ (e.g. Dopita et al. 1997). Although there is significant extinction to the emission-line region, the emission lines are sufficiently bright that these UV lines might still be detectable. Indeed, our shock model, coupled with $A_V = 3$ mag of extinction, predicts $F_{C IV} \approx 2 \times 10^{-18} W m^{-2}$, which is observable with the Space Telescope Imaging Spectrograph (STIS). However, we note that the C IV flux will be an order of magnitude fainter for every magnitude of visual extinction by which we have underestimated the
true obscuration, so while its detection would unequivocally rule out photoionization, its non-detection would not provide a definitive result.

5. Summary

We have presented near-infrared spectra of the nucleus of NGC 5128, covering the wavelength range 0.9–2.5 µm. The emission line ratios are characteristic of a LINER, and can be modeled fairly well by shock excitation or photoionization by a power law continuum although shocks provide a noticeably better fit. Coupled with the similarities between Cen A and Vir A, we favor shocks as the dominant excitation mechanism in NGC 5128. Ultraviolet spectroscopy might be able to confirm this through the detection of high-ionization lines (e.g. C IV λ0.1550 µm), but the high obscuration in the UV could easily push them below a feasible detection threshold.

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van der Werf, P. P., Genzel, R., Krabbe, A., Blietz, M., Lutz, D., Drapatz, S., Ward, M. J.,

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Table 1: Emission line fluxes through the different spectroscopic apertures. The 1\''4 × 1\''6 aperture measurement have been calibrated as described in the text, and are subject to a ∼ 20% systematic uncertainty, in addition to the random errors listed. Fluxes indicated with a dagger (†) are strongly affected by an uncertain background level as a result of poor OH line subtraction.

<table>
<thead>
<tr>
<th>Line</th>
<th>( \lambda_{\text{rest}} ) (( \mu \text{m} ))</th>
<th>Line fluxes ( \left( 10^{-18} \text{ W m}^{-2} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1''4 \times 1''6 )</td>
<td>( 5''8 \times 1''6 )</td>
</tr>
<tr>
<td>[S II]</td>
<td>0.9532</td>
<td>54 ± 4</td>
</tr>
<tr>
<td>[C I]</td>
<td>0.9850</td>
<td>10 ± 1</td>
</tr>
<tr>
<td>[S II]</td>
<td>1.0330</td>
<td>40 ± 5</td>
</tr>
<tr>
<td>He I</td>
<td>1.0830</td>
<td>50 ± 4</td>
</tr>
<tr>
<td>Pa( \gamma )</td>
<td>1.0939</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1.2567</td>
<td>26 ± 2</td>
</tr>
<tr>
<td>Pa( \beta )</td>
<td>1.2819</td>
<td>22 ± 2</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1.6435</td>
<td>25 ± 4</td>
</tr>
<tr>
<td>H(_2)</td>
<td>2.1213</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Br( \gamma )</td>
<td>2.1657</td>
<td>17 ± 3</td>
</tr>
</tbody>
</table>

Table 2: Comparison of excitation models. All fluxes have been normalized to Pa\( \beta \) = 100, and the observations have been corrected for reddening. The photoionization model has \( n_H = 10^5 \text{ cm}^{-3} \) and \( U = 10^{-4} \). The shock excitation model is for a 120 km s\(^{-1}\) shock with precursor in a medium with density \( n_H = 3 \times 10^4 \text{ cm}^{-3} \) and an equipartition magnetic field.

<table>
<thead>
<tr>
<th>Line</th>
<th>( \lambda_{\text{rest}} ) (( \mu \text{m} ))</th>
<th>Measured</th>
<th>photo</th>
<th>shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>[S III]</td>
<td>0.9532</td>
<td>393 ± 29</td>
<td>849</td>
<td>390</td>
</tr>
<tr>
<td>[C I]</td>
<td>0.9850</td>
<td>68 ± 7</td>
<td>62</td>
<td>50</td>
</tr>
<tr>
<td>[S II]</td>
<td>1.0330</td>
<td>251 ± 31</td>
<td>682</td>
<td>186</td>
</tr>
<tr>
<td>He I</td>
<td>1.0830</td>
<td>291 ± 23</td>
<td>1291</td>
<td>&gt;109</td>
</tr>
<tr>
<td>[Fe II]</td>
<td>1.2567</td>
<td>121 ± 9</td>
<td>77</td>
<td>94</td>
</tr>
<tr>
<td>Pa( \beta )</td>
<td>1.2819</td>
<td>100 ± 9</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Fig. 1.— Nuclear spectrum of NGC 5128, extracted through a $1''4 \times 1''6$ aperture. The emission lines are labeled, as are regions of CO and atmospheric absorption. This spectrum was taken in non-photometric conditions, and the flux scale has been bootstrapped as described in the text.
Fig. 2.— $\frac{[\text{Fe II}]}{\text{Pa} \beta}$ vs $\frac{[\text{S III}]}{\text{Pa} \beta}$ line ratio diagram. The regions expected to be occupied by different classes of object are separated by dotted lines as shown in the inset, and those few objects for which data exist for both forbidden lines are plotted. We have plotted reddening-corrected line ratios for Seyfert galaxies (solid squares), starburst galaxies (open circles), and LINERs (open squares), using data from Kirhakos & Phillips (1989), Simpson et al. (1996), and Alonso-Herrero et al. (1997) and references therein, assuming Case B ratios to convert $\text{H} \alpha$ and $\text{Br} \gamma$ fluxes to $\text{Pa} \beta$. The six-pointed star is the Galactic supernova remnant RCW 103 (Dennefeld 1986). The solid lines are theoretical predictions of photoionization models of different densities, as described in the text.