THE ASTROPHYSICAL JOURNAL, **315**:L103–L106, 1987

THE REDDENING OF CYGNUS A FROM A MEASUREMENT OF PASCHEN-ALPHA

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Received 1986 December 16; accepted 1987 January 27

ABSTRACT

New observations of the strength of Paα, Hα, and Hβ lines in Cygnus A are used to determine the reddening to the narrow emission-line region in this galaxy. The observed Paα:Hα:Hβ ratios are well fitted by a pure Menzel-Baker case B spectrum with $E(B-V) = 0.85 \pm 0.1$. There is no evidence for significant collisional excitation of Hα and no evidence for an obscured broad-line component at Paα.

Subject headings: galaxies: individual — galaxies: nuclei — interstellar: matter — radio sources: galaxies

I. INTRODUCTION

There has been considerable discussion recently concerning the importance of dust obscuration in active galaxies. It is necessary to determine the amount of reddening and obscuration produced by dust to (a) correctly analyze the emission-line spectrum to give the physical conditions near to the central engine, (b) understand the emission mechanisms that produce the observed continuum spectral energy distribution over a wide range of wavelengths and the way in which the intrinsic spectrum of the central engine may be subsequently modified, and (c) illuminate the relationships between the various different classes of active galaxy. The hydrogen line spectrum offers a relatively simple system in which the effects of reddening and different physical conditions may be disentangled. This is particularly true of analyses that include observations of Paschen-α ($\lambda = 1.875$ μm). Compared with the optical Balmer lines, the effects of dust extinction are considerably reduced for Paα, yet the line is produced by a transition from the same upper level as is responsible for Hβ. This *Letter* reports new observations of Paα, Hα, and Hβ in the powerful radio galaxy Cygnus A (3C 405) at $z = 0.056$.

Cygnus A is a prototype for the radio-luminous narrow-line radio galaxies (NLRGs). These sources have radio luminosities that are in many cases as great as radio-loud quasars (Cygnus A would be seen in the 3C sample even if removed to $z > 1$) but do not show the strong nonstellar optical continuum and broad permitted lines that characterize quasars. The relationship of the NLRGs to the quasars and broad-line radio galaxies (BLRGs) is not clear. Fabbiano *et al.* (1986) have recently observed the NLRG 3C 219 and claim to find evidence for a highly reddened broad-line component at Paα. Such a component would extend to the NLRGs and BLRGs the proposition by Lawrence and Elvis (1982) that many narrow-line Seyfert 2 galaxies are actually broad-line Seyfert 1 galaxies in which the broad-line–emitting region is obscured by dust.

In the next section we describe our new observations of the hydrogen line spectrum of Cygnus A. In § III it is shown that the ratios of Paα, Hα, and Hβ are explained by simple reddening of the case B values, with no requirement for collisional enhancement of Hα, and upper limits are placed on any broad-line component to Paα.

II. OBSERVATIONS

New spectrophotometric observations of Paα, Hα, and Hβ were made using the 3.8 m United Kingdom Infrared Telescope (UKIRT) on 1986 May 11 and the 2.2 m University of Hawaii telescope on 1986 October 4. These observations are described below.

a) *Measurement of Paschen-α*

Observation of the infrared spectrum of Cygnus A was made using the CGS2 instrument at the f/35 Cassegrain focus of UKIRT. The CGS2 is a cooled-grating spectrometer utilizing a seven-element array InSb detector. A 637 lines mm^{-1} grating was used at first order, giving a pixel size of 0.0036 μm and a resolution of $R \approx 550$. This corresponds to a velocity resolution of about 550 km s^{-1}, which is well matched to the 500 km s^{-1} width of the narrow optical emission lines measured by Osterbrock and Miller (1975).

The spectrum of Cygnus A was calibrated using observations of the standard K0 III star BS 7615 to determine the atmospheric transmission and instrumental response. To sample sufficient continuum so that the detection and measurement of Paα was not affected by uncertainties in the continuum level and to allow for a consistency check with published broad-band photometry, a total of 12 grating positions were used to cover the entire wavelength range from 1.945 to 2.045 μm. These were stepped so as to sample at twice the resolution over the entire wavelength range and sample at 6 times the resolution in the 0.03 μm region centered around the Paα line itself. This latter additional threefold oversampling was subsequently removed by binning.

The infrared beam was centered on the emission-line maximum noted by van den Bergh (1976) and Pierce and Stockton (1986) using precise offsets from nearby stars. The infrared beam size was measured to be circular and 4″.0 in diameter, so the position of the radio core of Cygnus A, which is about 1″.5 to the southeast of the emission-line maximum, should be

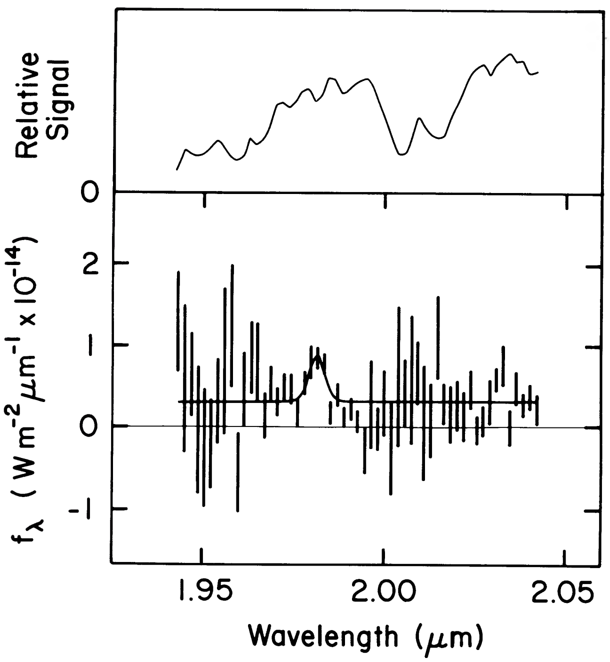

FIG. 1.—The infrared spectrum of Cygnus A (*bottom*). The strong narrow Paα line is indicated. The continuous curve represents a model comprising a fitted continuum and Gaussian emission component as described in the text. Attention should be paid to the variation in the error bars in the spectrum which is caused by the varying atmospheric transmission over the wavelength interval and by the different degrees of oversampling used in the observation. The upper box shows the relative signal from a source with a flat infrared spectrum (such as Cygnus A) observed through one Mauna Kea atmosphere.

included in the beam. A reference throw of 20″ in the north-south direction was used.

The infrared spectrum of Cygnus A is shown in Figure 1 in units of W m^{-2} μm^{-1}. The error bars at each point in the spectrum represent the standard error derived from the many individual integrations at each grating position. The error bars vary along the spectrum because (*a*) the area around Paα was more heavily sampled and (*b*) the atmospheric transmission function changes with wavelength. The relative signal of an infrared source with flat infrared spectrum observed through one atmosphere is shown in the upper portion of Figure 1.

A narrow Paα line at 1.981 μm is clearly detected in the spectrum of Cygnus A. Again, it is necessary to note that the uncertainties in the spectrum around Paα are much smaller than elsewhere on account of the greater atmospheric transmission at this wavelength and the increased effective integration time produced by the additional oversampling around Paα used in the observations. The $(H - K)$ color of Cygnus A is 0.92 (Lebofsky 1981), implying an essentially flat spectrum in f_λ over the small wavelength range sampled here. A flat continuum was therefore fitted to the 14 independent data points with $\lambda < 1.965$ μm and the 25 points with $\lambda > 1.999$ μm using a χ^2 statistic. These continuum points are hence all over 2500 km s^{-1} from the central velocity of Paα. The fitted continuum has a flux density of 3.1×10^{-15} W m^{-2} μm^{-1} with an uncertainty of 0.45 W m^{-2} μm^{-1}, equivalent to a K magnitude of 12.87 ± 0.15. This agrees satisfactorily with the broad-band $K = 12.69 \pm 0.05$ measurement made through an 11″.5 aperture by Lebofsky (1981). The red $(H - K)$ color suggests that at least 40% (and probably more) of the K radiation in the 11″.5 aperture is nonstellar, and such a component could well produce a relatively flat growth curve between 4″ and 11″.5 since the nonstellar component is likely to be contained wholly within the former.

The flux in the Paα line was determined by fitting a Gaussian line profile to the continuum-subtracted spectrum in the wavelength range 1.969–1.993 μm. This had the central intensity, central wavelength, and the full width at half-maximum (FWHM) as free parameters. The measured flux is $3.1 \pm 0.4 \times 10^{-17}$ W m^{-2}. The uncertainty in the continuum level increases this uncertainty to about 0.5×10^{-17} W m^{-2}. The detected line is narrow, with a FWHM velocity width of 720 ± 100 km s^{-1}. This is consistent with an intrinsic width of about 500 km s^{-1}, as seen in the optical emission lines, and the instrumental broadening of 550 km s^{-1}. The equivalent width of Paα is 0.010 μm, or 0.5%.

The small velocity width and relatively low equivalent width of Paα in Cygnus A emphasizes the advantages afforded by spectrometers with greater resolution than the 1% given by the circular variable filters usually used for extragalactic Paα measurements. The higher resolution also allows for higher spectrophotometric accuracy because the atmospheric transmission can be determined at a wavelength sampling of less than the width of the emission feature of interest. This is particularly important for wavelengths near to the edge of the atmospheric K window ($\lambda < 2.1$ μm), equivalent to redshifts less than 0.12.

b) Measurement of the Balmer Lines Hα *and* Hβ

There is no published absolute spectrophotometry of the Balmer lines in Cygnus A. Osterbrock and Miller (1975) published a precise value of the Balmer decrement through a 4″ × 2″ aperture but calibrated the absolute fluxes of all their spectral lines using an earlier absolute measurement of [O III] λ5007 in a larger 9″.4 aperture. In view of the complex extended geometry of the line-emitting region in Cygnus A and evidence for variations in the Balmer decrement across this region (Pierce and Stockton 1986), it was decided to obtain new spectrophotometry of the Balmer lines through an aperture that closely matched that of the infrared measurement described above.

The Faint Object Spectrograph (FOS) was used at f/10 Cassegrain focus on the University of Hawaii 2.2 m telescope. The Galileo/Institute for Astronomy three-phase Texas Instruments CCD was used as the detector. A long slit 4″.5 wide was orientated so as to straddle both the emission-line maximum and the radio core position. The image scale on the CCD was 0″.6 pixel^{-1}, and the dispersion was 0.7 Å pixel^{-1} with a spectral resolution of ~ 8 Å. Two integrations of 15 minutes and 30 minutes, respectively, were taken to encompass the spectral regions of Hα and Hβ. These spectra were calibrated photometrically by observations of BD +25°3941 (Stone 1977).

Spectra were extracted from the CCD images, which had been reduced in the standard way, using a pseudoaperture 4″.0

wide centered on the location of the emission-line maximum. Line fluxes in Hα and Hβ were determined by fitting a continuum on either side of the lines. No attempt at fitting the emission lines was made in view of the possibly complex shape of the line profiles. The Hα line is partially blended with [N II] $\lambda\lambda$6548, 6583, but the lines merge only at about one-sixth of the peak intensity in Hα and do not significantly affect the Hα measurement at the 5% level.

The Hα and Hβ line fluxes are tabulated in Table 1 together with the Paα measurement. Uncertainties in the fluxes of the Balmer lines are believed to be about 7% (although the Balmer decrement is probably good to 5%). The measured Hβ flux of 0.85×10^{-17} W m^{-2} appears to be consistent with the 1.2×10^{-17} W m^{-2} inferred by Osterbrock and Miller (1975) in the 9''.4 aperture and the map of emission-line intensity given by Pierce and Stockton (1986). The Hα:Hβ decrement measured here is 6.24 ± 0.3, similar to the 6.6 measured in a similar aperture by Osterbrock and Miller (1975).

III. DISCUSSION

The most interesting presentation of these data is in terms of the Paα/Hα:Hα/Hβ diagram (cf. Lacy *et al.* 1982). Figure 2 shows the present observations of Cygnus A on this diagram, together with the Menzel-Baker case B recombination point, Paα/Hα = 0.10 and Hα/Hβ = 2.8 (see, e.g., Osterbrock 1974) and the reddening vector from Savage and Mathis (1979) used by Lacy *et al.* (1982)—$A_{\mathrm{Pa}\alpha} = 0.37\ E(B-V)$, $A_{\mathrm{H}\alpha} = 2.52\ E(B-V)$, and $A_{\mathrm{H}\beta} = 3.65\ E(B-V)$.

The Cygnus A data in Figure 2 are well represented by a case B recombination spectrum with 0.85 ± 0.05 mag of reddening in $E(B-V)$. This extinction is higher than the value of 0.69 given by Osterbrock and Miller (1975) despite the lower value of Hα/Hβ recorded here because (*a*) the Osterbrock and Miller value was derived from the mean of the decrements observed in Hα/Hβ, Hα/Hγ, and Hα/Hδ (the latter having a markedly lower c value than the others) and (*b*) they used a slightly different reddening curve. Including such systematic uncertainties, an overall uncertainty in $E(B-V)$ of 0.1 is probably appropriate.

There is no evidence for any collisional enhancement of Hα. Collisional excitation of Hα can occur through X-ray heating of the gas near the ionization front (see, e.g., Netzer 1982; Halpern and Steiner 1983; Gaskel and Ferland 1984). Ferland and Osterbrock (1985) presented evidence of this effect in the Hα:Hβ:Lyα ratios in the two NLRGs 3C 192 and 3C 223, which both had dereddened Hα/Hβ of about

TABLE 1

HYDROGEN LINE FLUXES AND RATIOS

Line/Ratio	Value
Hβ 4861	0.85×10^{-17} W m^{-2} ± 7%
Hα 6563	5.30×10^{-17} W m^{-2} ± 7%
Paα 18750...	3.1×10^{-17} W m^{-2} ± 18%
Paα:Hα	0.58 ± 19%
Hα:Hβ......	6.24 ± 5%

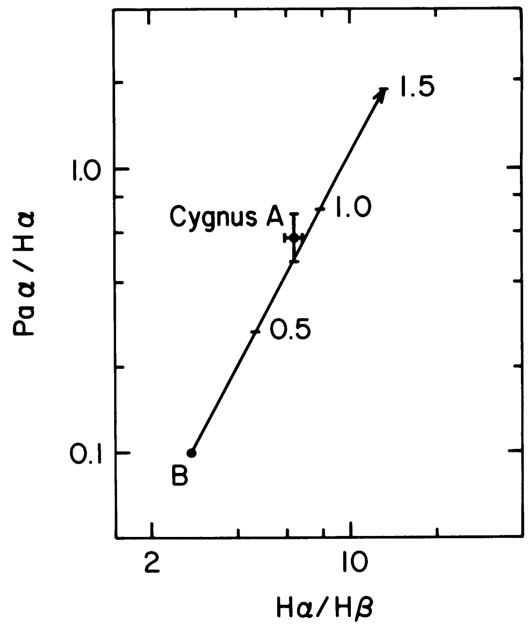

FIG. 2.—The Paα/Hα:Hα/Hβ diagram for Cygnus A. The point B represents the Menzel-Baker case B values, and the vector emanating from that point indicates the effect of a standard reddening curve, with values of $E(B-V)$ marked.

3.2. Because the Paα/Hβ ratio is not significantly altered by the collisional excitation (see, e.g., Gaskel and Ferland 1984), the effect of such excitation is to move a spectrum diagonally to the lower right on Figure 2. The reason that Cygnus A does not appear to show this effect is not known but may be linked to the fact that the ratio of soft X-ray to hydrogen line emission is somewhat greater for 3C 192 and 3C 223 than for Cygnus A. Using the flux densities in X-rays and Hβ for 3C 192 and 3C 223, given by Fabbiano *et al.* (1984) and Ferland and Osterbrock (1985), and the upper limit to the nuclear X-ray flux density of Cygnus A from Feigelson and Schreier (1979) and Arnaud *et al.* (1984), the ratio of X-ray to Hβ emission is at least 5 times greater in 3C 192 and 3C 223 than in Cygnus A after allowing for the extinction to the narrow-line–emitting regions. This may be related to the unusual extended geometry of the narrow-line–emitting region, which is located 1''.5 (roughly 2.4 kpc if $H_0 = 50$ km s^{-1} Mpc^{-1}) from the position of the radio core. Observations of Paα in 3C 192 and 3C 223 (at redshifts of 0.060 and 0.137, respectively) are possible from the ground using a spectrometer such as CGS2 on UKIRT and would be interesting.

Given that the foreground Galactic reddening is unlikely to be greater than $E(B-V) = 0.4$ (van den Bergh 1976; Spinrad and Stauffer 1982), this result implies that there is considerable reddening intrinsic to Cygnus A. Cygnus A has, of course, an appearance that is suggestive of a dust lane similar to that in Centaurus A (see, e.g., Osterbrock 1983), although van den Bergh (1976) and Pierce and Stockton (1986) have pointed out that the resemblance may be superficial at best.

The second interesting result concerns the apparent absence of broad wings in the infrared Paα line. As discussed by Osterbrock and Miller (1985) and by Osterbrock (1983), Cygnus A is unusual among NLRGs in the strength of its nonstellar continuum. Osterbrock (1983) deduced that 60% of the light at 5000 Å in a 4″.0 × 2″.7 aperture was produced by the featureless continuum. This may be compared with 10%–20% in most NLRGs and essentially 100% in most BLRGs. In view of this and the frequent recent discussion of whether some narrow-line active galaxies are really obscured broad-line sources, the limits on the broad-line flux are of some interest. While it is conceivable that errors in the positioning of the infrared beam led to the exclusion of broad-line radiation from the radio core position, the large continuum flux density suggests that most of the light from the nucleus was indeed included in the aperture.

The fitting analysis described above was repeated using a sum of both a Gaussian narrow component and a broad component with triangular profile, both of varying intensity. The FWHM of the broad component was chosen to be 2000 km s^{-1}, which is representative of the widths of the broad lines in BLRGs (Grandi and Osterbrock 1978). Unfortunately, an unexpected dip in the observed spectrum just longward of Paα at 2.00 μm complicates the analysis. This depression in the continuum coincides with an atmospheric absorption feature due to CO_2 at 2.01 μm, as evidenced by the increased error bars on the spectrum in Figure 1 and may represent imperfect calibration from the standard star. Fitting a broad component on both sides of Paα indicates that the maximum flux in such a component is very low, 0.5×10^{-17} W m^{-2}, or 0.16 of the narrow line. Fitting only on the blue wing, however, allows a component of up to 2.5×10^{-17} W m^{-2}, or 0.8 of the narrow line flux, to be present, and this may be a more realistic limit.

Nevertheless, in conventional BLRGs the broad components of the permitted lines are generally at least 10 times more luminous than the narrow components (e.g., Osterbrock, Koski, and Phillips 1976). It is clear from the fitting analysis and from inspection of Figure 1 that no such component is seen at Paα in Cygnus A. If Cygnus A is really a conventional BLRG in disguise, then this would require an extinction to the broad line region of at least $A_V \approx 25$ mag.

IV. SUMMARY

The detection of a strong narrow Paα line in Cygnus A has allowed us to determine unambiguously the reddening to the narrow emission-line region in this prototypical active galaxy as $E(B - V) = 0.85 \pm 0.1$. The high Balmer decrements seen in the optical spectrum of this galaxy appear to be caused purely by this extinction with no requirement for collisional excitation of the Hα line. There is no evidence for a significant broad-line component to the Paα line.

We are grateful to Tom Geballe and Dolores Walther for assistance in making the infrared observations and to Alan Stockton for collaborating on the optical observations. We also acknowledge many interesting discussions about Cygnus A with Alan Stockton and a helpful comment from Steven Willner.

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