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# PHOTOGRAPHIC PHOTOMETRY AND THE OPTICAL SPECTRUM OF THE SEYFERT GALAXY IC 4329 A

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## ABSTRACT

Spectrophotometric and photographic observations of IC 4329 A show that this Seyfert galaxy has reduced dimensions $D \times d = (13.6 \times 7.6)$ kpc and a high luminosity $M_{\rm ph} = -20.2$. The nucleus is stratified in three zones: first, a region where the wide components of the Balmer lines are formed having $N_e \sim 10^9$ cm$^{-3}$ and a velocity dispersion of $\sim 5000$ km s$^{-1}$; second, a region where the forbidden lines and the shorter wavelength peak of the Balmer lines are formed, characterized by $T_e \sim 12{,}000$ K and $N_e \sim 10^6$ cm$^{-3}$; finally, the longer wavelength peak of the Balmer lines originates in a gas cloud receding from the nucleus with $V = 2100$ km s$^{-1}$.

*Subject headings:* galaxies: individual — galaxies: photometry — galaxies: Seyfert

## I. INTRODUCTION

IC 4329 A was previously studied by Disney (1973), who found it to be an extreme case of a Seyfert galaxy and one of the most luminous extragalactic H$\beta$ emitters. The 10 $\mu$m observation of this galaxy (Kleinmann and Wright 1974) indicates a luminosity just above the mean for the Seyfert galaxies.

In the present paper photographic photometry of IC 4329 A is presented and magnitude, luminosity, and diameters of the main body derived. Furthermore, the total fluxes in the broad H$\alpha$, H$\beta$, and the forbidden $\lambda$5007 as well as the energy distribution between 3600 and 7300 Å were also measured.

## II. OBSERVATIONS

The spectrophotometric data were obtained with the dual channel computer–controlled scanner attached on both the 60 inch (1.5 m) and 36 inch (91 cm) telescopes of the Cerro Tololo Inter-American Observatory during April and May of 1973. Spectra of 114 Å mm$^{-1}$ at H$\alpha$ were obtained using a Westinghouse fiber optic image tube with the Cassegrain spectrograph of the 60 inch telescope. They were calibrated using the spot sensitometer. Photographic plates were obtained with the 60 inch telescope of the Bosque Alegre station (Córdoba).

## III. REDUCTION AND RESULTS

The photographic photometry of IC 4329 A was carried out using 40$^{\rm m}$ exposure 103a-O plate following the method described by Sérsic (1968). The apparent total photographic magnitude corrected for galactic absorption was found to be $m = 13.04$. Adopting a Hubble constant of 100 km s$^{-1}$ Mpc$^{-1}$ and the mean radial velocity $V = 4578 \pm 154$ km s$^{-1}$, a true distance modulus $m - M = 33.3$ was obtained; consequently, the absolute photographic magnitude results in $M_{\rm ph} = -20.25$. If we adopt $(M_{\rm ph})_\odot = 5.41$, the corresponding luminosity is $\mathscr{L}/\mathscr{L}_\odot = 1.83 \times 10^{10}$. In addition we estimated the major and minor diameters of the galaxy as $D = 13.6$ kpc, and $d = 7.6$ kpc, respectively.

The mean radial velocity measured from the [O III] emission lines and the brighter peak of H$\alpha$ was corrected for galactic rotation and reduced to the Sun.

The spectrum of this galaxy was described by Disney (1973) and Martin (1974) as having very wide emission Balmer lines with a double peak at H$\beta$. These features are also present in our spectra. Moreover, we have also detected a double peak in H$\alpha$. Figures 1 and 2 illustrate the H$\alpha$ and H$\beta$ profiles, respectively, with the above mentioned spectral features. The radial velocity difference measured from the peaks corresponding to the shorter wavelengths (H$\alpha_{\rm sh}$, H$\beta_{\rm sh}$) and the longer ones (H$\alpha_l$, H$\beta_l$) is $V = 2185 \pm 200$ km s$^{-1}$. The shorter wavelength peaks of the Balmer lines have the same redshift as that of the forbidden lines.

The observed blended profiles of H$\alpha$ + [N II] and H$\beta$ + $\lambda$4958 [O III] (Figs. 1 and 2, *filled circles*) are well approximated by a superposition of Gaussians (*heavy dashed line*). The parameters $I_0$ and $\sigma$ were obtained by trial and error and are listed in Table 1. We remark that variations of about 8% in the central intensity ($I_0$) lead to noticeable differences between observed and calculated profiles. For the [N II] lines we have adopted the dispersion obtained from the observed profile of $\lambda$5007 [O III]. For the peaks of the Balmer lines we adopted alternatively the above $\sigma$ for one peak, varying at the same time the dispersion of the other. The best fit was obtained by adopting the same dispersion for the both peaks. The asymmetry of the wings in the Balmer lines might be produced, as suggested by the composed Gaussians, by a shift of the maximum of the wide component with respect to the

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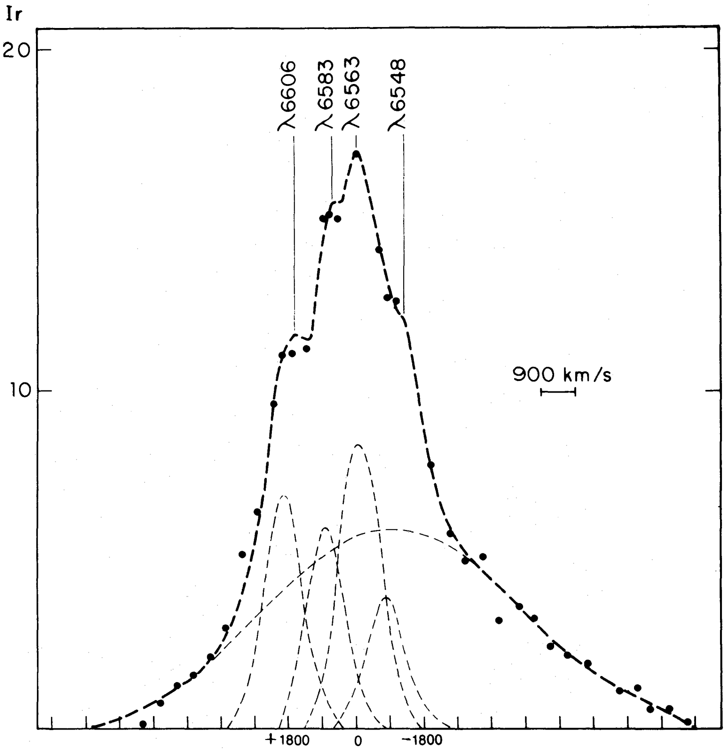


FIG. 1.—The observed and calculated profiles of Hα + [N II] are represented by filled circles and heavy dashed line, respectively.

shorter wavelength peak. The shift for Hα is toward the shorter wavelength, while for Hβ it is in the opposite direction. If the shifts are supposed to be in the same direction, the observed points of one of the lines have systematic difference ($\Delta V = 1400$ km s$^{-1}$) with respect to the calculated Gaussian distribution.

Table 2 gives in succession the observed intensity (relative to the intensity of $H\beta_{sh}$), the full width at half maximum (FWHM), and the full width at zero intensity (FW0I). Absorption lines of an integrated stellar spectrum are clearly observed at Na D and Mg λ5180.

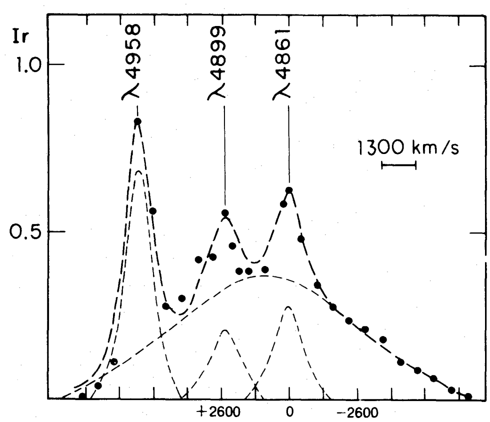


FIG. 2.—The observed and calculated profiles of Hβ + [O III] are represented by filled circles and heavy dashed lines, respectively.

From the spectrophotometric observations we have measured the total fluxes in the broad Hα, Hβ, and the forbidden λ5007 lines. Therefore, adopting a distance of 45 Mpc for the galaxy, the corresponding luminosities could be determined. These values and the total fluxes are given in Table 3. Continuum measurements, made at points selected to lie as much as possible in clear regions, uncontaminated by emission lines, are listed as $f_\nu$ in Table 4.

## IV. INTERPRETATION

The Balmer lines profiles consist of a double peak roughly similar to the forbidden lines in profiles with very extensive wings. If we assume mass motion or turbulence as the causative factor of the Balmer

TABLE 1

PARAMETERS OF GAUSSIAN CURVES

| Line | $I_0$ | $\sigma$ (km s$^{-1}$) |
|---|---|---|
| 6583 [N II] | 0.6 | 786 |
| 6606 $H\alpha_l$ | 0.7 | 786 |
| $H\alpha_b$ | 0.6 | 4935 |
| $H\alpha_{sh}$ | 0.85 | 777 |
| 6548 [N II] | 0.40 | 770 |
| 4958 [O III] | 0.69 | 838 |
| 4899 $H\beta_l$ | 0.20 | 855 |
| $H\beta_b$ | 0.36 | 5295 |
| $H\beta_{sh}$ | 0.28 | 855 |

TABLE 2

RELATIVE EMISSION LINES AND FULL WIDTHS

| Ion | Line (Å) | $I/IH\beta_{sh}$ | FWHM $\times 10^3$ km s$^{-1}$ | FW0I $\times 10^3$ km s$^{-1}$ |
|---|---|---|---|---|
| [Ar III] | 7135 | 0.42 | ... | ... |
| He I | 7091 | 0.42 | ... | ... |
| [S II] | 6730–17 | 0.88 | ... | ... |
| [N II] | 6583 | 2.38 | 1.3 | 3.5 |
| $H\alpha_l$ | 6606 | 3.12 | 1.4 | 3.6 |
| $H\alpha_b$ | 6563 | 14.80 | 9.1 | 17.3 |
| $H\alpha_{sh}$ | 6563 | 3.53 | 1.6 | 4.1 |
| [N II] | 6548 | 1.59 | 1.3 | 3.7 |
| O I | 6300 | 0.67 | 1.6 | 2.7 |
| [O III] | 5007 | 5.11 | 1.3 | 4.1 |
| [O III] | 4958 | 1.99 | 1.5 | 3.1 |
| $H\beta_l$ | 4899 | 0.52 | 1.4 | 3.3 |
| $H\beta_b$ | 4861 | 6.66 | 8.81 | 16.3 |
| $H\beta_{sh}$ | 4861 | 1.00 | 1.2 | 3.7 |
| [O III] | 4363 | 0.55 | 1.1 | 2.4 |
| $H\gamma_b$ | 4340 | 1.29 | 6.2 | 10.6 |
| $H\gamma_{sh}$ | 4340 | 0.60 | 2.0 | 3.8 |

profiles, the existence of at least two regions of quite distinct properties should be required. A region where the wide component of the Balmer lines is produced is characterized by a high velocity dispersion ($\sim 5000$ km s$^{-1}$) as indicated by the wing profiles, and high electronic density $N_e \sim 10^9$, so that all forbidden lines that could be expected to be observed are collisionally de-excited. The ratio $H\alpha/H\beta = 6.6$ given by the total fluxes (Table 3) was corrected for reddening by comparing the observed ratio with the expected one $H\alpha/H\beta = 2.8$, assuming radiative recombination (Pengelly 1964) under case B conditions (Baker and Menzel 1938). We assume that the absorption $A_\lambda$ has a linear dependence on the reciprocal of the wavelength and that the visual absorption $A_v = 3.0E_{B-V}$. $A_\lambda$ is calculated as a function of the $H\alpha/H\beta$ ratio from the equation $A_\lambda = (4.69/\lambda - 1.45) \log (H\alpha/2.8H\beta)$, where $\lambda$ is given in microns. A rough estimate of absorption in $H\beta$ yields 3.1 mag. The luminosity in $H\beta$ after applying the reddening correction become substantially increased ($\mathscr{L}_{H\beta} \sim 1.2 \times 10^{42}$ ergs s$^{-1}$). From the de-reddened $\mathscr{L}_{H\beta}$, the mass and volume occupied by the ionized gas can be evaluated. To do this, we assume that the emission coefficient for the $H\beta (J_{H\beta})$ is the same as under recombination conditions at $10^4$ K. The necessary relations are:

$$L_{H\beta} = 4\pi J_{H\beta} 4/3\pi R^3 ,$$

$$4\pi J_{H\beta} = 1.24 \times 10^{-25} N_e N_p \text{ ergs s}^{-1} \text{ cm}^{-3} .$$

TABLE 3

FLUXES AND LUMINOSITIES OF IC 4329 A

| Line | Flux $F_\nu$ (ergs s$^{-1}$ cm$^{-2}$) | Luminosity $\mathscr{L}_\nu$ (ergs s$^{-1}$) |
|---|---|---|
| $H\alpha$ | $1.82 \times 10^{-12}$ | $4.55 \times 10^{41}$ |
| $H\beta$ | $2.73 \times 10^{-13}$ | $6.82 \times 10^{40}$ |
| 5007 [O III] | $3.11 \times 10^{-13}$ | $7.77 \times 10^{40}$ |

We also assume the number of protons to be equal to that of electrons, and we adopt this number to be about $10^9$ cm$^{-3}$. Hence the mass of the ionized gas and the radius of the corresponding sphere are $M_{H\,II} \sim 8\,M_\odot$ and $R = 1.32 \times 10^{16}$ cm, respectively.

The electronic temperature and density of the region where the forbidden lines and short wavelength peak of the Balmer lines are formed, were derived from the observed intensities listed in Table 1. According to Boyarchuck, Gersberg, and Pronik (1969) the relative intensities of $I$[S II]/$IH\beta_{sh}$; $I$[N II]/$IH\beta_{sh}$; $I\lambda$4363[O III]/$IH\beta_{sh}$; and ($I\lambda$4958 + $I\lambda$5007[O III])/$IH\beta_{sh}$ yield $T_e$ and $N_e$ of the ionized gas. We adopted the cosmic abundance O I/H I $\sim 10^{-3.17}$; N I/H I $\sim 10^{-4.04}$, and S I/H I $\sim 10^{-4.7}$, given by Allen (1962). Figure 3 shows the ($N_e$, $T_e$) diagram. The data for the isointensity curves are taken from the above mentioned author. The curves give a solution for $N_e \sim 10^6$ cm$^{-3}$ and $T_e \sim 12{,}000$ K. The electronic temperature was also computed from the intensity ratios of the nebulium lines. The obtained $T_e \sim 60{,}000$ K appears to be too high, and it is difficult to see how the observed intensities of [N II] and [S II] are consistent with such temperature. The observed intensity ratios of the [O III] lines in this galaxy can be explained accepting a high

TABLE 4

CONTINUUM FLUXES IN IC 4329 A

| Wavelength $\lambda$ | $f_\nu$ (ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) |
|---|---|
| 3444 | $0.718 \times 10^{-26}$ |
| 3628 | $0.816 \times 10^{-26}$ |
| 3742 | $0.123 \times 10^{-25}$ |
| 4096 | $0.157 \times 10^{-25}$ |
| 4449 | $0.280 \times 10^{-25}$ |
| 5346 | $0.597 \times 10^{-25}$ |
| 6150 | $0.104 \times 10^{-24}$ |
| 7213 | $0.131 \times 10^{-24}$ |

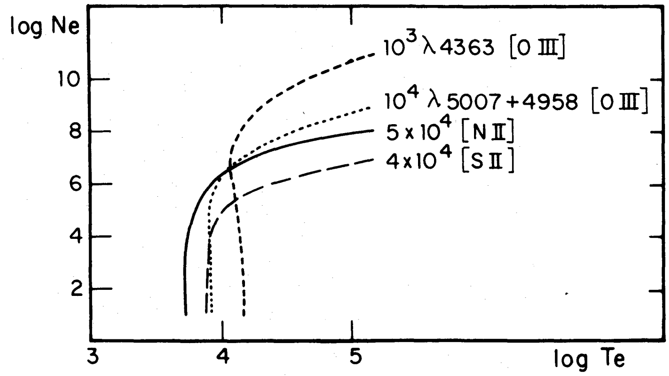


FIG. 3.—Isointensities curves of the function $\theta(N_e T_e)$ for the emission lines of the ions O III, N II, and S II

density, $N_e \approx 10^6$ cm$^{-3}$, rather than a high temperature.

The observed energy distribution of IC 4329 A has been corrected for reddening, using the relationship given above. Comparing the corrected energy distribution with that of NGC 4151 (Anderson 1970), there seems to be some evidence of a nonthermal contribution associated with IC 4329 A (see Fig. 4).

The stellar component in this galaxy is probably due to G0 and later stars as suggested by the strong intensity of the absorption lines λ5180 Mg I and Na D.

According to Oke (1972), the presence of absorption lines such as Ca II and Mg I and the value of the absolute flux $F_\lambda$ at λ4000 set an upper limit to the spectral index $\alpha$ of the nonthermal source. From the observed Mg I line and an unreddened absolute flux $F_{\lambda 4000} = 1.2 \times 10^{29}$ ergs s$^{-1}$ Hz$^{-1}$ of IC 4329 A, we found an upper limit of $-1.4$ for the $\alpha$ index.

We have combined the continuum of an elliptical galaxy (Schild and Oke 1971), with nonthermal continua having $\alpha = -1.4$ and $\alpha = -2.1$, respectively. The nonthermal contributions were built up with different ratios—10, 30, and 50%—for λ5556. The best fit (Fig. 4, *dashed line*) was found for 50% of the nonthermal contribution with $\alpha = -1.4$ at λ5556.

## V. CONCLUSIONS

This work allows us to conclude that IC 4329 A is a galaxy of somewhat reduced dimensions $D \times d = (13.6 \times 7.6)$ kpc and high luminosity $M_{\rm ph} = -20.25$. The nucleus is stratified in different zones. There is a region where the wings of the Balmer lines are formed having a radius of about $10^{16}$ cm and high density of about $10^9$ cm$^{-3}$. In such a region the gas would be moving at the high velocity of approximately 5000 km s$^{-1}$. The total amount of matter involved in the broad line emission, $M_{\rm H\,II} \sim 8\, M_\odot$, does not appear to be too large. A second region where the forbidden lines and the short wavelength peak of the Balmer lines are formed has $N_e \sim 10^6$ cm$^{-3}$ and $T_e \sim 12{,}000$ K, while the velocity of the gas is about 700 km s$^{-1}$. It is still possible to distinguish a third region where the longer wavelength peak of the Balmer lines is formed. This might be an ionized cloud emerging from the nucleus with a velocity of about 2100 km s$^{-1}$ receding from

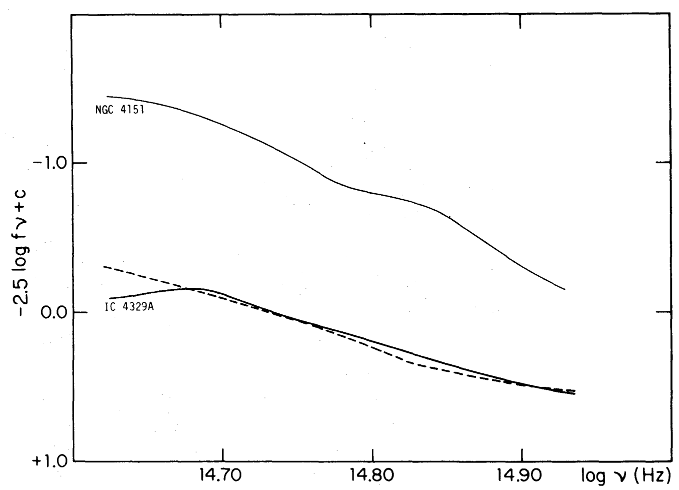


FIG. 4.—*Solid lines*, the unreddened energy distribution of IC 4329 A and the continuum of NGC 4151. *Dashed line*, the result of combining the continuum of an elliptical galaxy with a nonthermal continuum with $\alpha = -1.4$.

us. The ionized cloud, whose size should be of the order of 7″, could be detected from Hα photographic plates. Some evidence for the presence of a nonthermal source with $\alpha = -1.4$ was inferred from the unreddened continuum. This fact agrees with the continuum observed in Seyfert galaxies of class 1 (Khachikian and Weedman 1974) which have emission line profiles similar to IC 4329 A. The derived luminosity, $\mathscr{L}_{H\beta} = 1.2 \times 10^{42}$ ergs s$^{-1}$, is comparable to that observed in radio galaxies with broad emission lines (Osterbrock, Koski, and Phillips 1976).

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