1982ApJ...254..489N

THE ASTROPHYSICAL JOURNAL, **254**:489–493, 1982 March 15

THE BROAD AND NARROW LINES IN THE SPECTRUM OF THE QUASAR 3C 351

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Received 1981 August 3; accepted 1981 October 2

ABSTRACT

3C 351 is the only quasar so far in which the broad and narrow components of Lyα and Hβ can be easily separated. The combination of Lyα from previous *IUE* data and our new optical observations suggests that Lyα/H$\beta \approx 12$ in *both* components. By comparing this line ratio with the results of a photoionization calculation for the narrow-line region, we find a line-of-sight reddening $E_{B-V} \approx 0.25$, most of which is probably intrinsic. Applying this reddening to the observed broad emission lines gives an intrinsic intensity ratio Lyα/H$\beta \sim 52$, indicating that collisional enhancement of Hβ may not be important. The intrinsic intensity ratio Hα/H$\beta \sim 14$ is like that observed in some broad-line radio galaxies, suggesting that some quasars may be very luminous members of that class.

Subject headings: line profiles — quasars

I. INTRODUCTION

The broad-line intensity ratio Lyα/Hβ in quasars and Seyfert galaxies has attracted much attention in recent years, because it is observed to be much weaker than predicted. Several mechanisms have been proposed to explain the discrepancy, including line transfer and collisional processes in a low ionization gas, and reddening by internal and external dust (see Davidson and Netzer 1979 and references therein, also Kwan and Krolik 1981; Weisheit, Shields, and Tarter 1981; MacAlpine 1981; Canfield and Puetter 1981; and Collin-Souffrin *et al.* 1981). Much of the discussion so far has been rather theoretical since the observational material needed to decide between different models involves weak and blended lines that are difficult to measure.

One way to investigate the relative importance of these processes is to compare the intensity ratios Lyα/Hβ for the broad- and narrow-line regions separately, since it is simpler to model the lower density narrow-line regions where line transfer effects and collisional processes are much less important. There are only a few objects in which it is possible to separate the broad and narrow components of Hβ—and even fewer have been observed in the Lyα region. The N galaxy 3C 390.3 has been investigated by Ferland *et al.* (1979) and reexamined by Netzer (1981), who concludes from studying the narrow lines that there is reddening by dust in the source itself. (See also the work by Oke and Goodrich 1981.) The low redshift quasar 3C 351 is another example noted by Green *et al.* (1980), who compare their ultraviolet (*IUE*) spectrum with previous optical spectroscopy by Neugebauer *et al.* (1979) and by Grandi and Phillips (1979, hereafter GP). We have reexamined their conclusions by combining our new optical data with the ultraviolet data of Green *et al.* We use our measured narrow-line intensities to construct a model for 3C 351 and to estimate the amount of reddening in the source.

II. THE VISUAL AND ULTRAVIOLET SPECTRUM OF 3C 351

The spectrum of 3C 351 was observed at McDonald Observatory with the Digicon spectrograph on the 2.1 m Struve reflector and the IDS spectrograph on the 2.7 m reflector as part of a program to monitor spectral variability of quasars and active nuclei (e.g., Netzer *et al.* 1979, where the observing techniques and equipment are also briefly described). Five spectra obtained between (UT) 1978 May 10 and 1980 June 18 show no evidence for variability within the 5–10% calibration uncertainties, and 20% is an upper limit to real continuum variation, so we have combined all data to produce the spectrum shown in Figure 1. The spectrum has been corrected for atmospheric absorption (λ6280 feature and B band at λ6870) by observations of a hot standard star through similar air mass. Figure 1 also includes the continuum points given by Neugebauer *et al.* (1979) and obtained in 1977 August. The earlier continuum is about 50% brighter and is steeper than ours. The ultraviolet spectrum was obtained by Green *et al.* (1980) on 1978

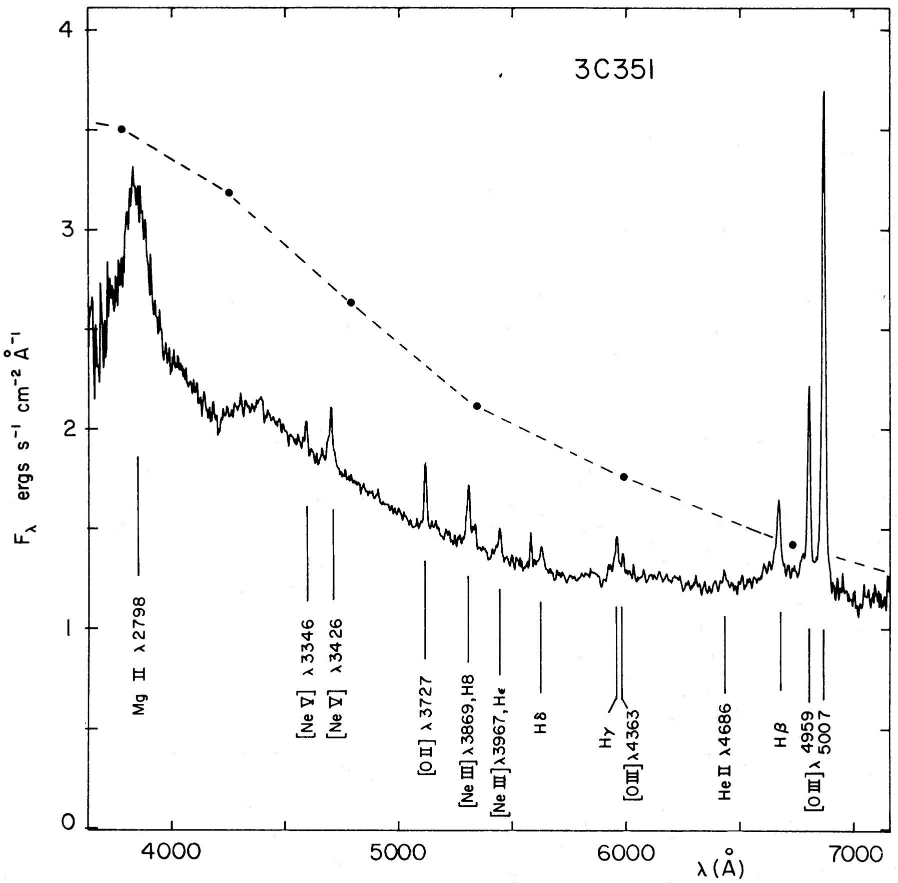

FIG. 1.—The composite optical spectrum of 3C 351. The observed flux F_λ is in units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1}, uncorrected for galactic reddening and accurate to 5–10%. The earlier continuum spectrophotometry in 1977 August from Neugebauer *et al.* (1979) is shown by points connected by the dashed line.

April 17, less than a month before our 1978 May 10 observation which, however, does not include Hβ. Even if the continuum changed between the two observations, a comparison of our optical with the ultraviolet lines is probably still valid as line intensities in several quasars have been observed to remain constant even throughout large continuum changes (see Netzer *et al.* 1979 and references therein).

Our observed equivalent widths and observed line intensities are given in Table 1, together with estimated rms uncertainties. The relative contributions of the broad- and narrow-line components of Hβ were determined by combining a broad- and a narrow-line profile. The former was obtained by smoothing the observed Mg II λ2798 profile by eye but excluding a small contribution due to Fe II emission near λ2950. The intrinsic width is 10,000 km s^{-1} (FWHM). Uncertainties in this profile due to other Fe II blends are negligible, given the quality of the Hβ spectrum. The [O III] λ5007 profile (intrinsic FWHM~600 km s^{-1}) was used for the narrow-line component. The contribution of the narrow-line component was judged by subtraction of the [O III] λ5007 profile from the observed Hβ, requiring the remaining broad component to be consistent with the smoothed Mg II λ2798 profile scaled in intensity. The resulting composite found to be the best fit to the observed Hβ line is shown in Figure 2. We find the intensity ratio of the narrow to broad components $H\beta(n)/H\beta(b)=0.19\pm0.04$ (rms). Most of the uncertainty in this ratio arises in the measurement of the broad-line intensity, because of the uncertainty in defining the continuum, especially at longer wavelengths where the signal is smaller and a correction must be made for atmospheric (B band) absorption. Calibration uncertainties are also larger at the ends of the observed spectral range. This same composite Hβ profile was a good fit to Hγ and Hδ within the observational uncertainties and was scaled down to estimate their intensities. For all the broad-line intensities the greatest source of uncertainty is in estimating the continuum. For the

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TABLE 1

MODEL VALUES COMPARED WITH MEASURED LINE STRENGTHS

Line	W(obs)	I(obs)	I(corr)[a]	Model
Hα(n)	695[b] Å	97±10[b]	74	2.8
Hα(b)				...
[O III] λλ4959, 5007	56	10.4±0.5	10.2	14
Hβ(n)	5.6	1[c]	1	1
Hβ(b)	29	5.2±1.0	5.2	...
He II λ4686(n)	1.0	0.20±0.05	0.21	0.29
He II λ4686(b)	<6.5	<1	<0.42	...
[O III] λ4363	1.2	0.23±0.08	0.25	0.31
Hγ($b+n$)	14	2.6±0.3	2.9	...
Hδ($b+n$)	6.5	1.2±0.2	1.4	...
Hε, [Ne III] λ3969	1.8	0.36±0.04	0.43	0.4
H8, He I λ3889	1.7	0.37±0.06	0.44	0.15
[Ne III] λ3869	3.7	0.79±0.05	0.95	0.9
[O II] λ3727	3.2	0.74±0.05	0.91	1.0
[Ne V] λλ3346, 3426	...	0.99±0.06	1.3	0.65
Mg II λ2798(n)	<1.5	<0.5	<0.8	0.8
Mg II λ2798(b)	58	20.5±1.5	35.5	...
C III] λ1909(n)	...	...	...	9
C IV λ1549(n)	...	...	...	14
Lyα(n)	16.5	11.1±1.5[d]	48	50
Lyα(b)	94	63±11[d]	270	...

[a] $E_{B-V}=0.25$.

[b] From Neugebauer *et al.* 1979.

[c] Observed $F[H\beta(n)]=6.6\pm0.5\times10^{-15}$ ergs s^{-1}.

[d] Our measurement of Green *et al.* 1980 data (see text).

narrow lines, intensities were found by least-squares fitting of the [O III] λ5007 profile.

We find good agreement between our line intensities and those given by GP, except for the broad components of Hβ which they find to be a factor of 2 larger than ours. To investigate this further, we have made a detailed comparison of our Figures 1 and 2 with their Figures 1 and 2, making allowance for their slightly wider instrumental resolution (FWHM ~ 10 Å). The agreement over the entire spectral range is excellent and places strong limits on any change in continuum shape between the time of their observations and ours. There is a small bump in the GP continuum a few angstroms longward of the [Ne V] λ3426 feature that is not present in ours. Their continuum beyond [O III] λ5007 is lower. For reasons mentioned earlier, this region of the spectrum is subject to larger calibration and other uncertainties. Adoption of GP's continuum in this region would increase our value of intensity of Hβ(b) by about 25% and would not explain the discrepancy of a factor of 2. The agreement of their Hβ and [O III] λλ4959, 5007 profiles with ours is also very good, but if we choose the ratio $\mathrm{H}\beta(n)/\mathrm{H}\beta(b)=0.08$ given by GP, our synthetic profile does not match their data or ours. Thus we prefer to use our measured Hβ intensities.

It is difficult to compare GP's results, or ours, with those of Neugebauer *et al.* (1979) owing to the broad passbands used by the latter, but their total intensity of Hβ is about 6 times larger than ours; this is too large to believe as a real change and is probably a mistake, especially since their Mg II λ2798 and [O III] λ5007 intensities are similar to ours, within the quoted uncertainties.

The Lyα profile was decomposed into broad and narrow components using the original data of Green *et al.* (1980), kindly supplied by R. Green. We used the narrow and broad profiles that were used to fit the Hβ and convolved them with a Gaussian of $2\sigma=1800$ km s^{-1}. This is close to the combined resolution of the *IUE* SWP camera and reduction procedure estimated by Green (private communication). The ultraviolet continuum we have chosen is probably higher than the one used by Green *et al.* resulting in a weaker Lyα (see Table 1). The best fit obtained this way gives $\mathrm{Ly}\alpha(n)/\mathrm{Ly}\alpha(b)=0.18\ (+0.25,\ -0.03)$ and is shown in Figure 2. Green (private communication) suggests that one reason why this differs from the ratio given by Green *et al.* (1980) is that they use a much broader narrow-line component with a full width at half-maximum of 3500 km s^{-1}.

Our most important results are that (1) the intensity ratio Lyα/Hβ is nearly the same for both the narrow- and broad-line components, and (2) that its value (~12) is significantly larger than those (~5) often derived for the broad lines of quasars and active galactic nuclei.

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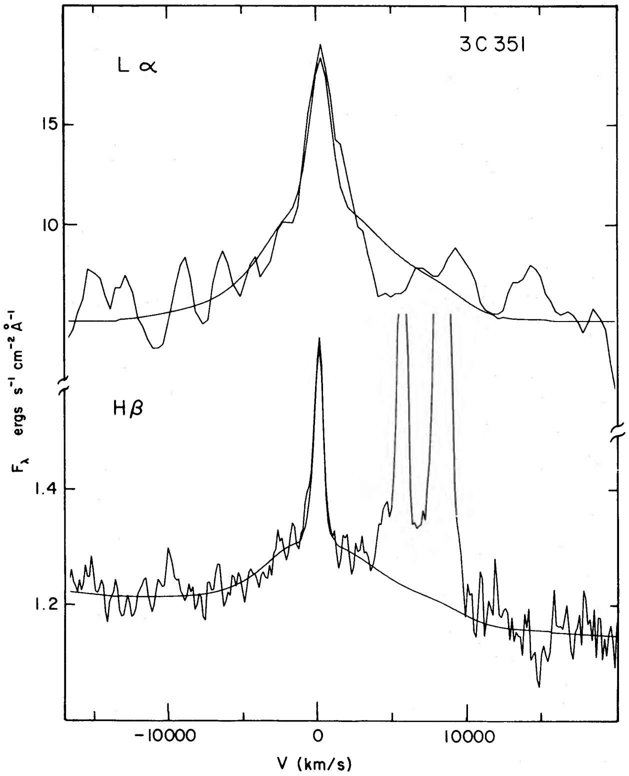

FIG. 2.—The velocity profile of Lyα (from the *IUE* data obtained by Green *et al.* 1980) compared with our data for Hβ, showing the best fitting synthetic profiles as described in the text. For the cases illustrated, the intensity ratios of narrow to broad components are $\mathrm{Ly}\alpha(n)/\mathrm{Ly}\alpha(b)=0.18$ and $\mathrm{H}\beta(n)/\mathrm{H}\beta(b)=0.19$.

III. DISCUSSION

There are several ways to explain the unexpectedly small observed Lyα/Hβ in quasars and broad-line galaxies. One suggestion is that the Balmer lines are formed in a warm, low ionization zone of the high density clouds where optical depth and collisional excitation processes are very important (e.g., Ferland *et al.* 1979; Weisheit, Shields, and Tarter 1981; Kwan and Krolik 1981; Collin-Souffrin *et al.* 1981). In this model the small observed Lyα/Hβ is mainly due to the enhancement of Balmer lines over their case B intensities. Another view is that processes involving reddening by dust are important and can explain part or all of the effect (e.g., Netzer and Davidson 1979; Shuder and MacAlpine 1979; Netzer 1980; MacAlpine 1981). Line transfer processes in the low density gas are not nearly as important, and the amount of reddening there can therefore be found by analysis of the narrow-line strengths.

The expected Lyα/Hβ ratio in a low density gas near a nonthermal ($F_\nu \propto \nu^{-\alpha}$) ionizing continuum has recently been discussed by Netzer (1981) in connection with the case of 3C 390.3. The emergent Lyα flux depends on the ionization parameter U (ratio of incident photon flux to gas density) and the spectral index α, as is the case for the high density gas (Davidson 1977). Lyα/Hβ can vary between about 35 and 100 over the acceptable range of U, for $N_e \gtrsim 2\times10^4$ cm^{-3} and $0.5 \lesssim \alpha \lesssim 1$. For lower densities Lyα/Hβ is about two-thirds of these values.

In 3C 351 $\mathrm{Ly}\alpha(n)/\mathrm{H}\beta(n) \approx 11$, and the *minimum* extinction correction required to bring it into agreement with the predicted value is $E_{B-V} \approx 0.13$. For better estimates we need better values for U and α, but they are difficult to obtain since reddening may also affect the observed continuum. The relative strengths of narrow lines in the visible region are less dependent on extinction, and we can use these with a photoionization model to find a first approximation to U and α and, hence, estimate a theoretical Lyα/Hβ intensity ratio. This can be compared with the observed ratio to derive the reddening which can be applied to the optical lines, thus allowing an improved estimate of U and α.

The observed value of the [O III] (λ5007+λ4959)/λ4363 line ratio in 3C 351 indicates densities $\lesssim 10^5$ cm^{-3} which, with $\alpha \sim 1$ and solar oxygen abundance, would give [O III] λ5007/Hβ a factor of ~2 stronger than observed (see Ferland 1981). It therefore seems that O/H is lower than its solar value in 3C 351. Another line ratio, He II λ4686/Hβ, suggests $\alpha \sim 1$ (MacAlpine 1981 and references therein). These and other line ratios limit the range of parameters in our model.

Table 1 gives results for one specific model with $F_\nu \propto \nu^{-1.1} \exp(-\nu/40 \text{ ryd})$ ionizing continuum, $U=3\times10^8$ cm s^{-1}, He/H=0.1, and metal abundances one-fourth of solar values. This is a constant pressure model with $N_e = 2.4\times10^3$ cm^{-3} at the illuminated side of the cloud. It gives Lyα/Hβ=50, which requires $E_{B-V}=0.25$ to agree with the observations, if we assume galactic-type extinction (Seaton 1979). Reddening by the above amount was applied to all observed lines and is compared with the model in Table 1. Evidently there is good agreement for most lines, which suggests that conditions in the narrow-line region of 3C 351 may not be too different from those assumed here. Crucial, yet unavailable, information to check this model is the intensities of the narrow C IV λ1549 and C III] λ1909 lines. Predictions are given in Table 1. Note that a comparison with observation depends on the uncertain strength of the λ2200 extinction.

A spectral index $\alpha = 2.0$ was estimated from the *IUE* continuum in the rest wavelength range 900–1100 Å. If the extinction of $E_{B-V}=0.25$ is applied, we derive a continuum even flatter than that deduced from the He II λ4686 line strength. We suggest that there is less dust reddening the continuum source than the emission-line regions. The situation can be quite complicated since the dust location will determine its scattering and absorption properties. Another reason for the discrepancy could be that our extrapolation of the observed ultraviolet continuum is invalid.

The model shown here is only one of several with somewhat different values of U and α that can fit the observations equally well. Obviously such models cannot fully describe the complex cloud distribution expected in quasars. More realistic cases must involve a range of densities and distances, and thus a range of U. There are too many unknowns to justify such an attempt.

The value of $E_{B-V}=0.25$ found here is larger than expected from galactic absorption ($l=90°$, $b=+36°$). Using the procedure described by Burstein and Heiles (1978), we find a galactic $E_{B-V}=0.005\pm0.007$, and a value of 0.07 is found from the formulae of de Vaucouleurs, de Vaucouleurs, and Corwin (1976). The remaining dust must therefore be outside our Galaxy. This adds one more to the growing list of objects where the presence of dust has been established or suspected (Netzer 1981 and references therein). A word of caution is in order. The galactic-type extinction so often used to correct line and continuum intensities may not be appropriate for quasars. The large ultraviolet flux and the level of ionization expected near quasars are very different from conditions in the interstellar medium near the Sun. In particular, the 2200 Å absorption feature may have a different strength or may not even exist in dust near quasars. There is, in fact, growing evidence that reddening deduced from line ratios and the λ2200 feature in active nuclei are not quite the same [e.g., Neugebauer *et al.* (1980) for the case of NGC 1068].

We have not attempted to model the broad-line region of 3C 351 because of the lack of more ultraviolet line intensities. It is interesting to note, however, that the dereddened $\mathrm{Ly}\alpha(b)/\mathrm{H}\beta(b)$ is in the range given by standard photoionization calculations, and Hβ may be very close to its recombination case B intensity. The Hα intensity measured by Neugebauer *et al.* (1979) and our Hβ intensity give an observed ratio $\mathrm{H}\alpha/\mathrm{H}\beta\sim19$ or a dereddened ratio ~14 (assuming that there has been no change in line intensity between their observations and ours). This is much larger than published ratios for other quasars or Seyfert 1 galaxies, but similar values are quite common in broad-line radio galaxies (e.g., Grandi and Osterbrock 1978). Like the broad-line radio galaxies, 3C 351 has extended double radio structure ($\gtrsim$200 kpc) with a very weak compact component coincident with the optical image (Miley and Hartsuijker 1978). Such a weak compact component is common among radio galaxies but rare among well-resolved radio quasars. However, the extreme asymmetry of the radio source is not typical of either class, as noted by Miley and Miller (1979).

To summarize, the spectrum of 3C 351 shows a distinct narrow-line component that, by comparison with line strengths calculated from a photoionization model, allows us to estimate the reddening along the line of sight, $E_{B-V}\approx0.25$. Most of this reddening is probably intrinsic to the quasar. 3C 351 is similar in many ways to the broad-line radio galaxy, 3C 390.3, where separation of the broad- and narrow-line components also suggests the presence of dust (Netzer 1981). Even though 3C 351 has the high radio and optical luminosities typical of radio quasars, the large $\mathrm{H}\alpha/\mathrm{H}\beta$ intensity ratio is unusual and is more like the values found in some broad-line radio galaxies.

We are very grateful to Richard Green for sending us the ultraviolet data. We thank P. M. Rybski, R. G. Tull, S. Vogt, and D. R. Doss for help with the equipment, and A. K. Uomoto for help with observations and reductions. Hagai Netzer thanks the Department of Astronomy, University of Texas, for hospitality. This research was supported by grants from the United States-Israel Binational Science Foundation, Jerusalem, Israel (BSF 2305) and the United States National Science Foundation (grant AST 79-01182).

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