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STELLAR ABSORPTION FEATURES IN HIGH-REDSHIFT RADIO GALAXIES

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ABSTRACT

We present evidence for stellar absorption features in a composite ultraviolet spectrum of high-redshift radio galaxies. A large fraction of the ultraviolet light from these objects appears to be starlight. Explanations for the alignment of the optical/infrared continuum and the radio axis in these objects must take this into account. The overall shape of the spectrum suggests that the star formation rate in these objects was higher in the immediate past.

Subject headings: galaxies: evolution — galaxies: formation — radio sources: galaxies

I. INTRODUCTION

The discovery of the "alignment effect" between the optical-infrared continua and the radio axes in high redshift radio galaxies, observed independently in the 4C "ultra-steep spectrum" sample (Chambers, Miley, and van Breugel 1987) and the 3CR sample (McCarthy *et al.* 1987), has stimulated discussion on the nature of the continuum in these objects. Recently it has been suggested that the extended blue-ultraviolet flux from these objects is due to electron scattering (Fabian 1989; Rawlings and Eales 1989), or dust scattering (di Serego Alighieri *et al.* 1989; Tadhunter, Fosbury, and di Sergeo Alighieri 1989) of the nonthermal continuum from an obscured active nucleus (see also Barthel 1989). However, unlike the power-law continuum of active nuclei, the broad-band spectral energy distributions (SEDs) of high-redshift radio galaxies have distinct shapes which are reasonably well fitted by galaxian SEDs, and by stellar population synthesis models (e.g. Lilly 1988, 1989*a*; Chambers and Charlot 1990; see also review by Chambers and Miley 1989).

In this *Letter* we present the first evidence that stellar absorption features are present in composite spectra of these objects. The overall shape of the UV spectrum indicates that the star formation rate in these objects in general was higher in the immediate past. Both of these results lend credence to the suggestion by McCarthy *et al.* (1987) and Chambers, Miley, and van Breugel (1987) that radio source–induced star formation is responsible for the alignment effect. Recently, theories of radio source–induced star formation have been discussed by Rees (1989), Begelman and Cioffi (1989), De Young (1989), Daly (1990), and Chambers (1989). Furthermore, Chambers and Charlot (1990) have shown that young ages for the aligned radio galaxies are consistent with the broad-band optical/infrared SEDs.

II. THE DATA

High-redshift radio galaxies are faint, with integrated apparent magnitudes of $\gtrsim 21$ mag, corresponding to rest frame ultraviolet flux densities of a few μJy. In order to examine the shape and structure of the underlying continuum, as well as to search for faint emission features, we have examined the spectra of seven radio galaxies with $z > 1.5$. The spectra were obtained with a variety of instruments at Lick, KPNO, and MMT.

In Figure 1 we present a composite spectrum from observations of two of the brightest radio galaxies with $z \sim 1.8$, 3C 256 and 3C 239. The composite is constructed from individual flux-calibrated spectra of 3C 256 and 239 rebinned to a linear wavelength scale with 2.5 Å pixels and shifted to the rest frame while preserving the flux scale. The individual spectra of each of the two galaxies were combined after weighting them by their relative exposure times. The spectra of 3C 256 and 239 were then combined with equal weights, as the signal-to-noise ratio in each were similar. The signal-to-noise ratio in the final spectrum (Fig. 1*a*) is greater than 4 at 2100 Å. A cubic spline was fitted to the continuum after interactively flagging out the emission lines. This produced a smooth representation of the overall continuum shape. Pixels containing emission lines that lay above this smooth continuum were replaced with the spline continuum. The emission lines removed in this manner were Lyα, N v 1240, O IV 1344, C IV 1549, He II 1640, O III] 1663, C III] 1909, N II] 2142, and C II] 2326. In order to best compare with the models, the data were rebinned to 20 Å per pixel on the same scale as the model spectra. This binned spectrum is shown in Figure 1*b*.

The combined spectrum of seven radio galaxies with $z > 1.5$, amounting to 21 hr of integration with 3 m class telescopes, was also constructed from spectra of the galaxies 3C 256, 3C 239, 3C 241, 3C 322, 3C 454.1, 4C 40.36, and B2 1056+40; however, the signal-to-noise ratio was not significantly improved since 3C 256 and 3C 239 dominated the signal.

III. RESULTS

The combined spectrum of 3C 256 and 3C 239 shows a number of stellar absorption features. The most significant of these are the features at ~1300 Å, 1480 Å, and 1840 Å. All of these features are well away from the location of any strong emission lines. Additional features can be seen at ~1400 Å, 1640 Å, and 1720 Å. (Table 1 of Panek and Savage 1976 lists the strongest features observed in the ultraviolet spectra of O and B stars; see also Underhill, Leckrone, and West 1972 and Code and Meade 1979 for comparison.)

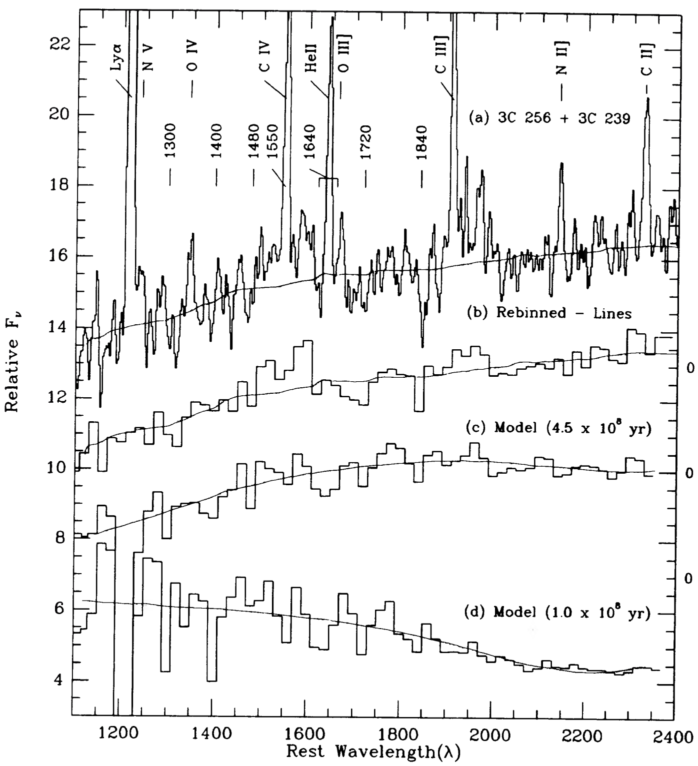

FIG. 1.—(*a*) The combined spectrum of 3C 256 and 3C 239 and (*thin solid line*) 150 Å median-filtered SED. Strong emission lines include Lyα, N V 1240, O IV 1344, C IV 1549, He II 1640, O III] 1663, C III] 909, N II] 2142, and C II] 2326. Known stellar absorption features are mostly blends and include those at ~1300 Å, 1400 Å, 1480 Å, 1549 Å, 1640 Å, 1720 Å, and 1840 Å (e.g., Panek and Savage 1976; Underhill *et al.* 1972). (*b*) Rebinned spectrum of 3C 256 and 3C 239 with emission lines excised as described in the text and (*thin solid line*) median-filtered SED. (*c*) Synthetic spectrum from Bruzual model of the ultraviolet spectrum of a starburst with an exponentially decaying star formation rate of characteristic time 10^8 yr. The age of the spectrum (*c*) is 4.5×10^8 yr. Also shown is a low-frequency cubic spline fit to the model (*thin solid line*). (*d*) Synthetic spectrum and spline fit from the same Bruzual model, but at an *earlier* time, when the age is 10^8 yr. The zeros of the flux intensity for spectra (*a*), (*b*), and (*c*) are given on the right.

The statistical significance of any given single feature is only a few sigma, but the overall agreement of the entire ultraviolet spectrum of the composite high-redshift radio galaxy with features present in the spectrum of hot stars is striking. The cross correlation of the observed spectrum with a synthetic spectrum is discussed below.

The overall shape of the spectrum, as determined with a 150 Å median filter, is shown as a thin solid line in Figures 1*a* and 1*b*. In both cases the SED shows a roughly flat region from beyond 2400 Å to 1500 Å and then a "break" below 1500 Å. This characteristic SED is seen in the composite of seven radio galaxies described above as well as in other high-redshift radio galaxies in the literature (e.g., 3C 294, McCarthy *et al.* 1990; 0902+34, Lilly 1989*b*; Her 201, Windhorst 1989; 4C 41.17, Chambers, Miley, and van Breugel 1990).

IV. STELLAR POPULATION SYNTHESIS

In Figures 1*c* and 1*d* we present synthetic spectra of a star-forming galaxy to compare with the data. We used an updated version (Bruzual 1989) of the Bruzual (1983) stellar population synthesis code. In the spectral range of interest, the stellar spectra used in the synthesis are from the *OAO* and *IUE* observations. The model has only 20 Å resolution. All tracks and spectra are for solar metallicity only. The models presented below are computed with a Scalo (1986) initial mass function (IMF) with a lower and upper cutoffs of 0.08 $M_\odot$ and 75 $M_\odot$, respectively. For the most extreme regions of the H-R diagram, the Bruzual code uses interpolations between Kurucz (1979) models and observed stellar spectra. This gives the correct average spectral intensity but undersamples narrow spectral features. We have applied an empirical correction for this by fitting observed stellar spectra from Code and Meade (1979). A second check on our empirical correction is provided by our fit to NGC 4214 discussed below.

The overall shape of a galaxy's ultraviolet spectrum is sensitive to the recent star formation history, i.e., time scales of $\lesssim 10^8$ yr. During a burst of constant or increasing star formation, the spectrum is dominated by the shortest lived stars and thus is relatively flat in f_ν. If the star formation rate is decreasing or has halted, then the spectrum reflects an evolving combination of stars governed by the history of the star formation rate and the IMF. The model spectra shown in Figures 1*c* and 1*d* are from a single model where the star formation rate is taken to be an exponential decay with a characteristic time of 1.0×10^8 yr and a Scalo IMF.

Spectrum 1*d*, with an age of 10^8 yr, is equivalent to a simple burst of star formation lasting 10^8 yr. It provides a reasonable fit (when plotted in f_λ) to the observed *IUE* spectrum of the blue irregular galaxy NGC 4214 and the condensation NGC 4214A in particular (Huchra *et al.* 1983), although the fit can be improved by the addition of an underlying constant star formation rate over a longer time scale. This is in good agreement with the modeling and conclusions of Huchra *et al.* (1983) who showed that the observed spectrum of NGC 4214 is *not* consistent with a *declining* rate of star formation for any reasonable IMF.

Spectrum 1*c* is the synthetic spectrum produced by the model at an age of 4.5×10^8 yr. Several aspects of the comparison between this model and the data deserve comment.

1. The model yields a good fit to the overall shape of the spectrum. This is especially remarkable considering we have used the simplest model (exponentially decay SFR) one could imagine. Deviations from the model would be expected for realistic variations in the SFR and the effect of combining different galaxies with different ages. We note that for a given star formation rate modest adjustments in the IMF do not make a large difference. Salpeter, Kennicutt, and Miller-Scalo IMFs were investigated and produced only small changes in the spectral features for the ages and spectral regions discussed here.

2. The individual absorption features are also reasonably well fitted by the model. We have tested this with a cross-correlation analysis of the data and the synthetic spectra. While the formal significance of such an analysis is poorly defined, the cross correlation of spectra 1*b* with 1*c* (after removing the low-frequency structure with a cubic spline fit and not including the Lyman-α feature) produces a correlation spectrum with a single significant peak at the correct location, 4 σ above the noise. The two individual autocorrelation peaks are 5 σ, limited by the number of smoothed data points. The significance of the correlation feature drops to ~3 σ if half the data are used.

3. The observed absorption features are somewhat stronger than those of the model and those of *IUE* spectra of nearby star-forming regions, i.e., the blue irregular galaxies NGC 4214 and NGC 4670 (Huchra *et al.* 1983), the metal-poor dwarf

galaxies observed by Hartmann, Huchra, and Geller (1984) and Hartmann *et al.* (1988), and the starburst nucleus of galaxy NGC 7714 (Weedman *et al.* 1981). Unfortunately the strongest feature, C IV absorption is filled in by the strong C IV emission in the high-redshift radio galaxies. The strength of the absorption features should increase with metallicity. This may indicate that the high-redshift radio galaxies have higher than solar abundances. Furthermore some of the lines may have significant interstellar components. The Si III and Si II features at λ1300, in particular, could be blended with interstellar O I λ1300. The signal-to-noise ratio and resolution of our spectra are inadequate to allow us to distinguish between stellar and interstellar absorption.

4. The overall shape of the SED, i.e., the "1500 Å break," cannot easily be attributed to nonstellar sources. Furthermore, the strength of the absorption features, especially the large blends unlikely to be affected by interstellar absorption, suggests that any nonstellar component of the continuum is small. The large positive excursions near C IV 1549 and C III] 1909 might suggest the presence of broad components to these emission lines. However, if this were the case, a broad component of the Lyman-α line should be observed and none is seen, whereas these spectral features are expected in the stellar interpretation.

5. Assuming 100% of the ionizing photons are converted into Lyα, the model predicts a Lyα emission line flux with an equivalent width of 204 Å for spectrum 1*a* and 173 Å for spectra 1*d* and 1*c*, respectively. This can account for at least half of the observed Lyα flux (e.g. Spinrad 1989), although it is obviously sensitive to the upper mass cutoff of the IMF. The high ionization lines (e.g., C IV 1549 and N V 1240) cannot be produced by photoionization from the derived stellar population and probably arise from photoionization by an (obscured) nonstellar continuum (e.g., van Breugel and McCarthy 1989).

V. DISCUSSION

The spectral features in the extended emission of high-redshift radio galaxies presented here are well matched by features found in the observed ultraviolet spectra of hot stars and nearby starburst galaxies. The alignment of the ultraviolet/optical/infrared continuum with the radio axis (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987; Chambers, Miley, and Joyce 1988; and Eisenhardt and Chokshi 1989) therefore suggests that the radio source is playing an important role in the star formation history of these galaxies.

The overall shape of the rest-frame UV SED of high-redshift radio galaxies is well matched by a Bruzual model with a *decreasing* star formation rate. While the ultraviolet luminosity in the aligned radio galaxies indicates that the star formation rate in these galaxies is high ($\gtrsim 100\ M_\odot\ \mathrm{yr}^{-1}$), it was higher in the immediate past. If the UV light were dominated by an increasing or constant star formation rate, then the spectrum shortward of 1500 Å would be relatively flat (f_ν) as in the bluest star-forming galaxies (e.g., NGC 4214, NGC 4670, Mrk 66). However, the "1500 Å break" seen in the spectra indicates that the integrated light is not dominated by the most luminous (and short-lived) stars, but by a system with a decreasing star formation rate. (To produce such a break with constant star formation by modifying the IMF would require an upper mass cutoff of $\sim 10\ M_\odot$. Partial reddening may also affect the spectrum, but the enormous Lyα flux indicates little dust.) Therefore the observed spectra suggest that the star formation rate in these objects has systematically decreased over the past $\lesssim 10^8$ yr. Furthermore, this conclusion applies to the whole aperture, i.e., regions of $\sim$30 kpc, since even a small region with an increasing star formation rate would dominate the present spectra. This implies a remarkable synchronism of a dramatic star formation episode spread out over much of the galaxy, and the radio source is a natural culprit for organizing such an event. If the star formation event were a random event loosely related to the radio source, then one might expect to see an increasing or constant star formation rate as often as a decreasing one. Since each of the spectra of aligned radio galaxies examined indicate a decreasing star formation rate, it may be that the most luminous radio sources do not achieve their high radio luminosity until after they have triggered the bulk of the star formation. Alternatively, the peak star-forming episode may be hidden by a (radio-loud) quasar phase.

The characteristic time for the decline of star formation rate suggested by the modeling of the ultraviolet spectrum ($\lesssim 10^8$ yr) is in good agreement with the time scale and star formation rates suggested by Chambers and Charlot (1990) to explain the broad-band optical-infrared SEDs of aligned radio galaxies and is comparable to the ages of the radio sources. A dramatic star formation episode with a normal IMF can explain both large-scale and small-scale features in the observed SEDs of aligned radio galaxies. Nonetheless, a requirement for the radio source–induced star formation model is that the age of the stellar population be less than or equal to the age of the radio source. Gopall-Krishna and Wiita (1987) show that at $z = 1$ powerful sources with sizes typical of the 3CR galaxies ($\sim$250 kpc at $z = 1$) have ages of $\sim 4 \times 10^8$ yr. The implied ages for the same linear sizes at $z = 2$ are somewhat larger due to the higher IGM pressure and therefore lower advance speeds. McCarthy, van Breugel, and Kapahi (1990) also argue for large radio ages based on the observed arm length asymmetries. Thus our derived ages of $\lesssim 4 \times 10^8$ yr from the fit to the ultraviolet stellar features and those determined by Chambers and Charlot (1990) meet the requirement that the stellar and radio ages be similar (but see Alexander and Leahy 1987).

VI. CONCLUSIONS

Starlight appears to contribute a large fraction of the ultraviolet spectrum of high-redshift radio galaxies. A number of independent spectral features that are present in the observed spectra of hot stars are present in composite high-redshift radio galaxy data. The overall shape of the UV spectrum is consistent with integrated starlight and inconsistent with a pure power-law continuum. In spite of the very high star formation rates inferred from the UV flux, the overall shape of the UV spectrum indicates that the star formation rate was systematically higher in the previous $\lesssim 10^8$ yr.

This result confirms the assertion that a large fraction of the extended optical emission from objects that have traditionally been called "high-redshift radio galaxies" (e.g., Spinrad 1986) is mostly due to stars and the "ultraviolet excess" (e.g., Lilly and Longair 1984) is dominated by recent star formation. Explanations for the alignment of the optical/infrared continuum with the radio axes of these objects (Chambers, Miley, and van Breugel 1987; Chambers, Miley, and Joyce 1988; McCarthy *et al.* 1987; McCarthy and van Breugel 1989) must take this into account. These results are strong evidence in support of the radio source–induced star formation explanation of the alignment effect.

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