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THE NATURE OF THE STELLAR CONTINUUM IN THE RADIO GALAXY 3C 65

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ABSTRACT

We present a deep spectrum of the $z = 1.175$ radio galaxy 3C 65 and show that the continuum is dominated by a stellar population that, by our best estimate, is ~ 4 Gyr old. For cosmological models with $\Lambda = 0$, such an age would be inconsistent with $\Omega_0 \sim 1$ for $H_0 \gtrsim 50$. There is also evidence for broad Mg II emission, most likely scattered from a hidden quasar nucleus.

Subject headings: cosmology: observations — radio continuum: galaxies

1. INTRODUCTION

Radio sources and objects associated with them currently comprise the principal sites at which we may hope to detect and study stellar populations in the early universe. Such studies can potentially delineate the course of galaxy formation and evolution. Moreover, if a dominant evolved stellar population is observed in galaxies at sufficiently high redshifts, the inferred epoch of galaxy formation can strongly constrain cosmological theories.

Powerful radio sources near our present epoch are exclusively found in galaxies dominated by an old stellar population and having a basically elliptical morphology. By contrast, many radio galaxies at redshifts greater than about 0.8 show complex and elongated structures and blue colors (indicating a sizable contribution from young stars, if the radiation is of stellar origin), as well as strong emission lines (McCarthy 1993 and references therein). Moreover, the elongated optical structure tends to be aligned with the radio structure in such objects (Chambers, Miley, & van Breugel 1987; McCarthy et al. 1987). The physical mechanism behind this alignment remains uncertain, although polarization of the aligned component in at least one galaxy (Scarrott, Rolph, & Tadhunter 1990) and the detection of broad Mg II $\lambda 2798$ emission in others (di Serego Alighieri, Cimatti, & Fosbury 1994) indicates that scattering of light from a bright quasar nucleus, hidden from our direct view, is likely to be at least partly responsible.

Until recently, virtually all arguments on the stellar composition of high-redshift radio galaxies have been based on broadband colors. Lilly (1989) and Rigler et al. (1992) have promoted the view that radio galaxies comprise an underlying old stellar population, which is fairly constant from object to object (in order to give the observed small dispersion in the K-band magnitude-redshift relation), and a much more variable flat-spectrum component, which predominates at short wavelengths and is responsible for the observed alignment between the optical and radio structure. This interpretation is consistent with the assumption of a uniform, early epoch of formation for most galaxies. A competing model has been put forward by Chambers & Charlot (1990) in which the main burst of star formation has a time constant of $< 10^8$ yr rather than the $\sim 10^9$ yr assumed by Lilly (1988). In these models, asymptotic giant branch stars contribute a significant fraction of the red light at early ages. Chambers & Charlot (1990) find that they are able to reproduce the observed colors of a wide range of high-redshift radio galaxies using a single model at different ages. The epoch of star formation is therefore different for different objects and is directly related to their colors. This scheme also seems to be consistent with the small dispersion and continuity of the (K, z) relation.

In both of these scenarios, for most galaxies one expects the presence of a spectral discontinuity near a rest wavelength of 4000 Å either from the usual 4000 Å break seen in the spectra of G and K giant stars (if there is a significant contribution from old stellar populations) or a combination of the 4000 Å break from asymptotic giant branch stars and high-order Balmer absorption lines and the Balmer limit from young main-sequence stars (if the Chambers-Charlot model is correct). However, no such break has been found in recent deep spectra of several radio galaxies at $z \sim 1$ (Hammer, Le Fèvre, & Angonin 1993; Le Fèvre & Hammer 1994). This absence is especially surprising for the reddest galaxies, such as 3C 65, for which both the colors (Lilly & Longair 1984) and the morphology (Rigler & Lilly 1994) are similar to those expected for a passively evolving elliptical galaxy.

In order to place tighter constraints on the presence of old stars in 3C 65, we have obtained deep spectroscopy with Low-Resolution Imaging Spectrometer (LRIS) on the Keck I telescope. We find that this galaxy does in fact show a strong contribution from stars that likely are at least 3–4 Gyr old.

2. OBSERVATIONS AND RESULTS

We used the 300 grooves mm^{-1} grating with an OG 570 order-separating filter to give a dispersion of 2.48 Å pixel^{-1} and a useful wavelength range of 5700–9500 Å. The 1″ wide slit (projecting to ~ 4 pixels on the Tektronix 2048 × 2048 CCD) was placed at position angle 89°.6, along the axis joining the radio galaxy and the blue companion $\sim 3''$ W, and close to the radio position angle of 85°. We obtained 12 1200 s exposures through intermittent thin cirrus. The spectra were reduced by standard techniques; however, because some of the exposures were obtained under nonphotometric conditions, we normalized our calibration to the average of four exposures obtained when it was essentially clear. From the stronger emission lines, we obtained a mean redshift of 1.175; the only significant discrepant position was that for Hγ, which lies at the far end of our useful spectral region, where our wavelength calibration may be uncertain. Figure 1 shows our spectrum of 3C 65, extracted using a 1″.1 window along the slit, smoothed with a Gaussian with $\sigma = 7.5$ Å, and restored to the rest frame wavelength scale.

We note that strong absorptions are present near 3830 and 3930 Å; these can be reasonably identified with the CN band

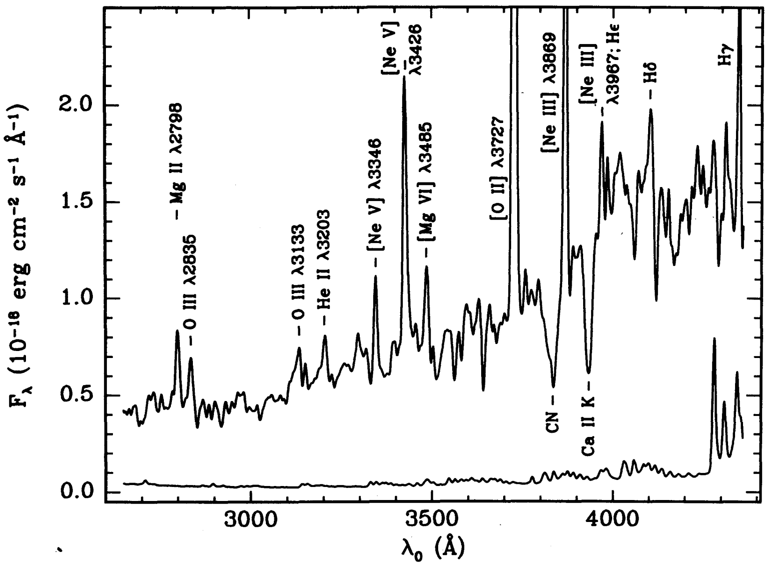

FIG. 1.—Spectrum of 3C 65. The lower trace gives the 1 σ noise in the sky signal, which dominates the total noise even in the strongest galaxy emission lines.

and the Ca II K line. To check these identifications, we have fitted and removed the [Ne III] λ3869 and Hγ lines and used their measured intensities as a basis for removing the weaker [Ne III] λ3968, Hδ, and Hϵ lines. The result of this subtraction is shown in Figure 2, where we have also overplotted 2 and 4 Gyr Bruzual-Charlot instantaneous-burst isochrone synthesis models. The removal of the emission features makes the 4000 Å break clearly visible. Although both models give acceptable fits to the 4000 Å break, the 4 Gyr model appears to better fit the Ca II K line and the CN band, which are the most prominent uncontaminated absorption features. The 4 Gyr model also gives the best fit to the spectrum in the 2900–3200 region, as shown in Figure 3*a*; in particular, the amplitude of the break near 3100 Å, due mostly to a complex of Al I and Fe I lines, is a strong function of age for populations between 2 and 4 Gyr old. However, the continua of the spectrum and the model clearly diverge at the stronger break near 2900 Å, even though several of the expected strong absorption features continue to be present.

We believe that there is a plausible explanation for this sudden divergence. Figure 3*b* shows the difference between the observed spectrum and the 4 Gyr model shown in Figure 3*a*, scaled by 0.9. Though the residual is quite noisy, it appears to show broad Mg II emission on a weak blue continuum. The red wing of the broad Mg II almost exactly coincides with the expected 2900 Å break, effectively filling in the depression. Given that the presence of strong [Ne V] is an almost certain indicator of photoionization by an active nucleus, and that broad Mg II has now been found in other high-redshift radio galaxies (di Serego Alighieri et al. 1994), a scattered quasar component in 3C 65 is not a complete surprise. But one would not normally have expected 3C 65, as the least active of the $z \sim 1$ 3C galaxies, to have been a particularly promising candidate for such a detection. We shall discuss the implications of this result in a wider context in § 3.1.

While we find that individual spectral features seem to best match solar-metallicity models with minimum ages between 3.5 and 4 Gyr, occasional flaws in the data and uncertainties about the effects of resolution differences between the data and the models make it difficult to quantify the range of models that provide acceptable fits. Furthermore, our wavelength range is too limited to obtain useful constraints from the continuum slope. We do, however, have a deep, high signal-to-noise ratio CCD image of 3C 65 centered in a continuum-dominated band at rest frame 3400 Å, and we can use the color derived from this image and published *H*-band photometry of Rigler et al. (1992) as a discriminant among models. For a 4″ diameter synthetic aperture, we find $F(3400)/F(H) = 0.374 \pm 0.045$, where we have corrected for Galactic reddening and a measured 9% contamination of our 3400 Å band by emission lines

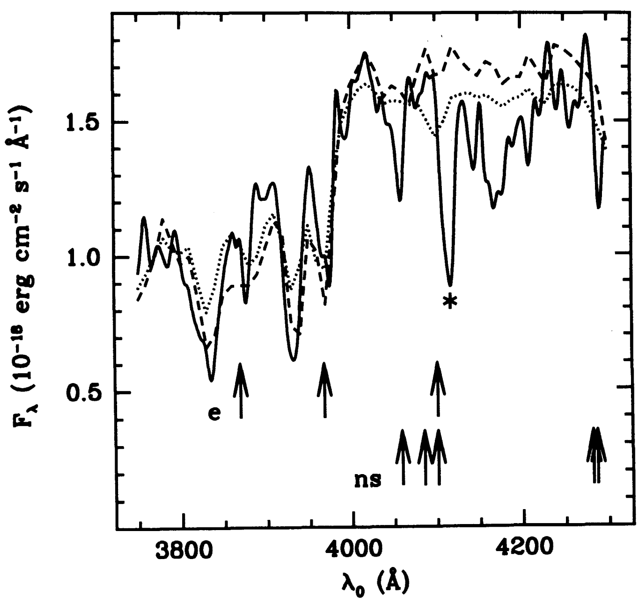

FIG. 2.—Spectrum of 3C 65 from 3750 to 4300 Å (in the rest frame), after removal of [Ne III] and Balmer emission lines. The relatively strong [Ne III] λ3869 and Hγ lines were first fitted and removed to give as smooth an underlying continuum as possible; the measured intensities of these lines were then used as a basis for removing the weaker [Ne III] λ3967, Hδ, and Hε lines. The [Ne III] line ratios are determined by atomic parameters, and we assumed case B and 10^4 K for the Balmer lines. The dotted and dashed curves are 2 and 4 Gyr Bruzual & Charlot (1993) instantaneous-burst models, using a Scalo (1986) IMF. Arrows indicate the positions of subtracted 3C 65 emission lines (e) and the strongest night-sky features (ns). The feature indicated by the asterisk (*) is due to a flaw.

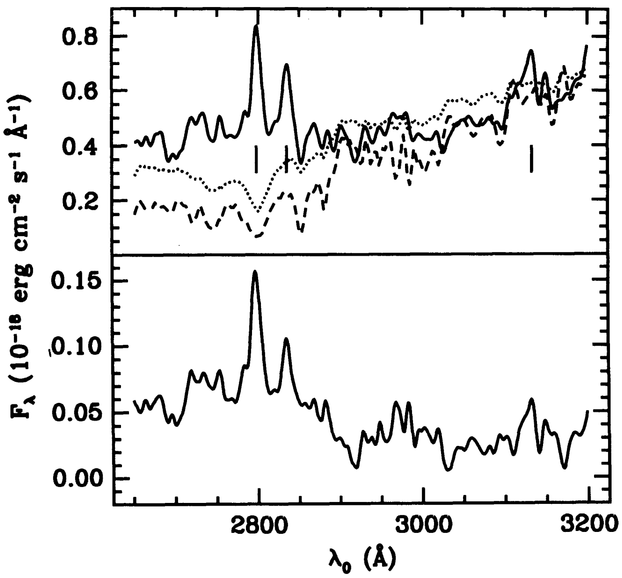

FIG. 3.—(*Top*) Spectrum of 3C 65 from 2650 to 3200 Å (in the rest frame). The dotted and dashed curves give the 2 and 4 Gyr Bruzual & Charlot models shown in Fig. 2, with the same normalization. In this figure, emission lines in 3C 65 have *not* been removed; positions of Mg II λ2798, O III λ2835, and O III λ3133 are indicated. (*Bottom*) The difference between the 3C 65 spectrum and the 4 Gyr model, where the latter has now been scaled by a factor of 0.9 from its normalization in the top panel. The hump stretching from ~2700 Å to ~2900 Å may be scattered broad Mg II emission.

(principally [Ne V] λλ3346, 3426, [Mg VI] λ3485, and He II λ3203). We estimate the corresponding emission-line contamination of the H band (rest frame 7600 Å) to be less than 1% of the total flux. For solar metallicity models, this ratio corresponds to 4.0 Gyr, with the 90% confidence interval running from 2.9 to 9 Gyr. We used models with a Scalo (1986) initial mass function (IMF); a Salpeter (1955) IMF gives an age of 3.7 Gyr. The fits are not sensitive to the upper mass limit of the IMF, as long as it is greater than $\sim 2\ M_\odot$.

Under what conditions could our results be consistent with younger ages? The overall accuracy of the current models is a concern, because of the large number of parameters involved. In addition, one clear limitation is the restriction of the models to solar metallicities: a higher metallicity would mean a lower age both because increased line blanketing would give redder colors and because stronger absorption-line features would tend to mimic a more evolved population in the 2–4 Gyr range over the region covered by our spectrum. Internal reddening could also affect the photometry (though not the spectral features) in a similar way, but if the dust distribution is similar to, or more concentrated than that of the stars, very large amounts would be needed, since embedded dust is not very effective in producing global reddening (e.g., Witt, Thronson, & Capuano 1993). Finally, although wholly ad hoc, an IMF sharply truncated on the high-mass end at $\sim 1.5\ M_\odot$ might well have spectra and colors close to those we observe, without any evolution at all.

On the other hand, there are plausible effects that would cause us to *underestimate* the age. For example, we have ignored any scattered continuum: if we are correct in suggesting the presence of broad Mg II, there would certainly also be a scattered blue continuum component, which would mean that the stellar component alone is redder, and hence older, than our photometry indicates. Also, the instantaneous-burst approximation we have used, although appropriate for attempting to determine a lower limit to the age, is unrealistic. If star formation tails off fairly rapidly, an instantaneous burst may still be an adequate approximation; however, if significant star formation continues to (or resumes at) times close to the observed epoch, the spectrum of the initial burst will have been diluted in much the same way as it would be by a scattered component. Finally, an actual metallicity less than solar would again result in an underestimate of the age.

3. DISCUSSION

3.1. *The Nature of the Aligned Component in High-Redshift Radio Galaxies*

As we have mentioned, the presence of broad Mg II in 3C 65 is, in one sense, not too surprising. However, 3C 65 shows the least optical activity of any of $z \sim 1$ 3C radio galaxies. By contrast, 3C 368 shows the most activity: it has the strongest emission, the bluest continuum colors, the most marked alignment effect, and strong polarization in the aligned component (Scarrott et al. 1990). If any radio galaxy should, under the common assumptions, show evidence for a scattered quasar spectrum, this is the one. Yet a deep Keck spectrum of the northern aligned component in 3C 368 (Fig. 4) shows absolutely no evidence for scattered broad Mg II. We take this as evidence that the aligned component in high-redshift radio galaxies cannot be entirely due to scattered quasar radiation (scattering by $\sim 10^7$ K electrons could wash out such a feature, but fine-scale structure in the aligned component appears to be inconsistent with the expected density scale length for such electrons). The spectroscopy of 3C 368 will be discussed in more detail elsewhere.

3.2. *Cosmological Implications of an Old Stellar Population at $z \sim 1$*

If we assume that a ~4 Gyr age for the dominant stellar population in 3C 65 can be taken at face value, what constraints would such an age place on cosmological parameters? We consider only pressureless Robinson-Walker cosmologies

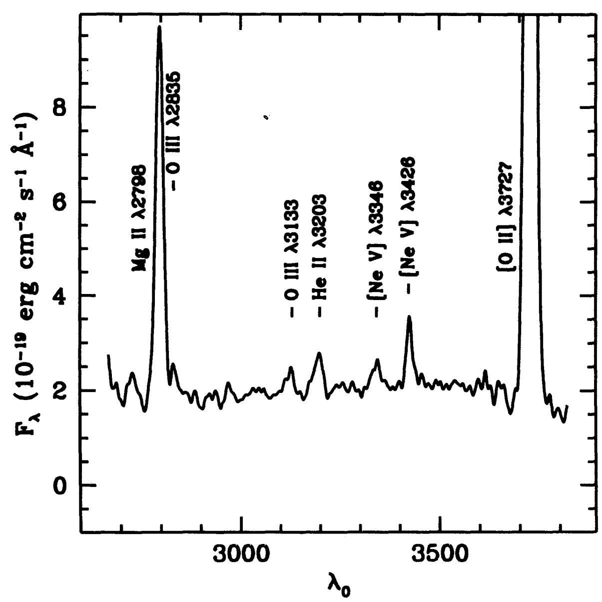

FIG. 4.—Spectrum of the northern aligned component in 3C 368. Note the absence of a significant broad Mg II component.

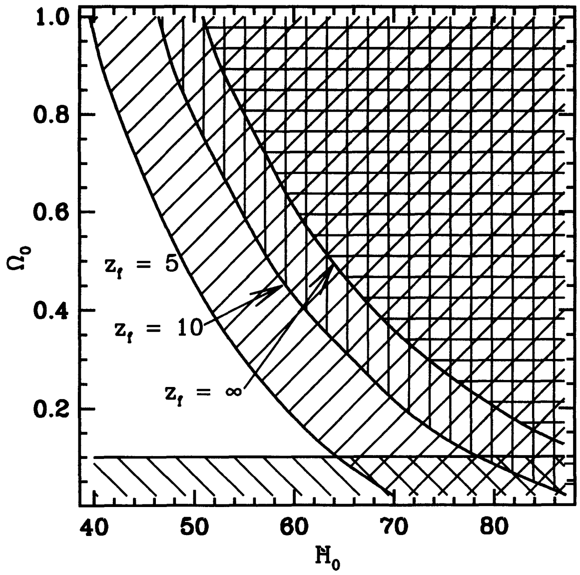

FIG. 5.—Allowed regions of the H_0-Ω_0 plane, assuming that the dominant stellar population in 3C 65 has an age of 4 Gyr and that the cosmological constant $\Lambda = 0$. Curves are given for two epochs for star formation in 3C 65, at redshifts $z_f = 5$ and 10, as well as for the upper bound at $z_f = \infty$. The horizontal line at $\Omega_0 = 0.1$ is a conservative lower limit to the mass density based on known mass in clusters of galaxies.

with $\Lambda = 0$. Figure 5 shows the permitted regions of the H_0-Ω_0 plane if a 4 Gyr–old stellar population, observed at a redshift $z = 1.175$, had been formed at a redshift $z_f = 5$, 10, or ∞.

It is apparent from Figure 5 that high values for the Hubble parameter, such as the $H_0 \sim 80$–90 recently obtained from measurements of Cepheids in the Virgo cluster (Pierce et al. 1994; Freedman et al. 1994), are incompatible with a universe near closure density ($\Omega_0 = 1$), required by standard inflation models. This result is reminiscent of the well-known conflict between high values for H_0 and the ages of Galactic globular cluster stars, inferred from models of stellar evolution. While the constraints from 3C 65 are still dependent on stellar evolution models, they employ models with a very different range of parameters and a shorter span of time. Even with $H_0 = 50$, closure density implies uncomfortably high redshifts for galaxy formation. Barring a major and unexpected problem with our understanding of the timescale of stellar evolution or a nonzero cosmological constant, it seems likely that we live in a universe with $\Omega \approx 0.1$–0.2 and one in which the earliest major episodes of star formation in galaxies occurred at $z > 5$. The recent investigation of the baryon fraction in galaxy clusters by White et al. (1993) also gives strong support to a low cosmic density.

While our conclusion results from the most straightforward interpretation of the data, the possibility remains that either the limitations of the current models or some fortuitous combination of star formation parameters such as stellar IMF and metallicity could have led us astray. In spite of such worries, we believe that a careful analysis of age-sensitive stellar absorption features in selected objects in the redshift range $1 < z < 1.5$ can place strong constraints on the epoch of earliest star formation and will usefully complement studies of higher redshift objects, for which only color information is likely to be available.

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