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THE AGES OF HIGH-REDSHIFT RADIO GALAXIES

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ABSTRACT

We compare the observed spectral energy distributions (SEDs) of high-redshift radio galaxies with stellar population synthesis models. We show that the "flat ultraviolet plus red bump" SED observed in these galaxies can be produced with a normal initial mass function (IMF) in $\lesssim 3 \times 10^8$ yr and persists for more than 6×10^8 yr if most of the stars form on time scales $\lesssim 1 \times 10^8$ yr. This implies that many of the observed powerful radio galaxies with $1 < z < 4$ are young and that they are being observed soon after the event that produced the bulk of their stars. If such an event were organized by the powerful radio sources associated with these objects, this could account for the alignment of the optical/infrared emission with the radio axes observed in these sources, while maintaining the low dispersion and continuity of the infrared Hubble diagram.

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

I. INTRODUCTION

Two recent developments have uncovered a remarkable problem in understanding the optical/infrared emission from distant radio galaxies.

One was pointed out by Lilly (1988) in interpreting the broad-band "flat UV plus red bump" SED of 0902+34 at $z = 3.395$. He proposed that the red bump was due to a significantly older (>1 Gyr) population, while the rest frame ultraviolet light could be accounted for by a small fraction of the galactic mass currently undergoing a starburst. Meanwhile, the discovery of more radio galaxies at very high redshifts ($2 < z < 4$) was proceeding apace (Chambers, Miley, and van Breugel 1988; Chambers 1989) including that of 4C 41.17 at $z = 3.800$ with a similar SED (Chambers, Miley, and van Breugel 1989). However, the existence of *old* galaxies at such large lookback times seemed surprising (the universe is 1.28 Gyr old at $z = 3.8$ for $H_0 = 50$, $q_0 = 0.5$).

The other important development was 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 "ultrasteep spectrum" sample (Chambers, Miley, and van Breugel 1987), and the 3CR sample (McCarthy *et al.* 1987). One early explanation for the alignment effect was that the radio source was triggering star formation along its axis. However, this interpretation became more problematical with the discovery that the infrared flux in the prototypical radio galaxy 3C 368 was also aligned along the radio axis (Chambers, Miley, and Joyce 1988). If the red bump in the SED of 3C 368 was due to an "old" population, then it was difficult to understand the origin and persistence of the alignment with the (presumably younger) radio source. There are now infrared images of several more aligned radio galaxies demonstrating reasonable agreement between the optical and infrared morphologies (Eisenhardt and Chokshi 1989).

The old ages advocated by Lilly (1988) to explain the red bump were inferred from a model in which the major star-forming episode lasted 1 Gyr. In this *Letter* we investigate whether the SED can be explained by star formation scenarios involving shorter time scales. We conclude that, independent of the detailed shape, a significant burst of star formation on time scales of $\lesssim 10^8$ yr followed by a modest tail of ongoing star formation gives good agreement with the observations.

II. THE MODELS

We used an updated version of the Bruzual (1983) code of stellar population synthesis (Bruzual 1989), to model the SEDs of a sample of high-redshift radio galaxies. Several aspects of our model calculations deserve comment.

First, all the models presented below are computed with a Scalo (1986) IMF with upper and lower cutoffs of 75 $M_\odot$ and 0.08 $M_\odot$, respectively.

Second, we have applied a correction to the model spectra to account for stars on the asymptotic giant branch (AGB). Since the poor understanding of the complex physical processes involved in the evolution of stars on the AGB (e.g., convective overshooting) makes the present models (Renzini 1981; Bertelli, Bressan, and Chiosi 1985) quite uncertain (Reid and Mould 1984; Renzini *et al.* 1985; Renzini 1987; Charlot and Fall 1990), we used the empirical work of Charlot and Fall (1990) to derive our AGB correction. They determined the contribution of AGB stars to the integrated V and near-IR light of a coeval stellar population from a complete survey of AGB stars in Magellanic Cloud clusters. They identified a peak contribution of 70% to 80% in the near-IR for ages between 3×10^8 and 2×10^9 yr, and a contribution of $\sim$20% in the visible band for ages in the range 5×10^8 to 3×10^9 yr. When correcting the synthesis models for the contribution from AGB stars, we convolved the results that Charlot and Fall (1990) obtained for a burst population with the appropriate expression for the star formation rate.

Third, although the code also does not contain spectra for blue horizontal branch (HB) stars, this does not affect our conclusions since at the ages of interest here the bulk of stars that undergo core helium burning are of intermediate masses, whose HB does not expand significantly into the blue (e.g., Maeder and Meynet 1989).

Finally, the present models are strictly valid only for a solar metallicity population, whereas high-redshift radio galaxies may form from lower, possibly primordial abundances. Assuming that the gas is of primordial composition when the star formation episode begins, and using current estimates of stellar yields (Woosley and Weaver 1986), we estimate that at the peak of star formation the metallicity will be only ~ 0.002, but becoming nearly solar ($\gtrsim 0.01$) after 2×10^8 yr. However, the large number of low-metallicity stars will affect the spectral evolution. We have estimated this effect using low-metallicity evolutionary tracks (Bertelli *et al.* 1986), and they do not affect our basic conclusions.

We used two expressions for the star formation rate (SFR), $\psi(t)$, that both correspond to a conversion of the gas into stars over a characteristic time scale τ, with the condition $\psi(t = 0) = 0$. The first has a tail governed by an exponential decline:

$$\psi(t) \propto \frac{M_g}{\tau}\left(\frac{t}{\tau}\right)^{\alpha} e^{-t/\tau}, \qquad (1)$$

with $\alpha > 0$ and where M_g is the mass of gas to be converted into stars. The second has a tail governed by a power law:

$$\psi(t) \propto \frac{M_g}{\tau}\left(\frac{t}{\tau}\right)^{-\alpha}\left[1 - \exp\left(-\frac{t}{\tau}\right)^{\beta}\right], \qquad (2)$$

with $\beta > \alpha > 0$.

III. COMPARISON WITH OBSERVATIONS

In Figure 1 we present the results obtained from two models found to give good agreement with the observations. The SFR of model A corresponds to formula (1) with $\alpha = 0.5$ and $\tau = 5 \times 10^7$ yr, and that of model B corresponds to formula (2) with $\alpha = 2$, $\beta = 3$, and $\tau = 5 \times 10^7$ yr. The choice of the IMF (Scalo) then completely specifies the galaxy spectra as a function of the age. For both of these models the FWHM of the SFR is $\sim 10^8$ yr. The criteria for choosing the SFR parameters involved a trade-off between producing the observed SEDs early and having them persist for a reasonable fraction of the age of the galaxy. By decreasing τ we can produce the observed SED faster. In the limit where star formation is instantaneous, the observed SEDs could be younger than 2×10^8 yr; however, this makes the luminosity at the peak of star formation greater. By increasing τ, one eventually reaches the regime investigated by Lilly (1988).

The evolution of the luminosity in various bands for models A and B and their SFRs are presented in Figures 1*a* and 1*b*. Small variations in time due to the discrete distribution of the stellar masses (and hence stellar lifetimes) in the code have been smoothed. The SEDs of the model galaxies remain approximately flat during the principal episode of star formation, lasting $\lesssim 10^8$ yr. Afterward the ultraviolet light declines (since the stars producing the UV light have lifetimes short compared to the star formation episode) following the slope of the decreasing SFR. Meanwhile, the evolution of all stars off the main sequence (high-mass stars nearly contemporaneously with the burst, AGB stars for $\gtrsim 3 \times 10^8$ yr, and low-mass stars on the red giant branch at $\gtrsim 12 \times 10^8$ yr) conspire to maintain a roughly constant visible and near-IR luminosity from the time the galaxy is born up to ~ 1 Gyr. Then the galaxy progressively reddens as the bulk of the stellar population "passively" evolves.

We have used these models to fit the observed SEDs of the high-redshift galaxies 0902+34 (Lilly 1988) and 4C 41.17 (Chambers, Miley, and van Breugel 1989), as well as several aligned 3CR radio galaxies with $z > 1$ for which multiple colors were available in the literature (Lilly and Longair 1984; Djorgovski 1987; Spinrad *et al.* 1985; Le Fèvre and Hammer 1988 and references therein; Lilly 1989*a*). Figures 1*c*, 1*d*, and 1*e* show that the observed SEDs of nine galaxies can all be fitted remarkably well with a single model (B) assuming only that we are observing each object at a slightly different age in the evolution of the model galaxy. The resulting model ages range from 3.3×10^8 yr for the youngest objects to $> 10^9$ yr for the reddest ones. (The spectra of these galaxies after ~ 1 Gyr would resemble the high-redshift "E + A" poststarburst galaxies discovered in Gunn, Hoessel, and Oke's 1986 survey of high-redshift clusters.)

In Table 1 we list some of the characteristics of each galaxy calculated from our model after scaling to the observed flux density. We estimated the free-fall time $\tau_{\rm ff} \approx 1 \times 10^8$ $(R/25\ {\rm kpc})^{3/2}$ $(M/5 \times 10^{11}\ M_\odot)^{-1/2}$ yr from the corresponding model mass M in stars and taking $R = 25$ kpc as a typical radius of the observed continuum. We also computed the Lyα emission due to hot stars by assuming case B recombination.

Note that while we do not expect these objects to be very dusty because of the large observed Lyα flux, any dust component would redden the SED and thus we would have *overestimated* the ages.

IV. DISCUSSION

We obtain young ages (a few times 10^8 yr) for the high-redshift radio galaxies by modeling the observed SEDs with a single episode of star formation of duration $\lesssim 10^8$ yr plus a modest tail and with a normal (Scalo) IMF. There are several arguments which suggest that such short ages for these galaxies are plausible.

First, the young ages inferred from these considerations are comparable to the free-fall time, and are thus a reasonable time scale for galaxy formation (e.g., Fall and Rees 1985).

Second, such small ages for the "flat UV plus red bump" galaxies are consistent with the observed lumpy and highly elongated morphologies which suggest that these objects are dynamically young as well. The reddening of the spectrum within ~ 1 Gyr is consistent with a simultaneous dynamical evolution suggested by the fact that the reddest objects are less elongated (Lilly 1989*b*).

Finally, young ages could account for the alignment effect if the radio source were responsible for triggering the formation of the bulk of the stars. In particular, the appearance of the red bump on short time scales could account for the observed infrared alignment with the radio axis. Rees (1989) and Begelman and Cioffi (1989) have recently proposed a new mechanism for how the powerful radio sources in high-redshift galaxies might stimulate star formation (see also DeYoung 1989 and Daly 1989). The fast rise time of our model SFR could be associated with star formation triggered by the passage of the radio source. The tail of star formation could then be due to secondary processes, e.g., supernovae-driven shocks. The star formation event induced by the radio source could even be shorter than in the present model (with a similar evolution to that shown in Fig. 1*b*), albeit with a corresponding rise in the peak luminosity. Given the strong evolution of the radio source population at these redshifts, such a scenario may play an important role in the formation of many giant ellipticals, or even spheroids. However, if the radio source is lumin-

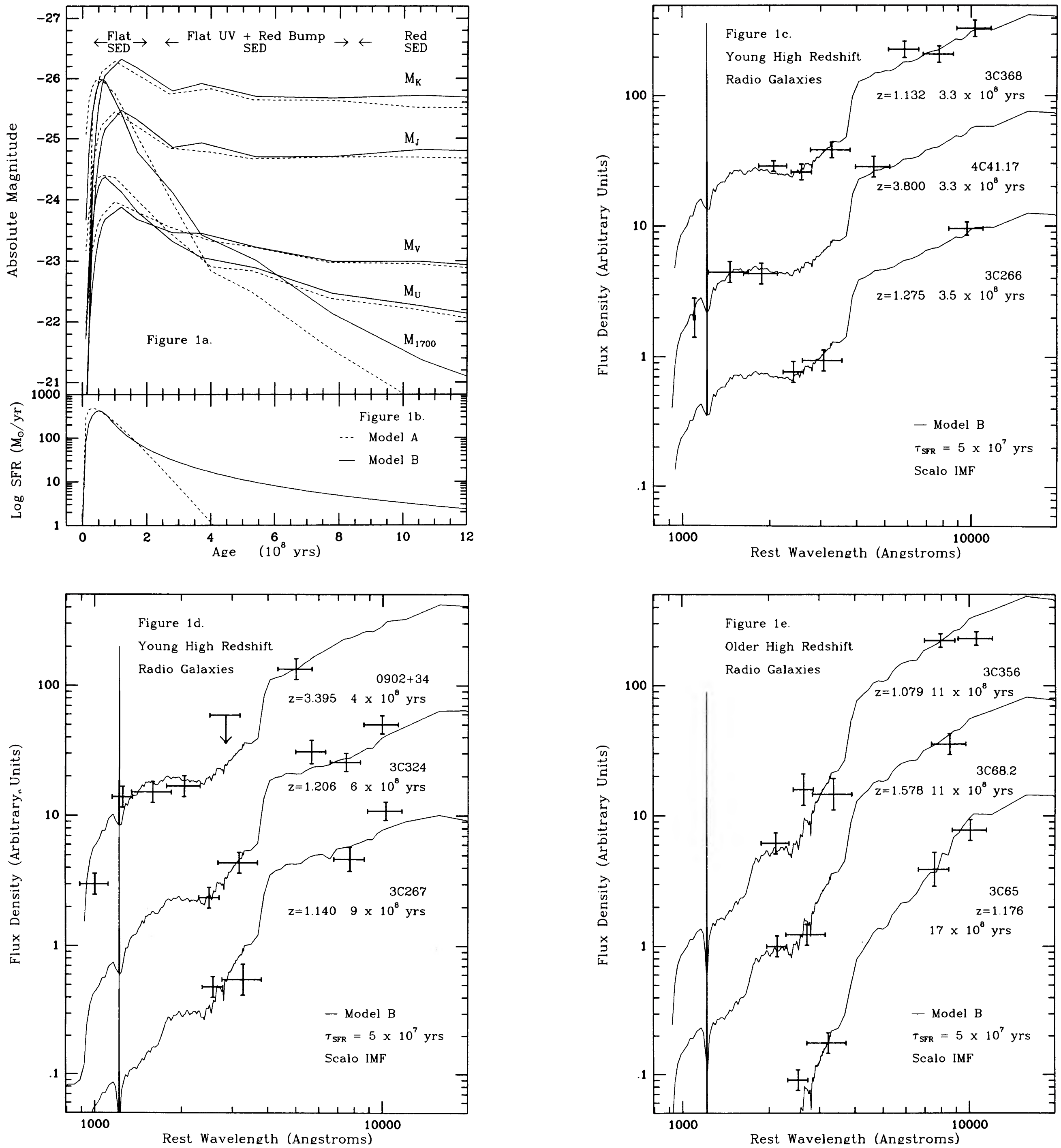

FIG. 1.—(*a*) Spectral evolution of galaxies formed on short time scales. The absolute magnitudes are for a model galaxy of 10^{11} $M_\odot$ and Scalo IMF. (*b*) Star formation rates for the two models discussed. Note that because of the semilog plot the exponential declining model A appears straight and the power-law model B is curved upward. (*c*), (*d*), and (*e*) Fits of model B to the observed spectral energy distributions of nine high-redshift radio galaxies in order of the age estimated for each. The width of the error bars is actually representative of the width of the photometric band used in the measurement. Vertical errors were assumed to be 0.2 mag for those measurements without quoted errors.

ous during the burst phase, one might expect to find at least one object in the 3CR sample in which the extended emission has a relatively flat SED.

Note that the dispersion in the mass of stars among the objects in Table 1 is 7.5×10^{11} $M_\odot$ for $q_0 = 0$ and 1.3×10^{11} $M_\odot$ for $q_0 = 0.5$. This is equivalent to a dispersion in absolute magnitude of 2 mag for $q_0 = 0$ and 0.3 mag for $q_0 = 0.5$ when all the objects are corrected to a "standard model age."

V. CONCLUSIONS

The observed SEDs of high-redshift radio galaxies (0902+34 and 4C 41.17 in particular) can be produced with a

TABLE 1

CHARACTERISTICS DERIVED FROM MODEL B OF THE STELLAR POPULATIONS IN HIGH-REDSHIFT GALAXIES SCALED TO THE OBSERVED FLUXES[a]

Name	3C368	4C41.17	3C266	0902+34	3C324	3C267	3C356	3C68.2	3C65
Redshift	1.132	3.800	1.275	3.395	1.206	1.140	1.079	1.578	1.176
age of galaxy in model ($10^8 yrs$)	3.3	3.3	3.5	4.0	6.0	9.0	11.0	11.0	17.0
z_F, $q_0 = 0$	1.21	4.22	1.37	3.82	1.37	1.37	1.35	2.01	1.68
z_F, $q_0 = 0.5$	1.25	4.90	1.43	4.48	1.46	1.52	1.52	2.42	2.12
mass $q_0 = 0$ (not incl. DM) ($10^{11} M_\odot$)	4.2	25.4	4.15	15.9	5.0	4.7	7.0	7.2	2.3
mass $q_0 = 0.5$(not incl. DM) ($10^{11} M_\odot$)	2.4	5.7	2.2	4.0	2.8	2.7	4.2	3.4	1.3
free fall time (not incl. DM) $q_0 = 0$, ($10^8 yr$)	1.0	0.4	1.0	0.5	0.9	1.0	0.8	0.8	1.4
free fall time (not incl. DM) $q_0 = 0.5$, ($10^8 yr$)	1.3	0.9	1.4	1.0	1.2	1.3	1.0	1.1	1.8
current SFR $q_0 = 0$, ($M_\odot/yr$)	147	875	127	365	52	22	22	22	3
current SFR $q_0 = 0.5$, ($M_\odot/yr$)	84	199	68	92	30	12	12	10	2
M/L (not incl. DM)	0.33	0.33	0.35	0.48	0.65	1.06	1.15	1.15	1.2
eq. width Ly α due to stars (Å)	97	97	100	103	109	117	118	118	121
observed rest frame eq. width Ly α (Å)		210		310					
M_V (rest frame) $q_0 = 0$	-25.11	-27.06	-25.08	-26.29	-25.02	-24.60	-25.20	-25.23	-23.74
M_K (rest frame) $q_0 = 0$	-27.90	-29.85	-27.83	-28.80	-28.03	-27.13	-28.30	-28.33	-27.25
M_V (rest frame) $q_0 = 0.5$	-24.50	-25.44	-24.39	-24.80	-24.39	-24.00	-24.65	-24.42	-23.12
M_K (rest frame) $q_0 = 0.5$	-27.29	-28.23	-27.14	-27.31	-27.40	-26.53	-27.75	-27.52	-26.63

[a] Assumptions: $H_0 = 50$ km s^{-1} Mpc^{-1} and Scalo IMF.

normal (Scalo) IMF in $\lesssim 3 \times 10^8$ yr if they formed the bulk of their stars on time scales comparable to the free fall time, $\lesssim 1 \times 10^8$ yr. This suggests that these objects may be relatively young and that we are observing them (at least the ones with the flat UV) near the time in which they formed most of their stars. The "epoch" of this type of galaxy formation would have extended over a fairly wide range of redshifts, from $z \sim 1$ to $z \sim 5$. Therefore, we do not require the large ages suggested by Lilly (1988). This is primarily due to the short time scale of formation, although the observationally derived AGB contribution accounts for $\gtrsim 20\%$ of the red light on the time scales considered.

The ability to obtain "flat UV plus red bump" SEDs on short time scales is consistent with the alignment effect (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987) and in particular may account for infrared alignments with the radio axes (Chambers, Miley, and Joyce 1988; Eisenhardt and Chokshi 1989) while maintaining the observed low dispersion and continuity of the Hubble diagram (Lilly 1989*b*). This is possible because the different evolving components (main-sequence, massive supergiants, AGB stars, and red giants) conspire to maintain roughly constant visible to near-infrared light from the time the galaxy is born up to $\gtrsim 1$ Gyr (afterward, it evolves passively).

Finally, using this model to compare different objects we note that if q_0 is small then the highest redshift galaxies are significantly more massive, whereas for $q_0 = 0.5$ the high-redshift radio galaxies appear to have a characteristic mass of $\sim 3 \times 10^{11} M_\odot$ in luminous stars.

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