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A COSMOLOGICALLY SIGNIFICANT POPULATION OF GALAXIES DOMINATED BY VERY YOUNG STAR FORMATION

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ABSTRACT

A population of galaxies whose light is dominated at all wavelengths from B to K by a very young stellar population has been found in an extremely deep optical and IR small-field survey. These galaxies must represent one of the main star-forming epochs in the history of the universe and approximately 10%–100% of the metals must have formed in them. They must have a redshift $z < 3.5$ and may constitute either a genuine protogalaxy population or a rejuvenation phase of galaxies that formed earlier. The faint I band star counts in the field eliminate the possibility that the Galactic dark halo may be composed of hydrogen-burning main-sequence stars.

Subject headings: galaxies: formation — stars: formation

I. INTRODUCTION

Recent advances in observations of faint objects have led to the discovery of many unique and curious objects at high z, which, while individually pathological, can provide information on the history of galaxy formation. Particularly noteworthy are the discovery of quasars out to $z \sim 4.5$ (e.g., Warren *et al.* 1987) and the discovery of a massive radio galaxy at $z \sim 3.4$ (Lilly 1988) that contains evolved stars and must have an age of ~ 2 Gyr, placing $z_{\rm form} > 4.6$ (a minimum value, for $q_0 = 0$, $H_0 = 50$ km s^{-1} Mpc^{-1}). On the basis of this evidence it now appears that some galaxies began forming at $z \sim 5$ or earlier.

However, it is quite possible that galaxy formation may have spread over a considerable range in z and that some, or even the bulk, of galaxy spheroids could have formed at later times (e.g., Baron and White 1987; Cowie 1988). Recently, Tyson (1987) has found a substantial population of flat-spectrum $(B-R)$ objects in the range $23 < I < 25$. Without further information, these can be interpreted either as modest-z irregulars ($z \gtrsim 0.8$) or as a population of rapid star-forming spheroids at $z \sim 3$. Cowie (1988) has given several indirect arguments why the latter may be the case.

In this *Letter* we shall briefly describe some early results from an ultradeep optical and IR survey. The program will be described in detail elsewhere (Lilly, Gardner, and Cowie 1988; Gardner *et al.* 1988), but the unique feature compared to previous deep surveys (see, e.g., Koo 1986; Tyson 1987) is that the fields are being surveyed to an unprecedented depth in the K band using the recently implemented *IRCAM* infrared array camera (McLean 1987) at the 3.8 m United Kingdom Infrared Telescope (UKIRT).

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The ultimate goal of the deep survey program is to observe each of four small high–Galactic latitude fields (each about 1′ on a side), that we call small selected areas (SSAs), for an on-target time of at least 3 hr in each of the U, B, V, and I bands and around 12 hr in the K band. The small size of the fields is dictated by the small size of the IR arrays and the need to mosaic the IR observations to obtain median flat fields.

The most complete results to data are for SSA 22 (R.A. [1950] = $22^{\rm h}00^{\rm m}00^{\rm s}$; decl. [1950] = $-1°00'00''$; $l = 62°$, $b = -45°$). This is a $75'' \times 75''$ field where we presently have 3 hr of exposure in B ($1\ \sigma = 27.7$), 70 minutes of exposure in V ($1\ \sigma = 26.8$), and 110 minutes of exposure in I ($1\ \sigma = 26.4$). In the infrared, a wide mosaic has given a total of 3 hr on-target exposure at each point in the field in K ($1\ \sigma = 20.7$), while 12 hr on-target exposure times have been obtained over a quadrant of the field where $1\ \sigma = 21.9$ in K. (The $1\ \sigma$ values refer to a $3''$ diameter aperture magnitude in the optical and to a $3''.6$ box in the K band.)

In the analysis of the SSA 22 data we have detected a population of galaxies which have a flat spectrum from B to K. We interpret these as galaxies whose light at all wavelengths is dominated by young stars. They could represent either protogalaxies or a population of galaxies that formed earlier but are now undergoing a large burst of star formation. These objects must lie at $z < 3.5$ if we are to match the flat $B-V$ colors.

II. SAMPLE AND ANALYSIS

Each of the optical images of SSA 22 was independently analyzed with two different object-identification, classification, and photometry programs by two of the authors. The two programs independently identified the same sample of 35 objects selected to have $I < 24$ in a $3''$ diameter aperture; we take this set as the primary data sample for this paper. (This limit is set at a nominal 9 σ detection in order to ensure that the sample is complete and uncontaminated and that colors are accurately determined.) Next, optical colors were determined independently in $1''.8$ and $3''$ diameter apertures for each object. For each of the I band detected objects, the K band magnitude was then measured in a 3″.6 × 3″.6 box. Ten of the 35 objects were detected at or above the 3 σ level in the K band. There are no objects detected in K to this level which were not previously identified in the $I < 23$ portion of the sample. While systematic errors might be present in the K band photometry, checks on galaxies with existing photometry and on the colors of stars in the field indicate that these are at or below the 0.3 mag level. This is quite adequate for the present analysis.

The final star-galaxy classification was based on morphological criteria. This was established by color classification of the brightest 20 objects ($I < 23$) for which classification was sought, in order of preference, as low-z galaxies, stars, and high-z galaxies. Clear morphological differences existed between the stars and the galaxies, so these morphological criteria were used to clarify the remaining 15 objects ($23 < I < 24$). In the end, we have six stars, 27 galaxies, and two ambiguous objects.

The six unambiguous stars all have $I < 23$. The stellar density lies close to the value predicted by the Bahcall and Soneira (1981) models at this Galactic latitude and longitude. Classifying by color, there is 1 G star, 4 K stars, and 1 early M star. The absence of very late-type stars and of any rapid rise in the stellar density in this magnitude range appears to rule out the possibility that the dark halo is composed of low-mass stars lying at the bottom of the hydrogen-burning main-sequence (Bahcall and Soneira 1981).

TABLE 1

FLAT-SPECTRUM GALAXIES

SSA 22 Number	I	$B-V$	$V-I$	$I-K$
10..........	22.1	0.60 ± 0.05	0.60 ± 0.05	≤ 2.2
16..........	22.6	0.34 ± 0.12	0.82 ± 0.12	≤ 2.7
24..........	23.5	0.03 ± 0.17	0.44 ± 0.20	≤ 2.4

Most of the 27 unambiguous morphologically classified galaxies down to $I < 24$ can be identified as low-z galaxies based on their colors (see Fig. 1). This procedure may, of course, allocate unusual objects to the normal population, and, as we have emphasized, this is particularly true at the faint end where error bars are larger. However, despite this, six of the 27 galaxies could not be fitted in this way.

The colors of three of these remaining six galaxies can be fitted by $z = 0.5$–1 galaxies (two irregulars and a $z = 0.5$ elliptical). The remaining objects have very flat spectra from B through to K. Object 16 can be fitted by a $z = 2$ Im galaxy (Fig. 1), but the other two galaxies still cannot be fitted. The difficulty is easily seen by an inspection of their colors (Table 1) or their fluxes as a function of wavelength derived from the

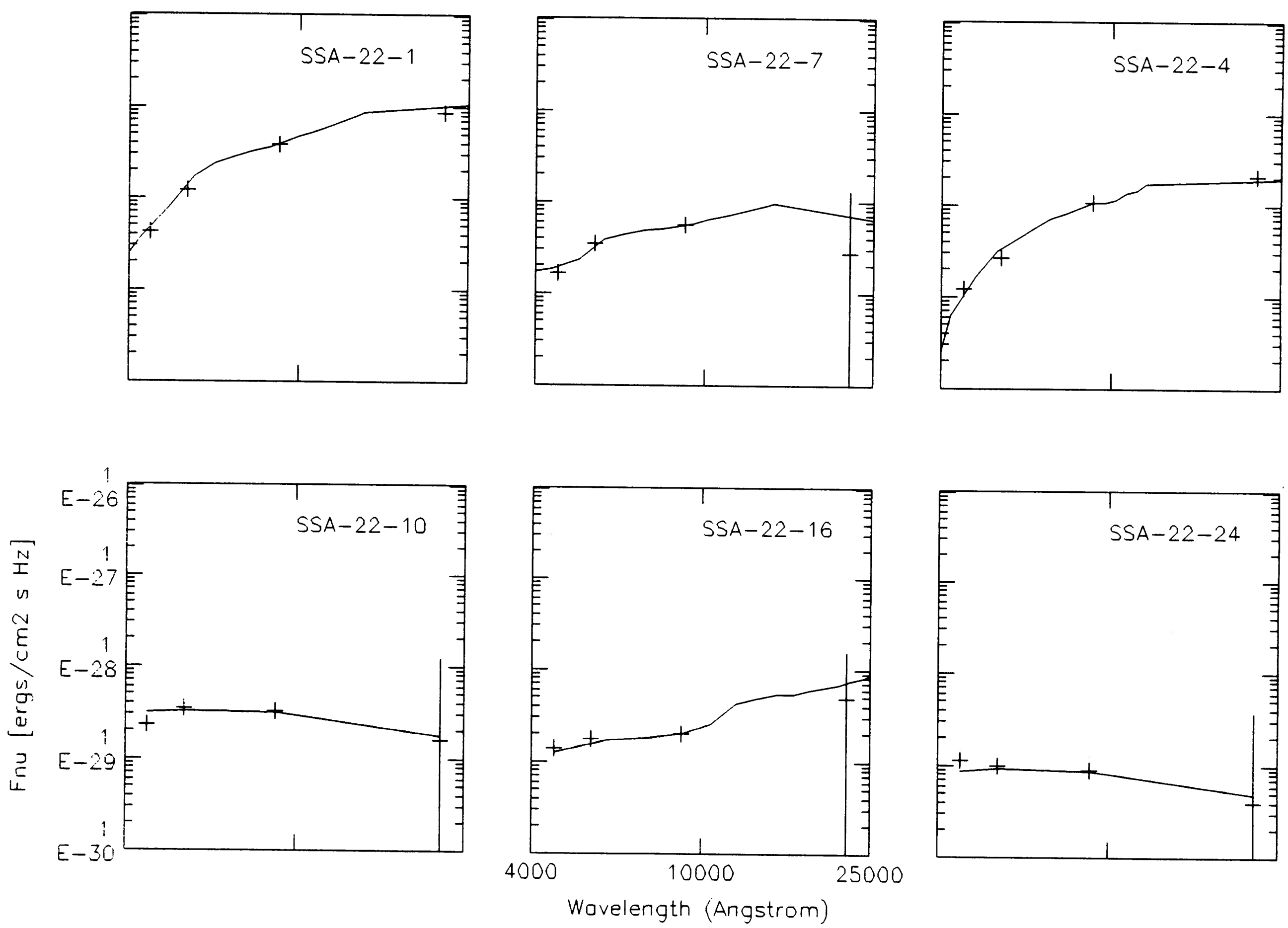

FIG. 1.—Spectral energy distributions for the flat-spectrum objects are compared with the Im continuum spectrum from Coleman, Wu, and Weedman (1980) shifted to the best-fitting redshift ($z = 2$) for SSA 22-16 and to a starburst spectrum at $z = 0$ for SSA 22-10 and SSA 22-14 (Johansson 1988). Also shown are three of the normal galaxies in the field; SSA 22-1 is fitted by an Sbc galaxy at $z = 0.42$, SSA 22-7 by an Im at $z = 0.45$ and SSA 22-4 by an elliptical at $z = 0.2$.

colors (Fig. 1). Without the K band data these objects could still have been classified as $z > 0.8$ irregulars as in Tyson (1987), but the K band data now eliminates this possibility. For object 24 in particular, F_ν *increases* slightly with increasing frequency from I to B and its $B-K$ color is at most 2.87 (2 σ). As can be seen from Figure 1, even Im galaxies cannot match the colors of objects 10 and 24 *at any redshift*. The reason is that, in order to produce the flat $V-I$ and $I-K$ colors we must get away from the rise in flux density at longer wavelengths, i.e., move the 4000 Å break through the K bandpass. However, at this very high redshift, the Lyman continuum break would pass through the B bandpass. Neither can the objects be understood in terms of a dominant flat-spectrum nucleus since all are extended, with comparable sizes and shapes at all wavelengths.

However, objects 10 and 24 can be understood as galaxies whose light is totally dominated at all our observed wavelengths by very recent star formation. Such very young objects, where stars are forming with a standard initial mass function (IMF) naturally produce a flat-spectrum galaxy (Meier 1976) as can easily be understood since the spectral energy distribution is dominated by the light from the most massive stars. In Figure 1 we compare these objects with a spectral energy distribution (SED) of a starburst galaxy at $z = 0$, taken from Johansson (1988). Unfortunately, there are virtually no continuum signatures for such an object with the exception of the Lyman continuum break (Meier 1976). We can therefore place only an upper bound on the redshift of these objects by the condition that the Lyman continuum break not have passed through the B band. This requires that $z \lesssim 3.5$ for object 10 and $z \lesssim 3$ for object 24.

III. DISCUSSION

Where might these flat-spectrum galaxies fit into a general scenario of galaxy formation and evolution? First, we have argued that their light must be produced by a very young stellar population. If the young stars formed in a burst, the time since the production of this population must be less than 100 M yr to avoid the formation of significant breaks and a rising spectrum in the red (Struck-Marcell and Tinsley 1978). After 10^9 yr of constant star formation, a galaxy resembles an Im SED (Bruzual 1983), which fails to fit these objects. Thus these galaxies are either very young objects (protogalaxies) or a rejuvenation phase of older galaxies in which the light is dominated at all wavelengths by a very recently occurring starburst. There is no easy way to eliminate this last possibility of a concealed older population. The most extreme case would be to assume that these galaxies are nearby starbursters occurring in an old elliptical galaxy. An old population of age 10^{10} yr representing 97% of the mass could be present without perturbing the K band flux above acceptable limits.

However, *irrespective of this*, if these flat-spectrum galaxies are indeed star-forming galaxies, they *must* contain a significant fraction of the star formation which has occurred in the history of the universe. This can be seen in entirely model-independent terms from their average surface brightness on the sky. For a young massive star-forming population, resulting in a flat spectrum (as seen in these objects), the sky surface brightness is linearly related to the metals produced by standard nucleosynthesis arguments (Lilly and Cowie 1987; Cowie 1988) and given by

$$S = \frac{1}{4\pi}\,\epsilon_\nu(\rho Z)c = 2.1 \times 10^{-25}\left(\frac{\rho Z}{10^{-43}\ \mathrm{g\ cm^{-3}}}\right)\ \mathrm{ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}\ deg^{-2}}, \tag{1}$$

where $\epsilon_\nu = 2840$ ergs g^{-1} Hz^{-1} for a Salpeter IMF (Cowie 1988) is the light produced per gram of released metals and ρZ is the average density of metals in the universe produced by the star formation. (This result is very insensitive to the assumed form of the IMF and is independent of quantities such as q_0 and the redshift and duration of the formation epoch.) A rough estimate of all the metals in spheroids ($1.4 \times 10^{-34}\ h^2$ g cm^{-3}) and disks ($2.2 \times 10^{-34}\ h^2$ g cm^{-3}) ($h = H_0/50$ km s^{-1} Mpc^{-1}) given in Cowie (1988) suggests that the production of metals in each component results in an average sky surface brightness of order $4 \times 10^{-25}\ h^2$ ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2}.

Now, the three flat-spectrum galaxies (objects 10, 16, and 24) *alone* contribute 1.2×10^{-25} ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} to the sky surface brightness, or 40 h^{-2}% of the light required to produce the spheroid metals according to equation (1). Therefore, these galaxies represent a significant fraction of the massive, metal-producing star formation in the history of the universe.

There is no way at present to rule out the possibility that this population actually constitutes the bulk of galaxy formation and that hence most galaxy formation took place at $z \lesssim 3.5$. As we discussed in the introduction, there is now clear evidence that *some* galaxy formation took place at $z \gtrsim 5$. The question at this point is how large a fraction of the metals formed at these earlier epochs. This fraction could be quite small indeed. One attractive speculation is that galaxy formation onset at $z = 5$–6 and rose to a peak at $z = 3$–4 (Cowie 1988). The blue population under discussion would then be the last of the protogalaxies. If this is indeed the case, slightly deeper observations should allow us to detect unambiguously the population at $z \sim 4$, which should have flat colors longward of V and a steeply dropping spectrum between B and V.

IV. SUMMARY

We may summarize thus: A rapid star-forming population of galaxies is present in the deep observations that onset at $I \geq 22$. A substantial fraction of these objects contain a very young ($t \sim 100$ Myr) stellar population that dominates the light. This population represents a very significant fraction of all the star formation in the history of the galaxies—within the uncertainties in metal production and the Hubble constant, from a few percent to 100% of all the metal production in all galaxies.

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