THE ASTROPHYSICAL JOURNAL, 366:7–15, 1991 January 1

GALAXIES CLUSTERING AROUND QSOs WITH $z = 0.9$–1.5 AND THE ORIGIN OF BLUE FIELD GALAXIES

PAUL HINTZEN[1]
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center; and Department of Physics, University of Nevada, Las Vegas

W. ROMANISHIN[1]
Department of Physics and Astronomy, University of Oklahoma

AND

FRANCISCO VALDES
National Optical Astronomy Observatory
Received 1988 July 26; accepted 1990 June 26

ABSTRACT

Deep direct CCD observations in Mould-Cousins R and I passbands have been obtained for the fields of 16 radio-loud QSOs with $0.9 < z < 1.5$. While we cannot confirm Tyson's report of excess galaxies with $R < 21$ lying within 30″ of quasars in this redshift range, we do find a statistically significant excess of galaxies within 15″ of the quasars and brighter than $R = 23$ and $I = 22$ (probability of chance occurrence $P < 1\%$). Assuming the excess galaxies are indeed physically associated with the corresponding QSOs, these galaxies are roughly 0–3 mag brighter in R than first-ranked galaxies are predicted to be and are therefore several magnitudes overluminous ($H_0 = 50$ km s^{-1} Mpc^{-1}; $q_0 = 0.0$). This possibility is not surprising in light of Yee and Green's tentative conclusion that galaxies in clusters associated with QSOs at redshifts near 0.6 are nearly 1 mag overluminous. Our data for one object, 1622+238 ($z = 0.927$), indicate that this quasar lies near the center of a rich, distant cluster of galaxies, but further observations are necessary to confirm the apparent association. Galaxy counts in the outer halves of our fields have been used to derive field galaxy counts as a function of magnitude to $R = 23$ and $I = 22$. After adjusting for the zero-point difference between Kron-Cousins R and Gunn r, our cumulative field galaxy densities agree within 7% with those derived by Yee and Green and by Sebok. The color-magnitude diagram for the field galaxies includes a large population (about 10%) of faint ($R \geq 22$), very blue galaxies ($R - I \leq 0.2$), presumably similar to the blue field galaxies reported in previous surveys at shorter wavelengths (e.g., Kron's and subsequent surveys). These objects are much bluer in $R - I$ than Magellanic irregular galaxies at any redshift, and it has been suggested that they may be galaxies undergoing initial formation. We find that strong line emission almost certainly must be present in the R passband to produce the bluest colors observed. This population could be comprised of low-redshift, low-luminosity (H II region) galaxies of the type studied by French and/or higher redshift galaxies with strong cooling flows and [O II]. Spectroscopic confirmation of the strong line emission in these objects should be feasible, despite their faint apparent magnitudes.

Subject headings: galaxies: clustering — quasars

I. INTRODUCTION

Associations between low-redshift quasars ($z < 0.6$) and groups or clusters of galaxies have been widely reported and extensively studied (Stockton 1978; French and Gunn 1983; Yee and Green 1984, 1987; Hintzen 1984; Heckman *et al.* 1984; Hintzen and Romanishin 1986). Recently, however, Tyson (1986) has reported an apparent excess of galaxies near quasars with $0.9 < z < 1.5$. Tyson's result is remarkable and potentially of great import because he estimates his limiting magnitude as $R = 21$, implying that the excess galaxies are several magnitudes overluminous, if physically associated with the quasars. Since Tyson's data were obtained with an unfiltered CCD, the interpretation of his limiting magnitude is quite uncertain. Also, he notes that the observed excess galaxies may be members of foreground "lensing" groups, though his statistical analysis of the prevalence of lenses implies that this is unlikely.

In order to confirm Tyson's result and extend the available data to fainter galaxy magnitudes, we have obtained deep CCD images in Mould-Cousins R and I of 16 radio quasars with $0.9 < z < 1.5$ and absolute values of $b > 35°$, chosen from the Véron-Cetty and Véron (1984) catalog, which includes only objects with M_V brighter than about -23.

II. OBSERVATIONS AND REDUCTIONS

The observations discussed were obtained 1987 May 2–3, using an 800 × 800 TI CCD at the prime focus of the 4 m telescope at Kitt Peak National Observatory. The CCD field covered approximately 4′ square at a scale of 0.298 arcsec pixel^{-1}. Conditions were photometric, and seeing varied from 0″.9 to 1″.5 FWHM. The R and I filters used were from the KPNO "Mould" set, and total integration times in each filter were typically 640 s (R) and 480 s (I).

After bias subtraction and field flattening, the I band images were also corrected to remove low-level fringing (about 1% of sky). Observations of M92 were used in conjunction with magnitudes and colors published by Christian *et al.* (1985) to set the photometric zero point to the Cousins system. Extinction corrections were applied using standard extinction coefficients for the KPNO CCD systems derived by L. Davis (1988, private communication). No corrections were applied for variations in photometric zero points with color, since the standard stars

[1] Visiting Astronomer, Kitt Peak National Observatory, a division of National Optical Astronomy Observatories, which is operated by AURA, Inc. under contract with the National Science Foundation.

used have $R-I$ colors similar to those for the galaxies, and the corrections are comparatively small. Intercomparison of data for standard star fields indicates that our R and I zero points are accurate to approximately 0.05 mag, but for the faint objects of interest in our sample, the photometric errors are dominated by photon statistics and systematic errors in sky subtraction, as discussed below.

III. OBJECT CLASSIFICATIONS AND PHOTOMETRIC ERRORS

After bias removal and flat-field corrections, the Faint Object Classification and Analysis System software (FOCAS) was used to detect and classify objects (Valdes 1982). A point-spread function (PSF) was constructed for each field using several isolated stars, and these PSFs were used to prepare a set of classification templates 0.7–100 times the width of the PSFs. Each detected object was then classified based on the template it best fitted. Objects with detection areas less than 50 pixels or profile widths smaller than 0.8 × PSF were classified as noise, and tests showed that this class effectively removed radiation events from the sample. Objects 0.8–1.15 × PSF were considered stars, and those 1.16–6.0 × PSF were classified galaxies. Larger objects, classified "diffuse," were considered to be large-scale noise and were therefore excluded from the subsequent analysis. Because all observations were obtained in good to excellent seeing, the separation between scale sizes for stars and galaxies was comparatively clean (Fig. 1). Galaxy completeness limits of $R = 23$ and $I = 22$ were adopted based on the magnitudes at which (1) the increase in galaxy counts with magnitude slows, (2) objects are substantially brighter than the visual detection limit, and (3) the scale size transition zone between galaxies and stars (Fig. 1) becomes populated, due to decreasing signal-to-noise ratio (S/N) in the fainter images. Assuming that field galaxy counts should increase exponentially with magnitude, our counts are 12% deficient at $R = 23$ and 8% deficient at $I = 22$.

The R and I magnitudes adopted in this study are FOCAS "total" magnitudes, derived for each object by "growing" the detection isophote to twice the original detection area. This

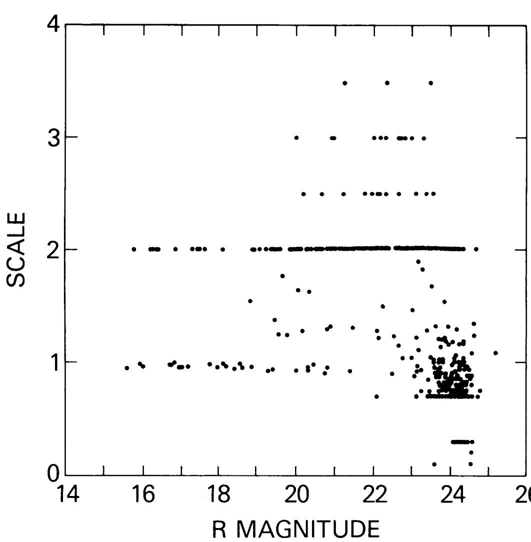

FIG. 1.—Classification scale size (essentially the object FWHM divided by the PSF FWHM) as a function of "total R" magnitude for objects in a typical field. Note the relatively clean separation between "stars" ($0.8 <$ scale < 1.15) and "galaxies" ($1.16 <$ scale < 6.0) for objects brighter than the adopted completeness limit, $R = 23$.

procedure should include at least 90% of the total flux for typical galaxies (Kron 1980*a*, Table 3). The combined flux for overlapping objects which are "split" by FOCAS is divided among the various components in proportion to their core fluxes. The completeness limits we have adopted are sufficiently bright, compared with sky noise, that the object areas used for photometry are always greater than 10 arcsec^2. Our "total" magnitudes should therefore be comparatively insensitive to systematic variations in "effective aperture" as a function of magnitude, since we satisfy Kron's (1980*a*, p. 312) minimum area criterion (see also Kron 1980*b*).

The photon counting errors for typical galaxies at our adopted completeness limits, limits, $R = 23$ and $I = 22$, are dominated by sky noise and produce typical rms uncertainties of 0.25 mag. The systematic errors caused by small offsets in the adopted sky levels are harder to estimate. FOCAS computes the mean counts per pixel within 2 σ of the mode of the sky histogram around each object. The mode itself is not used because it is a more noisy sky estimate. However, a correction for any asymmetry in the distribution of sky intensities due to faint unresolved galaxies is obtained by measuring the difference between the mean sky and the mode averaged over all objects. This correction, which is removed from the mean sky for all objects in the frame, is usually negative, since the mean is generally too bright relative to the mode, due to unresolved objects in the sky regions. If we assume the scatter in this correction over all the fields is a conservative estimate of the systematic sky photometry errors, then the systematic R and I uncertainties at the completeness limits are 0.09–0.14 mag. It therefore appears that photometric errors in the sky may be as important as differences in aperture definition in explaining differences in faint galaxy counts found by various investigators: At $R = 23$, a 0.2 mag relative offset of photometric zero points for different investigators would produce a 20% difference in derived galaxy densities.

The $R-I$ colors for detected objects were calculated from FOCAS "isophotal" magnitudes and therefore use only half as much "aperture area" as the "total magnitudes." This procedure decreases the (dominant) sky noise by $2^{1/2}$, roughly canceling the increase in rms uncertainty which results from combining two magnitudes to produce a color. We also experimented with colors derived from 2".7 radius apertures. The aperture colors yielded the same color distribution as the isophotal colors, but with increased scatter; hence our adoption of the isophotal values. Color-magnitude diagrams for stars and for galaxies in the fields observed are presented in Figure 2.

IV. FIELD GALAXY COUNTS IN R AND I PASSBANDS

Data for the 16 fields observed have been combined to produce a plot of galaxy densities ($R \leq 23$) as a function of radial distance from the quasars (Fig. 3). An excess of galaxies is apparent within 15" of the quasars. Outside this radius the galaxy distribution is quite flat, with a mean value presumably equal to the general density of field galaxies. The 15" radius corresponds to 158 kpc at $z = 0.9$ and 183 kpc at $z = 1.5$ ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.0$). Counts of galaxies within 15" of the QSOs are provided in Table 1 for each field. Because the counts are done independently in R and in I and because the galaxies' colors vary widely, the R and I counts listed often differ for a given QSO.

To determine field galaxy densities, we have used the outer annuli of the fields, the area 60"–120" from the QSOs, which

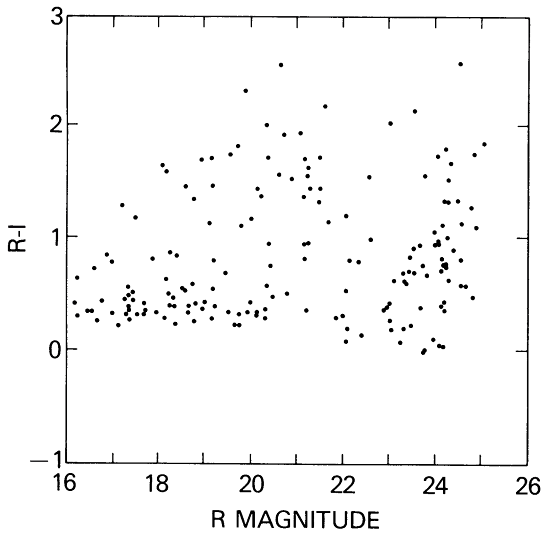

FIG. 2a

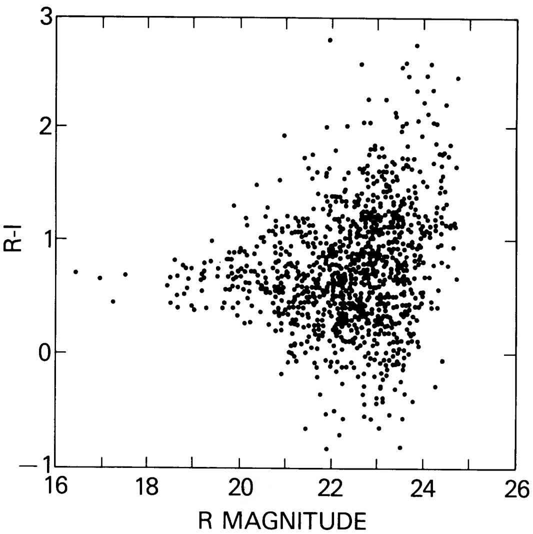

FIG. 2b

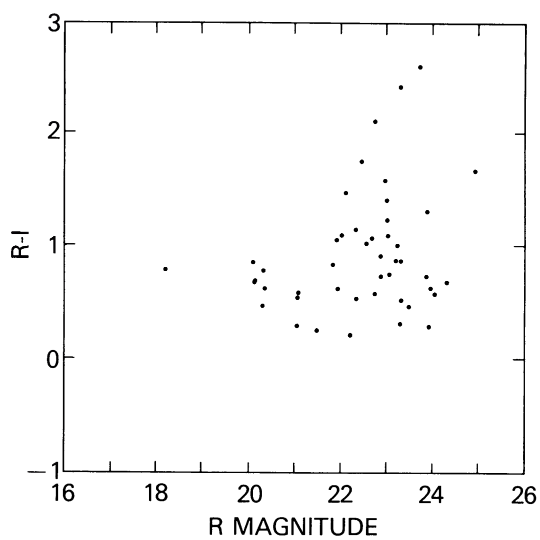

FIG. 2c

FIG. 2.—Color-magnitude diagrams for stars and galaxies in all fields combined. (*a*) Stars lying 60″–120″ from the quasars. Note the dominant ridge of G and K stars at all magnitudes [$0.3 < (R-I) < 0.8$], and the sharp rise in the number of M stars at fainter magnitudes. (*b*) "Field" or background galaxies, defined as those galaxies lying 60″–120″ from the QSOs. Note the substantial number of apparent blue galaxies at fainter magnitudes. (*c*) Galaxies within 15″ of the quasars.

subtend 8.7 arcmin^2 per field. This outer ring corresponds to radial distances from the QSOs of 0.6–1.3 Mpc for $z = 0.9$ and 0.7–1.5 Mpc for $z = 1.5$ and lies outside the clusters of galaxies around QSOs 1215+643 and 1622+238. Our combined counts for 16 fields in R and 15 fields in I resulted in the galaxy and star densities per square arcminute presented in Table 2 (these are cumulative counts to the magnitudes listed). Assuming that field galaxy counts should increase exponentially with magnitude, our counts are about 12% deficient at $R = 23$ and 8% deficient at $I = 22$.

Comparable data on field galaxy counts have been published by Yee, Green, and Stockman (1986, Table 3), Sebok (1986, who combined his data with those of Kron 1980*a*), and Tyson (1988, his deep "blank field" survey). Yee *et al.* used a Gunn r filter and calibrated using Gunn standards, while Sebok used a somewhat broader passband and Gunn's photometric zero point. Galaxy counts from those two surveys agree within 12% to $r = 22$. By computing synthetic $V-R$ colors for several stars with spectrophotometry and V magnitudes in Massey *et al.* (1988) and Gunn r magnitudes in Kent (1985), we derive $(r - R) \sim 0.3$. This should be roughly independent of color, as the Mould and Gunn filters have very similar effective wavelengths. If we account for this magnitude zero-point shift, our cumulative galaxy counts agree with those of Yee, Green, and Stockman (1989) to within 7% in the range $r = 20$–22.5.

By contrast, Tyson's (1988) celebrated "blank field" surveys includes only 12 fields, but it extends far deeper than other published studies. Converting our cumulative galaxy counts to differential counts (galaxies per square degree per magnitude, e.g., the differential count at $R = 21$ equals the cumulative count at $R = 21.5$ minus that at $R = 20.5$), allows a comparison with Tyson (1988). Our R data match the slope derived by Tyson (1988) for his differential R counts, but our counts are uniformly 0.2 dex higher than his. The source of this difference is not obvious: Tyson (1988) used "Landolt *BVRI* and Graham CTIO standards," so his magnitudes, like ours, are on the Kron-Cousins system, yet his galaxy counts in Cousins R are lower than those of Yee *et al.* and Sebok in Gunn r (they should be higher). Nevertheless, an offset of this size is typical of intercomparisons between studies (e.g., Kron 1980*b*).

V. EXCESS GALAXIES WITHIN 15″ OF THE QSOs

To assess the statistical significance of the excess of galaxies within 15″ of the QSOs, we combined the data for the 16 fields observed. Using the background counts from the outer portions of the fields (more than 200 pixels, or 60″, from the QSOs), we expect a total of 19.3 ± 4.4 galaxies brighter than $R = 23$ and lying within 50 pixels (15″) of the QSOs, whereas 32 are observed in the 16 fields (Table 1). Since the QSOs have isophotal areas averaging 455 ± 160 pixels, they obscure on average 5.8% of the 15″ radius circles covered by our galaxy counts. We therefore correct for galaxies lost in the glare of the QSOs by increasing the count of galaxies within 15″ of the QSOs by 5.8%, yielding 33.8 "effective galaxies."

The combined data for the QSO fields would be expected to effectively suppress nonrandom variations in galaxy counts for

TABLE 1

RADIO-LOUD QUASARS OBSERVED ($0.9 < z < 1.5$)

Object	z	$N(R)$[a]	$N(I)$[a]	R(1st)[b]	delta (R1st)[c]
0957+003......	0.907	1	...	22.8	−0.8
1001+226......	0.974	0	0	23.2	...
1012+022......	1.374	3	2	25.0	−3.2, −3.0, −2.9
1055+201......	1.11	1	1	24,0	−2.9
1215+643......	1.288	4	4	24.7	−4.6, −3.7, −2.8, −2.3
1218 ± 33......	1.519	2	1	25.4	−2.9, −2.8
1244+324......	0.949	2	3	23.1	−1.2, −0.1
1340+606......	0.961	0	0	23.2	...
1433+177......	1.203	0	0	24.5	...
1435+248......	1.010	1	1	23.4	−0.7
1454−060......	1.249	2	1	24.6	−2.7, −1.8
1517+176......	1.39	2	2	25.1	−2.3, −2.2
1620+356......	1.473	3	2	25.2	−4.9, −3.7, −2.3
1622+238......	0.927	5	3	23.0	−2.9, −0.8, −0.6, −0.5, −0.5
1628+363......	1.254	3	2	24.6	−6.4, −4.3, −1.7
1632+391......	1.082	3	3	23.9	−3.5, −2.8, −1.1

[a] $N(R)$ and $N(I)$ are the number of galaxies with $R < 23.0$ or $I < 22.0$, respectively, within 50 pixels (15″) of the QSO. Differences between $N(R)$ and $N(I)$ occur when a galaxy is fainter than the completeness limit in one of the two passbands.

[b] R(1st) is the predicted Mould-Cousins R magnitude as calculated by Romanishin (1990). for a first-ranked cluster galaxy at the QSO's redshift, assuming that no evolution has taken place since $z = 1.5$ ($H = 50$ km s^{-1} Mpc^{-1}, $q = 0.0$). Following Coleman *et al.* 1978, Romanishin calculated apparent magnitudes as a function of redshift for a "first-ranked" elliptical galaxy with $M(R) = -23.93$ and for an Sbc galaxy with $M(R) = -22.65$. At a given redshift, the R(1st) listed is the brighter of the predicted magnitudes for these two galaxies (for $z > 1.2$ the Sbc should be brighter than the E galaxy).

[c] The quantity delta (R1st) = R(galaxy) − R(1st), i.e., delta(R1st) is the difference between the predicted R magnitude for a first-ranked galaxy at the QSO's redshift and the observed R magnitude for each galaxy within 15″ of the QSO. Examination of the table demonstrates that all of the "excess" galaxies around the QSOs are brighter than a first-ranked galaxy is expected to be at the corresponding QSO's redshift.

the outer regions of the fields, and direct counts of galaxies in 0.194 arcmin^2 areas confirm this at $R = 23$. We therefore assume Poisson statistics are applicable and find that the probability of finding 33.8 galaxies within 15″ of the QSOs when 19.3 ± 4.4 are expected is less than 0.5%. The shallower I passband data yield similar results: 25 galaxies brighter than $I = 22.0$ are found within 15″ of the QSOs, corresponding to

TABLE 2

BACKGROUND COUNTS OF GALAXIES AND STARS[a]

	R PASSBAND		I PASSBAND	
MAGNITUDE	GALAXIES	STARS	GALAXIES	STARS
15.0..........	...	0.02 ± 0.01	...	0.05 ± 0.02
15.5..........	...	0.07 ± 0.02	...	0.09 ± 0.03
16.0..........	...	0.08 ± 0.02	...	0.15 ± 0.03
16.5..........	...	0.12 ± 0.03	...	0.18 ± 0.38
17.0..........	0.02 ± 0.01	0.15 ± 0.03	0.03 ± 0.02	0.30 ± 0.05
17.5..........	0.04 ± 0.02	0.25 ± 0.04	0.03 ± 0.02	0.36 ± 0.05
18.0..........	0.05 ± 0.02	0.32 ± 0.05	0.07 ± 0.02	0.51 ± 0.06
18.5..........	0.07 ± 0.02	0.41 ± 0.06	0.16 ± 0.04	0.63 ± 0.07
19.0..........	0.17 ± 0.03	0.52 ± 0.06	0.28 ± 0.05	0.75 ± 0.08
19.5..........	0.26 ± 0.04	0.64 ± 0.07	0.54 ± 0.07	0.87 ± 0.08
20.0..........	0.42 ± 0.06	0.73 ± 0.07	0.81 ± 0.08	1.13 ± 0.09
20.5..........	0.71 ± 0.07	0.86 ± 0.08	1.34 ± 0.10	1.28 ± 0.10
21.0..........	1.22 ± 0.09	1.00 ± 0.09	2.09 ± 0.13	1.42 ± 0.10
21.5..........	1.90 ± 0.12	1.24 ± 0.09	3.26 ± 0.16	1.60 ± 0.11
22.0..........	2.87 ± 0.14	1.35 ± 0.10	5.10 ± 0.20	1.75 ± 0.12
22.5..........	4.25 ± 0.18	1.44 ± 0.10	...	...
23.0..........	6.23 ± 0.21	1.59 ± 0.11	...	...

[a] Object densities are cumulative counts per square arcminute down to the specified magnitude limit. The quoted errors are $N^{-1/2}$, where N is the total number of objects in the specified bin.

26.1 galaxies after correction for the average area of the QSOs, while 14.8 are expected. The formal probability that this excess is due to random variations in galaxy densities is less than 1%. Therefore, despite the limited number of fields observed, the comparatively small probability that the observed excess is due to chance indicates a statistically significant excess of galaxies near the QSOs, arising either from physical companions to the QSOs or from members of foreground "lensing" groups.

Can our observations be reconciled with Tyson's (1986) report of excess galaxies brighter than $R = 21$ in quasars in this redshift range ($0.9 < z < 1.5$)? The excess "QSO–associated" galaxies detected in our survey to $R = 23$ and $I = 22$ do not include a significant excess as bright as $R = 21$: we find only six galaxies brighter than $R = 21$ within 15″ of 16 QSOs, while four field galaxies are expected. The 15″–30″ annulus surrounding the QSOs shows no significant excess of galaxies for the 16 fields combined, despite the clusters centered on 1215+643 and 1622+238. However, for $I < 21.0$, our counts of galaxies (14) within 15″ of the QSOs still show a marginally significant excess: the probability of finding by chance 14.7 "effective galaxies" near the quasars, when 6.2 are expected, is less than 5%.

By contrast, Tyson (1986) detected 32 galaxies estimated to be brighter than $R = 21$ and within 30″ of 23 quasars ($0.9 < z < 1.5$), but both the significance of the excess and the very large QSO–galaxy correlation function he derived (7 times the galaxy-galaxy correlation at $R = 21$) are greatly enhanced by the low density of background galaxies adopted for his survey. Since Tyson used an unfiltered CCD with sensitivity extending from 3800 Å to 1.1 μm, detailed comparison with our data is complicated by the fact that his passband includes both our R and I, to say nothing of U, B, and V.

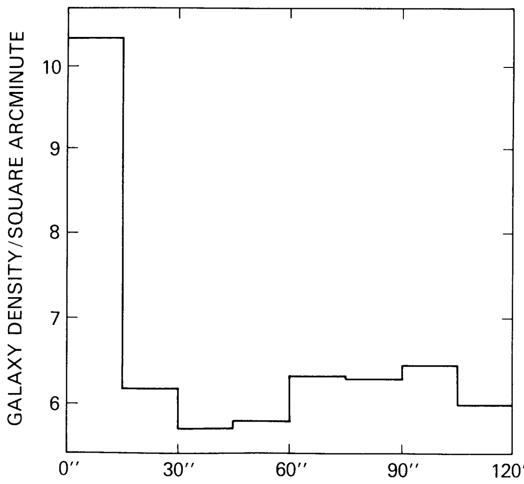

FIG. 3a

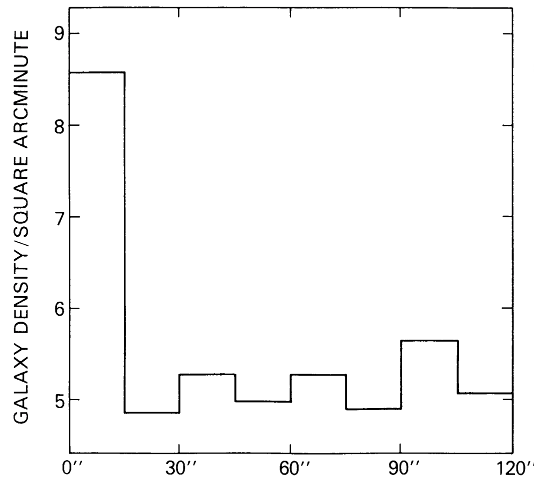

FIG. 3b

FIG. 3.—Mean galaxy densities (galaxies per square arcminute) for the fields observed are plotted as a function of distance from the QSOs. Note the excess galaxies within 15″ of the quasars. (*a*) Cumulative galaxy densities in the R passband to $R = 23$. (*b*) Cumulative galaxy densities in the I passband to $I = 22$.

However, Tyson's (1986) field galaxy densities do provide a means of calibration. His background galaxy density was derived from the "asymptotic galaxy counts" at the very corners of the chip, where the "selection function correction" (his Fig. 2) is a *factor* of around 10. The resulting counts are naturally highly uncertain, as demonstrated by the rms error bars in Tyson's Figure 3, which for large radii extend to 0 galaxies per square arcminute. The "asymptotic" field galaxy density he adopts, 0.33 galaxies per square arcminute (the dashed line in his Fig. 3), appears inappropriate for his data at smaller radii and is, in fact, only one-quarter to one-half the field galaxy density observed at $R = 21$ by other investigators. Yee *et al.* and Sebok find 0.85 and 0.93 galaxies per square arcminute, respectively, brighter than 21 in Gunn r (which, as noted earlier, is about 0.3 mag shallower than Kron-Cousins R). In the present survey we find a field galaxy density of 1.2 galaxies arcmin^{-2} brighter than Kron-Cousins $R = 21$, and Tyson (1988) found 0.76 field galaxies arcmin^{-2} brighter than isophotal $R = 21$ (a value we derived by integrating the functional fit in his Fig. 13).

Indeed, for radii of 50″–70″ from the high-z QSOs in Tyson's (1986) study, a field galaxy density of 0.75 arcmin^{-2} provides an excellent fit to the observed counts (see his Fig. 3). If we use this field galaxy density in analyzing Tyson's (1986) data, we find that the 32 galaxies he detects within 30″ of the quasars still constitute a statistically significant excess, since 14 field galaxies would be expected within this radius. However, a field galaxy density of 0.75 galaxies arcmin^{-2}, rather than 0.33, decreases the galaxy–QSO correlation functions derived by Tyson (1986, Figs. 4 and 5) by roughly a factor of 3–4, i.e., log $w(\theta)$ decreases by 0.5. In this case, the galaxy–QSO correlation function for Tyson's (1986) low-redshift QSOs ($z < 0.5$) drops from a factor of 20 down to a factor of 6 times the galaxy-galaxy correlation function, which is still a factor of 2–3 larger than the galaxy–QSO correlation function derived for low-redshift quasars ($z < 0.4$) by Yee and Green (1984).

For Tyson's high-z QSO sample, the galaxy–QSO correlation function drops from 7 times the galaxy-galaxy correlation function at $R = 21$ to only twice as large as the galaxy-galaxy function, with a very large uncertainty.

This should not obscure the fact that both Tyson's study and ours show statistically significant excesses of galaxies near quasars with redshifts from 0.9 to 1.5.

VI. COLORS OF THE GALAXIES AND FIELD STARS

Color-magnitude plots for galaxies and stars in the combined QSO fields are provided in Figure 2. The stars plotted in Figure 2*a* are those which lie 60″–120″ from the field center, the same region used to sample the "field galaxies" plotted in Figure 2*b*. A prominent strip of G and K dwarfs and subdwarfs is evident in Figure 2*a* at colors $0.3 < (R-I) < 0.8$. The fact that this band has constant color as a function of magnitude and retains its clean blueward cutoff even for the faintest stars argues against any systematic shift in color zero point with magnitude. The M stars, with $R-I$ values as large as 2 or more (M7 or M8) obviously become plentiful among the fainter stars.

The color-magnitude diagram in Figure 2*b* provides data for "field" galaxies from the outer portion of the fields, 60″–120″ from the quasars, while Figure 2*c* contains data for those galaxies within 15″ of the quasars. The color distributions of the field galaxies and "QSO–associated galaxies" are similar, though the latter sample may have an excess of red galaxies with $R \geq 22$ (or a deficiency of blue galaxies), compared with the field galaxy sample. About 60% of the galaxies near the quasars (GNQ) are expected to be field galaxies lying by chance near the line of sight to the QSO. The remaining GNQs are "excess," and, if they share the QSOs' redshifts, these galaxies must be 2 or more mag brighter than similar galaxies at the present epoch (Table 3). They might also be expected to be quite red, which appears to be true of the excess galaxies in our sample.

The effect of such massive luminosity evolution on colors is difficult to predict accurately. However, as pointed out by Bruzual (1983*a*), the dramatic evolutionary color changes predicted for bluer passbands would be postponed to much higher redshifts for $R-I$. Consider Bruzual's (1983*b*) models in $F-N$, comparable to, though slightly bluer than, our $R-I$ index. For $F-N$, all of Bruzual's evolving models reach their red extremes ($[F-N] = 1.5$–2.2) at $0.8 < z < 1.7$, roughly the red-

TABLE 3

POSITIONS, MAGNITUDES, AND COLORS OF OBJECTS NEAR THE QUASARS[a]

Object	Class	R.A.	Decl.	R	$R-I$
		0957+003			
1........	qso	0.0	0.0	17.30	...
2........	s	+8.6	+3.6	16.87	...
3........	g	−11.9	−7.2	22.03	...
4........	g	+8.4	+15.2	22.48	...
		1001+226			
1........	qso	0.0	0.0	17.91	+0.17
2........	s	−8.6	+11.9	18.82	+1.05
3........	g	−13.4	−12.5	20.90	+0.43
		1012+022			
1........	qso	0.0	0.0	16.82	+0.29
2........	g	+8.4	+8.9	21.85	...
3........	s	+4.8	+11.6	22.80	+0.60
4........	g	−9.2	−3.6	22.12	+1.49
6........	g	+5.1	−3.9	22.05	+1.11
7........	s	+8.4	−14.9	21.50	+2.04
		1055+201			
1........	qso	0.0	0.0	16.48	+0.22
2........	g	−6.3	+11.3	21.07	+0.55
3........	s	+8.4	+9.2	21.32	+1.73
		1215+643			
1........	qso	0.0	0.0	17.29	+0.33
2........	g	+14.3	−2.4	20.14	+0.68
3........	g	+20.0	+6.9	21.37	+0.88
4........	g	+6.3	+8.9	22.36	+0.54
5........	g	+6.0	+12.8	21.87	+0.84
6........	g	0.0	+10.4	21.05	+0.31
7........	s	−2.4	+16.4	23.58	+2.07
8........	g	−9.5	+13.4	22.73	+0.26
12........	g	−5.4	−16.7	21.24	+0.72
13........	g	−2.4	−19.4	21.91	+0.80
		1218+33			
1........	qso	0.0	0.0	17.89	+0.59
3........	g	−6.9	+11.0	22.58	+1.04
4........	g	−10.7	0.0	23.04	+0.76
5........	g?	+2.1	−9.5	22.49	+0.54
		1244+324			
1........	qso	0.0	0.0	17.24	+0.17
2........	g	−11.3	−3.6	21.94	+1.06
3........	g	−11.0	+2.7	23.24	+1.77
4........	g	−15.5	+4.5	23.41	+1.65
5........	g	+12.5	−5.1	22.97	+1.59
		1340+606			
1........	qso	0.0	0.0	17.49	+0.20
3........	g	−7.8	+17.6	23.36	+1.50
		1433+177			
1........	qso	0.0	0.0	18.05	+0.08
		1435+248			
1........	qso	0.0	0.0	19.63	+0.30
2........	s	+9.8	+14.9	14.99	+0.47
3........	g	−17.9	−3.0	19.90	+0.83
4........	g	−4.2	−4.5	23.12	...
5........	g	−5.1	−10.4	22.68	+1.08
6........	g?	−6.0	−14.6	22.71	...
		1454−060			
1........	qso	0.0	0.0	17.37	+0.36
2........	s	−9.8	−4.2	18.30	+0.38
3........	g	−9.5	−17.0	19.43	+0.65
4........	g	−0.3	−20.0	22.29	+0.99
5........	g	+6.0	−10.4	21.93	+0.62
6........	g?	+12.8	+3.6	22.77	...
		1517+176			
1........	qso	0.0	0.0	17.88	+0.29
2........	g	−5.7	+3.6	22.77	+2.11
3........	g	+0.3	−5.4	23.22	+0.88
4........	g	+6.6	−10.1	22.89	+0.88
5........	g?	+11.6	−5.4	22.92	+1.23
		1620+356			
1........	qso	0.0	0.0	18.14	+0.25
2........	g	−5.1	−6.6	21.49	+0.25
4........	s	−4.2	−16.4	20.09	+0.32
5........	g	+10.7	−11.9	21.05	+0.44
8........	g	−3.3	+6.6	22.87	+0.74
9........	g	−0.3	+10.1	20.31	+0.48
		1622+238			
1........	qso	0.0	0.0	17.81	+0.14
2........	g?	+8.4	+0.9	23.12	+1.48
3........	s	+6.3	+6.0	21.81	+0.37
5........	g?	+1.5	+14.3	22.53	...
6........	g	−3.0	+9.2	23.48	...
7........	g	−1.5	+11.0	22.51	+1.75
8........	g	−4.2	+13.7	23.30	+1.27
9........	g	−6.9	+9.5	20.12	+0.86
10........	g	−12.2	+9.5	21.94	+1.07
12........	g	−8.9	−3.3	23.03	+1.25
13........	s?	−15.8	−5.1	22.27	+0.28
14........	g	−4.2	−3.9	22.24	+0.22
15........	g	+7.2	−11.9	22.37	+1.14
		1628+363			
1........	qso	0.0	0.0	17.23	+0.18
2........	g	+2.4	+6.9	20.31	+0.78
3........	g	+3.9	+13.1	18.21	+0.78
4........	g	+8.6	+10.4	23.00	+1.11
5........	g?	−10.7	−8.9	22.92	...
6........	g	+11.9	−9.5	23.30	+2.08
		1632+391			
1........	qso	0.0	0.0	17.99	+0.27
2........	g	+4.2	−0.3	19.66	+0.61
3........	g	+3.3	+6.6	22.78	+0.58
6........	g	+8.4	−8.1	21.08	+0.59
7........	g	+10.1	−12.8	21.88	+0.71
8........	g?	+0.6	−14.6	22.25	+0.88

[a] Data are presented for objects of potential interest near the quasars, but these data are complete only for $R < 23.0$, $I < 22.0$, and radial distances $r < 15''$ from the quasars. This table therefore includes numerous galaxies which do *not* satisfy the criteria for the galaxy counts listed in Table 1. FOCAS classifications were assigned to each object independently in each of the two colors. Classes listed are "s" for stars and "g" for galaxies; a question mark indicates an uncertain or marginal classification in either R or I. The positions listed are offsets in arcseconds from the QSO's position with E and N positive. The R magnitudes listed are FOCAS "total" magnitudes obtained through Mould filters set to Cousins system zero points. The $(R-I)$ colors are based on isophotal magnitudes, to minimize sky-subtraction errors.

shift range spanned by the quasars in our sample. These same models yield 1–5 mag of brightening in F (approximately R) for galaxies with $0.9 < z < 1.5$, very roughly the luminosity evolution required to explain our observations, assuming the excess galaxies share the quasars' redshifts.

VII. CHARACTERISTICS OF THE "QSO–ASSOCIATED" GALAXIES

Even though our QSO sample spans a wide range of redshifts ($0.9 < z < 1.5$), the "QSO–associated" excess galaxies are not preferentially associated with the lower-redshift objects: as detailed in Table 1, the fields of the eight QSOs with $0.9 < z < 1.2$ contain a total of 13 galaxies within 15″ of the quasars, while the eight fields containing QSOs with $1.2 < z < 1.5$ have 19 such galaxies. The first two fields reproduced in Figure 4 (Plates 1–3) contain five and four galaxies within 50 pixels (15″) of the QSOs: 1622+238 ($z = 0.927$) lies near the apparent central galaxy of a distant cluster which may be at the quasar's redshift, while 1215+643 ($z = 1.288$) lies in a compact group of galaxies which appear to be too bright to share the quasar's redshift [Table 1, delta$R$(1st)]. Also shown in Figure 4, for comparison, is the field of 1433+177 ($z = 1.203$), a QSO with no excess galaxies. Positions, R magnitudes, and $R-I$ colors for galaxies within 15″ of the quasars are provided in Table 3.

How do the observed magnitudes of the "QSO–associated" galaxies compare with those expected for galaxies at the QSOs' redshifts? The R(1st) magnitudes listed in Table 1 are the values expected for first-ranked galaxies at each QSO's redshift (Romanishin 1990; see also the notes to Table 1). The differences between these predicted apparent magnitudes and the galaxies' observed magnitudes are also listed in Table 1, and it is evident that virtually all of the galaxies observed are brighter than first-ranked galaxies are predicted to be. About 19 field galaxies are expected within 15″ of our QSO sample. If we therefore delete the 19 most "overluminous" galaxies, we find that the remaining 13 are 0–2.3 mag more luminous than a first-ranked galaxy is predicted to be at the corresponding QSO's redshift, with a mean excess of -1.1 ± 0.8 mag. Therefore, if the excess galaxies are physically associated with the corresponding QSOs, the galaxies must be at least 1–3 mag overluminous, since they cannot all be first-ranked galaxies. This conclusion is sensitive to the value of q_0 adopted: for $q_0 = 0.5$, the "overluminosities" of the galaxies observed are decreased by 0.5–0.8 mag for $z = 0.9$ and $z = 1.5$, respectively. For a given q_0, our conclusion is very conservative, since we have preferentially eliminated the brightest galaxies as "field objects," even though statistically the fainter galaxies will actually dominate the field galaxy counts.

VIII. BLUE FIELD GALAXIES

While the observed increase in numbers of red field galaxies with increasing R magnitude was expected, the presence of a significant population of blue galaxies at fainter magnitudes ($R = 23$) is also of interest. The uncertainties in the galaxy colors are substantial in this region ($R-I < 0.5$), but the presence of a faint, blue population of galaxies seems well established (see also Tyson 1988) and is probably related to the faint blue galaxies reported by Kron (1980a) and others on the basis of observations in J and F passbands (the relationship between these blue field galaxies and the excess blue galaxies reported in clusters, the "Butcher-Oemler" 1978 effect, is not clear—see Koo 1988 for a critical discussion). In the case of the field galaxies, Kron found that the blue population was so large that the mean galaxy colors in his fields got bluer with increasing magnitude. We do not see a similar trend in mean colors for our sample because of the rapid increase with increasing redshift in the number of red galaxies detected in our much redder passbands. Nevertheless, a significant population of faint, blue galaxies is present; about 10% of field galaxies in our sample that are brighter than $R = 23$ are bluer than $R-I = 0.2$, consistent with Tyson's (1988) results.

Are the most extreme blue galaxies blue simply because of star formation, or is something else required to account for their colors? Because little work has been published on galaxy K-corrections in the $R-I$ color system, we undertook some simple models of the colors of actively star-forming galaxies at various redshifts. We concocted spectra of model "galaxies," redshifted them by various amounts, and found the resultant observed $R-I$ colors by convolving the redshifted spectra with transmission functions appropriate to the filters and detector. The color zero point in the Cousins system was derived by assuming that a standard E galaxy spectrum at zero redshift has $R-I = 0.64$. Details of the E galaxy photometry and the calculation of the colors can be found in Romanishin (1990), which gives K-corrections for galaxies in the Cousins $BVRI$ system.

The first blue galaxy spectrum considered was that given by Coleman, Wu, and Weedman (1980) for a Magellanic irregular galaxy (Im galaxy). The spectrum is defined down to a wavelength of 1400 Å, allowing calculation of $R-I$ colors for $z \leq 3$. The observed color of the Im galaxy, assuming no Galactic or intergalactic reddening, gets no bluer than $R-I = 0.34$ for $z \leq 3$. Figure 2b and Tyson's (1988) Figure 9b both show a significant population of background galaxies bluer than this bluest value for the Im galaxy. Figure 5 shows the expected $R-I$ color as a function of redshift for the Im galaxy and the additional spectra described below.

Because we could not find published UV–optical spectrophotometry for galaxies bluer than the Im galaxy, we studied a number of other approximations and limiting cases for the spectrum of a star-forming galaxy. The most extreme model for

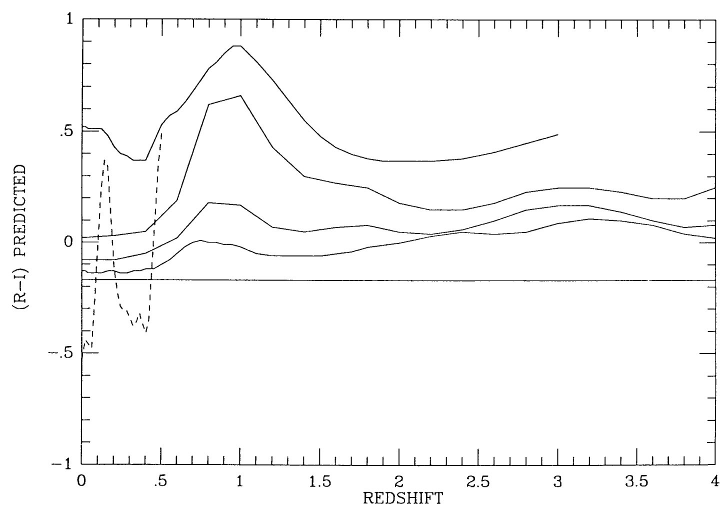

FIG. 5.—Predicted $R-I$ colors as a function of redshift for the spectra discussed in § VIII. The solid lines are for (from top [red] to bottom): an Im galaxy, a 1E8 yr old cluster, a zero-age cluster, an O star, and an "infinite" temperature blackbody (straight line at $R-I = -0.17$). The dashed line shows the colors expected for the "H II region" galaxy Mrk 36, when observed through Mould filters.

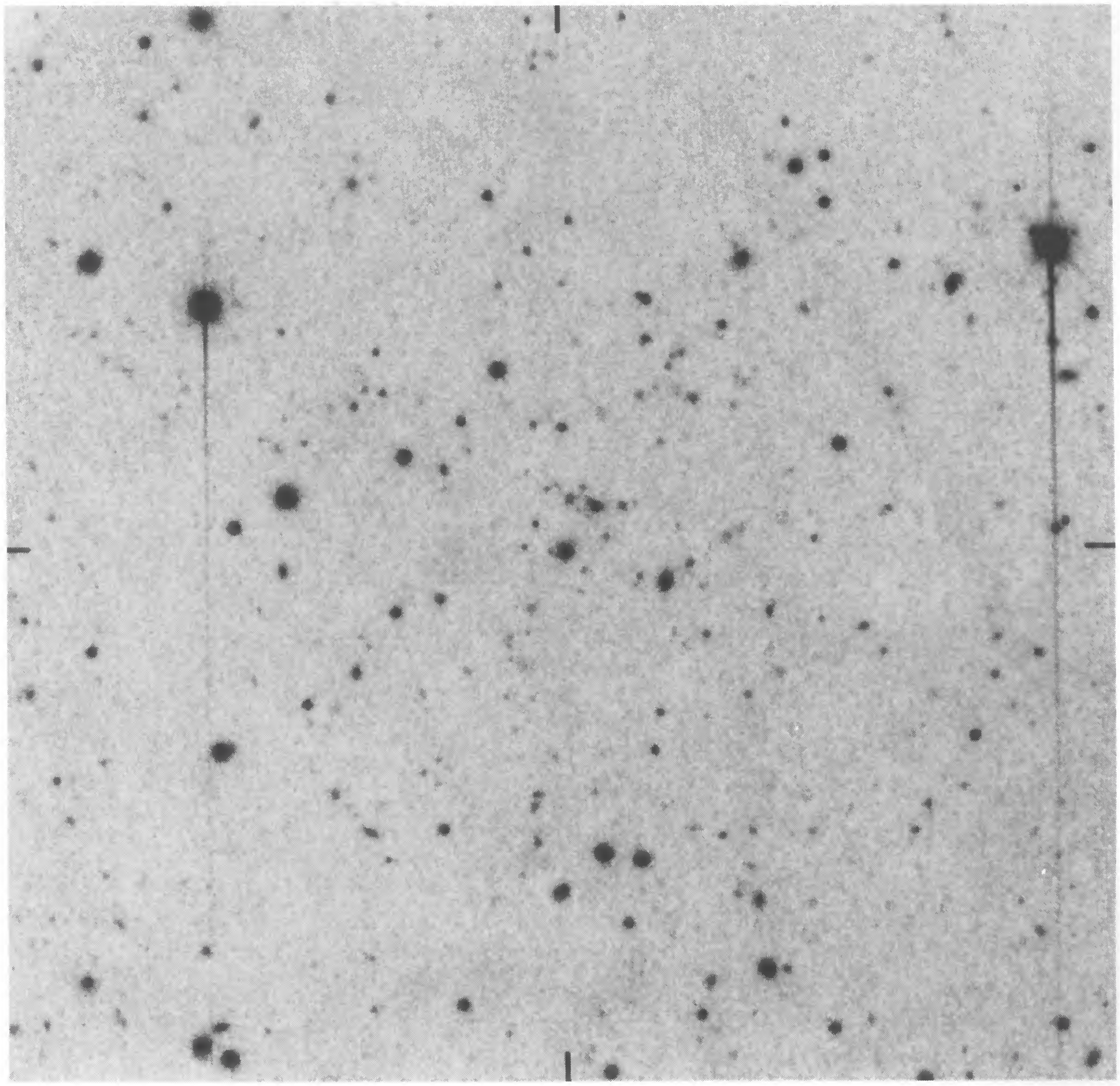

FIG. 4a

FIG. 4.—The R images are reproduced for three QSOs: (a) 1622 ± 238 ($z = 0.927$) and (b) 1215 + 643 ($z = 1.288$), which contain five and four galaxies, respectively, within 15″ of the QSOs and brighter than $R = 23$ (the mean field galaxy density within a 15″ circle is 1.2), and (c) 1433 + 177 ($z = 1.203$), a QSO with no excess galaxies. QSO 1622 + 238 is surrounded by a substantial cluster of galaxies, and the data in Table 1 indicate that the quasar and cluster may be associated if moderate galaxy evolution has occurred since $z = 0.9$. Galaxies in the cluster surrounding QSO 1215 + 643, on the other hand, are 2.3–4.6 mag brighter than a nonevolving first-ranked galaxy is expected to be at $z = 1.288$, so the galaxies must be a foreground (lensing?) group, unless typical galaxies have suffered about 4.5 mag of luminosity evolution since $z = 1.3$. However, such evolution is indeed seen in Bruzual's (1983a) most extreme models.

HINTZEN, ROMANISHIN, AND VALDES (*see* **366**, 13)

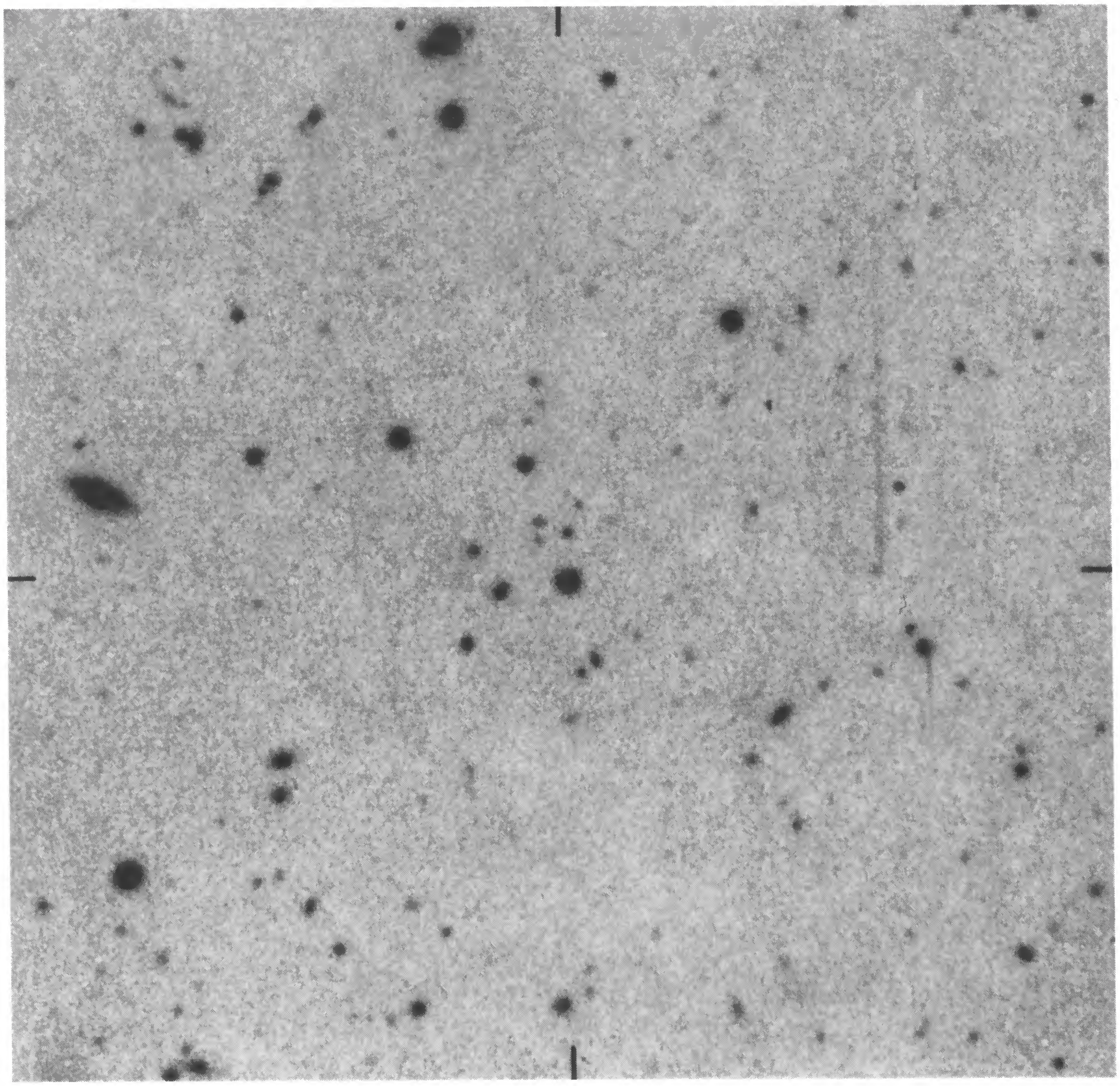

FIG. 4*b*

HINTZEN, ROMANISHIN, AND VALDES (*see* **366**, 13)

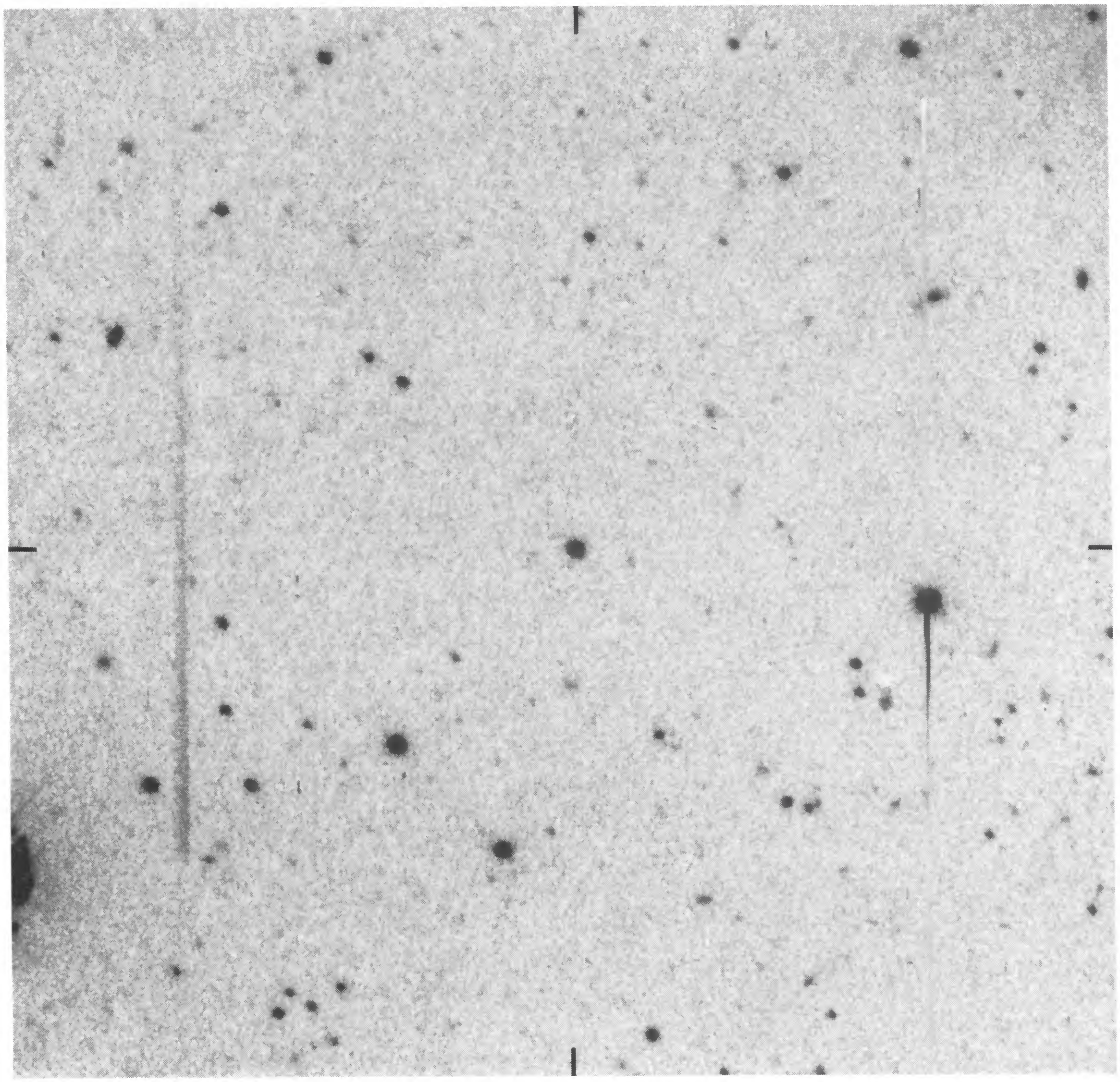

FIG. 4c

HINTZEN, ROMANISHIN, AND VALDES (*see* **366**, 13)

the color of a star-forming galaxy without emission lines is given by an "infinite" temperature blackbody (all wavelengths of interest on the Rayleigh-Jeans part of the curve so that $F_\lambda \propto \lambda^{-4}$). Such a spectrum has $R-I = -0.17$. This color is independent of redshift, because the distribution is a power law in λ.

An approximation to the spectrum of an extreme star-forming galaxy only slightly more realistic than the infinite temperature blackbody is to use the spectrum of a single O star. The spectrum used was the synthetic spectrum calculated by Kurucz (1980) for a star with $T_{\rm eff} = 40{,}000$ K, $\log g = 4$, and solar abundances. The O star has an $R-I$ similar to the hot blackbody at $z = 0$, but becomes several tenths redder at $z = 4$.

To approximate the composite nature of real galaxy spectra, we calculated spectra for two model "galaxies" consisting of stars with masses from 1 to 40 $M_\odot$, distributed in mass according to a power-law initial mass spectrum with $x = 1.5$ (approximately a Salpeter distribution). The 1000–12000 Å spectrum of this "galaxy" was derived by adding appropriately intensity scaled spectra of a number of stars with masses from 1 to 40 $M_\odot$, with the spectra taken from Kurucz (1980) for solar abundance, $\log g = 4$ models. Conversion from $T_{\rm eff}$ to stellar mass and absolute luminosity at V (needed to introduce scaling of spectra with mass) was derived from data in Allen (1973). The colors of this model galaxy are only slightly redder than the pure O star, due to the dominance of the spectrum by the hottest stars, particularly in the UV which the R filter samples at high redshifts.

Obviously, the model described above, while better than a single O star, is still a long way from a true evolving galaxy. One final approximation was to allow for star formation continuing at a steady rate for 10^8 yr. No true stellar evolution was included, as only main-sequence stars were in the model, but the most massive stars were removed from the model after their main-sequence lifetimes were over. In this case, the most massive stars no longer dominate the spectra quite so much, as they have a lifetime of about 6×10^6 yr, and as the model evolves the fractional contribution to the spectrum of lower mass stars increases.

These two model "galaxies" are rather simple minded, but we feel they probably represent the *bluest* colors expected for star-forming galaxies. Addition of the effects of stellar evolution, less massive stars, and dust would tend to redden the colors. The low metal abundances expected for first-generation stars might cause bluer colors than those used, but the effects should be minimal for the massive stars that dominate the UV. Addition of hotter stars, or a flatter IMF, might make the spectrum slightly bluer, but we feel the obvious effects of stellar evolution to red giants and the effects of dust would greatly swamp any such blueing effects. For example, the model galaxies discussed here are far bluer than any of the models of evolving galaxies discussed by Bruzual (1983*b*).

Another possible explanation for at least some of the extremely blue galaxies is that they are due to galaxies with strong emission lines. One class of galaxies which we will explore is that of the "H II region" galaxies, studied, for instance, by French (1980). Obviously, the effects of emission lines on the broad-band colors of galaxies depends sensitively on the strengths of the emission lines, line ratios, redshift, and filter used. The spectra of French show that the strongest emission lines in the H II region galaxies are invariably [O II], [O III], Hα, and Hβ. We have calculated the effects of these lines on broad-band colors and ignored all other lines. We used the Mould filter transmissions for this calculation. For the resolution needed here, we can lump the Hβ and [O III] lines into a Hβ + [O III] complex at rest wavelength of 4950 Å. The effects of the emission lines on the broad-band colors depends most strongly on the equivalent widths of the lines. For the low-luminosity H II region galaxies discussed by French, the median EW(Hβ) is $\sim$90 Å. Mrk 36 has EW(Hβ) = 84 Å and has the line flux ratio (Hβ + [O III])/Hα near the median value for the low-luminosity galaxies. We concocted a spectrum for Mrk 36 by assuming a continuum spectrum equal to the 10^8 yr cluster described previously, combined with the Hβ + [O III] and Hα emission lines scaled so that EW(Hβ) was 84 Å. The equivalent widths of the Hβ + [O III] complex is about 700 Å, and of Hα, about 600 Å. As these numbers are comparable to the FWHM of the R and I filters, we can see they will have a sizable effect on the galaxy broad-band colors at certain redshifts. The calculated colors for this spectrum are shown in Figure 5 as a dashed line. At redshifts ≤ 0.07, Hα adds to the R filter flux and the galaxy is very blue, with $(R-I) = -0.6$. Around $z \sim 0.08$, the Hα line is redshifted out of the R filter and into the I filter, causing the galaxy to become redder as the line adds to the I filter until at $z \sim 0.14$ the galaxy color reaches $R-I \sim 0.3$. At this redshift, the Hβ + [O III] complex enters the R filter and the color becomes blue, with $R-I \sim -0.3$ until $z \sim 0.4$, when the galaxy becomes redder as the Hβ + [O III] complex is redshifted out of the R filter and into the I filter. We note that the rather sharp excursions of color with redshift are due to the relatively sharp "edges" to the Mould bandpasses, and that observations with other filters, such as the original Cousins filter, with a long "tail" to the R filter, could result in quite a different color versus redshift plot.

Because at low redshifts the Hα line is in the R filter and no strong lines pass the I filter, the $R-I$ color becomes bluer with increasing line strength. For EW(Hβ) = 160 Å, the $z = 0.0$ $R-I$ color is -0.84.

Could such galaxies provide the extreme blue tail seen in the color distribution? The median absolute magnitude of the low-luminosity galaxies studied by French is ~ -15 ($H_0 = 50$ km s^{-1} Mpc^{-1}), and such galaxies would have $22 < R < 23$ for $0.04 < z < 0.7$. Thus, these emission line galaxies can indeed have the properties required to explain the blue tail of the $R-(R-I)$ galaxy distribution. Whether they actually have sufficient space density to account for the number observed can only be answered by spectroscopy of some of the faint blue galaxies. Obviously, color-color plots can also help disentangle the effects of emission lines and continuum color.

Galaxies in the redshift range 0.6–0.9 might have blue $R-I$ colors due to the presence of strong [O II] emission, which would augment the R luminosity in this redshift range. The colors of such galaxies will depend on their exact redshift and line ratios, as the Hβ + [O III] complex appears in the I bandpass for much of this same redshift range. We note that some galaxies with cooling flows have strong [O II] emission.

IX. CONCLUSIONS

Deep direct CCD observations in Mould-Cousins R and I passbands have been obtained for the fields of 16 radio-loud QSOs with $0.9 < z < 1.5$. We find a statistically significant excess of galaxies within 15″ of the quasars and brighter than $R = 23$ and $I = 22$, but, unlike Tyson (1986), we find no excess of galaxies brighter than $R = 21$. Assuming the excess galaxies share the nearby quasars' redshifts, these galaxies are several magnitudes overluminous compared with normal galaxies at the present epoch. One object, QSO 1622+238 ($z = 0.927$), appears to lie near the center of a very rich, distant cluster of galaxies.

Further imaging data for larger samples is required to resolve the discrepancy between Tyson's (1986) results and ours (at what magnitude do excess galaxies surrounding QSOs in this redshift range become prevalent?). Nevertheless, since we, like Tyson, find excess galaxies surrounding radio-loud QSOs with redshifts near unity, while Fugmann (1988) and Webster *et al.* (1988) report excess galaxies near QSOs at even higher redshifts (approaching $z = 3$), spectroscopy of these excess galaxies is needed to determine which are foreground (lensing?) objects and which, if any, are overluminous galaxies at the quasar's redshifts.

We have also presented data for and simple models of the very blue galaxies seen among objects in the general field. All of these galaxies are bluer in $R-I$ than Magellanic irregulars at any redshift ($z < 3$), and the most extreme examples apparently cannot be fit by any stellar continuum; emission lines probably must be present in the R passband. Spectroscopic confirmation of the presence of such emission lines should be possible despite the blue galaxies' faintness ($R \sim 23$).

We thank the KPNO mountain staff for their expert assistance while observing, the NOAO Central Computer Services staff for their assistance and patience during data reduction and analysis, and J. A. Tyson for valuable discussions. P. H. was supported by NASA grant 188-4151-07. W. R. was partially supported by NASA grant NAG8-576.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone).
Bruzual, G., 1983*a*, *Ap. J.*, **273**, 105.
———. 1983*b*, *Rev. Mexicana Astr. Af.*, **8**, 63.
Butcher, H., and Oemler, A., Jr. 1978, *Ap. J.*, **219**, 18.
Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., and Siegel, M. 1985, *Pub. A.S.P.*, **97**, 363.
Coleman, G. D., Wu, C.-C., and Weedman, D. W. 1980, *Ap. J. Suppl.*, **43**, 393.
French, H. B. 1980, *Ap. J.*, **240**, 41.
French, H. B., and Gunn, J. E. 1983, *Ap. J.*, **269**, 29.
Fugmann, W. 1988, *Astr. Ap.*, **204**, 73.
Heckman, T., Bothun, G., Balick, B., and Smith, E. P. 1984, *A.J.*, **89**, 958.
Hintzen, P. 1984, *Ap. J. Suppl.*, **55**, 533.
Hintzen, P., and Romanishin, W. 1986, *Ap. J.* (*Letters*), **311**, L1.
Kent, S. 1985, *Pub. A.S.P.*, **97**, 165.
Koo, D. C. 1988, in *Towards Understanding Galaxies at Large Redshift*, ed. R. G. Kron and A. Renzini (Dordrecht: Kluwer) p. 275.
Kron, R. 1980*a*, *Ap. J. Suppl.*, **43**, 305.
Kron, R. 1980*b*, *Phys. Scripta*, **21**, 652.
Kurucz, R. L. 1980, *Ap. J. Suppl.*, **40**, 1.
Massey, P., Strobel, K., Barnes, J. V., and Anderson, E. 1988, *Ap. J.*, **328**, 315.
Romanishin, W. 1990, in preparation.
Sebok, W. L. 1986, *Ap. J. Suppl.*, **62**, 301.
Stockton, A. 1978, *Ap. J.*, **223**, 747.
Tyson, J. A. 1986, *A.J.*, **92**, 691.
———. 1988, *A.J.*, **96**, 1.
Valdes, F. 1982, *FOCAS User's Manual* (Tucson: KPNO).
Véron-Cetty, M.-P., and Véron, P. 1984, *A Catalog of Quasars and Active Nuclei* (Munich: European Southern Observatory).
Webster, R. L., Hewett, P. C., Harding, M. E., and Wegner, G. A. 1988, *Nature*, **336**, 358.
Yee, H. K. C., and Green, R. F. 1984, *Ap. J.*, **280**, 79.
———. 1987, *Ap. J.*, **319**, 28.
Yee, H. K. C., Green, R. F., and Stockman, H. S. 1986, *Ap. J. Suppl.*, **62**, 681.

PAUL HINTZEN: Department of Physics, University of Nevada–Las Vegas, Las Vegas, NV 89154

W. ROMANISHIN: Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019-0225

FRANCISCO VALDES: KPNO-COM, P.O. Box 26732, Tucson, AZ 85276