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Bruce Partridge
Haverford College, bpartrid@haverford.edu

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A SEARCH FOR PRIMEVAL GALAXIES AT HIGH REDSHIFTS*

R. B. PARTRIDGE†
Haverford College, Haverford, Pennsylvania; and Kitt Peak National Observatory‡
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ABSTRACT

Using both photoelectric and photographic techniques, we have searched for *primeval galaxies*, those undergoing a bright initial phase, at high redshifts. Measurements were made in the optical and near-infrared. The negative results set constraints on models of galaxy formation and evolution. A companion paper by Davis and Wilkinson extends these results.

Subject headings: cosmology — galaxies — redshifts

I. INTRODUCTION

An outstanding problem in cosmology is galaxy formation: how, and when, did galaxies form? Published investigations of these questions fall into two general categories. In the first are studies of the nature and growth of instabilities in an expanding Universe (recent review papers include Rees 1971; Field 1974; Peebles 1974). This approach may be described as dynamical or hydrodynamical. Other writers have approached the problem *astrophysically*, asking what properties galaxies must have had in their formative period in order to produce the observed present properties of galaxies. "Astrophysical" models for galaxy formation include those of Weymann (1966), Partridge and Peebles (1967*a*, *b*), Tinsley (1972*a*, *b*, 1973*b*), Quirk and Tinsley (1973), and by extension Truran and Cameron (1971). Some of these papers are discussed in Field's (1974) review article.

Our concern in this paper will be almost exclusively with "astrophysical" models. Since frequent reference will be made to the papers listed above, we will abbreviate them as W, PP*a*, PP*b*, T2*a*, T2*b*, T3*b*, QT, and TC, respectively.

These models all have a number of elements in common. In particular, all attempt to explain two salient observations which bear on the early history of our own Galaxy. The first of these is the observation by Eggen, Lynden-Bell, and Sandage (1962) and Dixon (1966) that stars with high space velocities and high orbital eccentricities appear to have been formed during the initial collapse of the protogalactic gas cloud—and yet contain some heavy elements (see also Sandage, Freeman, and Stokes 1970). The second and related argument is due originally to Schmidt (1963): most of the metal enrichment in our Galaxy must have taken place rapidly, probably in a prompt burst of star formation (see also Dixon 1965, 1966). This latter view has very recently been reexamined and questioned by Talbot and Arnett (1973).

To explain these two observations, all the astrophysical models of galaxy formation rely on a high initial rate of star formation, or on an initial stellar population of massive, short-lived, stars. Either assumption implies that galaxies had a higher initial luminosity than they do now. These bright, newly formed, galaxies will be referred to as PGs (primeval galaxies) in the remainder of this paper. A number of the authors, particularly W and PP*a*, attempt to assess the possibility of detecting PGs at the large redshifts corresponding to their epoch of formation. The discovery of bona fide PGs would clearly help resolve some of the murky questions of galaxy formation.

This paper and a companion paper (Davis and Wilkinson 1974, henceforth DW) report the results of both photoelectric and photographic searches for PGs. In the next section, predictions of the observable properties of PGs are briefly reviewed. In this section are also discussed published observational results which set constraints on the properties of PGs. In § III an early photoelectric search is described, and in § IV a search for PGs on deeply exposed 120-inch (3-m) plates in the *B*, *V*, and *R* bands. These results are discussed in the final section. Since all the searches were negative—no PGs were detected for certain—the emphasis in the last section is on the limits our observations set on various published models of galaxy formation.

II. THE OBSERVABLE PROPERTIES OF PRIMEVAL GALAXIES

The purpose of this section is to determine a reasonable set of values for the observable parameters of PGs. Our values are drawn from the published models (W, TC, PP*a*, T2*a*, T2*b*, T3*b*, and QT): we are not here attempting to assess the validity of the assumptions underlying the published models. The parameters of direct observational interest are the magnitude (or flux density) of PGs, their angular diameter and brightness distribution, their spectrum (or at least color), and the number of them per square degree (areal density).

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† Visiting Astronomer, 1969 and 1970, Kitt Peak National Observatory; Alfred P. Sloan Foundation Research Fellow.

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Several of these parameters depend on the cosmological model assumed. With DW, we assume a standard isotropic, homogeneous, pressure-free, Friedmann universe, with the cosmological constant $\Lambda = 0$. Following Peebles (1971), we write $H_0 = 100h$ km s^{-1} Mpc^{-1}, with $0.5 \leq h \leq 1.0$. In analyzing the results, we will employ a range of values for the deceleration parameter q_0: 0.1, 0.5, and 1.0. For the last two values of q_0, at least, intergalactic matter may be present. We will discuss in § V the effect that intergalactic matter may have on our conclusions.

We must now turn to the more difficult problem of the *intrinsic* properties of PGs.

a) *Time of Formation*

Alternatively, this can be expressed as the redshift $z(t_f)$ when the PGs were highly luminous. In the simple gravitational instability picture (see Field 1974, or PP*a*), protogalactic gas clouds, being regions of enhanced density, expand at a slower rate than the Universe, reach a maximum radius at some epoch t_m, and then begin to collapse gravitationally. If pressure and rotation are ignored, the collapse ends in a singularity at $2t_m$. Most PG models assume $t_m < t_f \leq 2t_m$. TC is an exception: in that paper, it is argued that the bright flash of prompt star formation *preceded* the contraction of protogalactic gas clouds.

Obviously t_f is an important parameter to determine, and this paper attempts to establish observational limits on t_f. It is nonetheless useful to try to set some approximate theoretical bounds on t_f, as done, for instance, by PP*a* (who take $t_f \simeq 1.5 \times 10^8$ yr), or by Field (1974) who uses the results of Fish (1964) to argue that $t_f \geq 3 \times 10^7$ yr. One may set an upper limit on t_f in either of two ways. First, the absence of very strong evolutionary effects in the luminosity of massive elliptical galaxies out to redshifts of 0.46 (Tinsley 1972*c*) suggests an upper limit $t_f \lesssim 5 \times 10^9$ yr (this value depends, of course, on one's assumptions about H_0 and q_0). Second, Sunyaev (1971) has shown that the epoch of galaxy formation must have taken place at a redshift $z \gtrsim \Omega^{-1}$, where Ω is, as usual, the ratio of the present mass density to the critical density, $3H_0{}^2/8\pi G$. Clearly, this argument fixes a useful upper limit on t_f only for open cosmological models.

b) *Average Luminosity during the Bright Flash*

This is an equally important parameter. We compute the luminosity, as in W or PP*a* and PP*b*, by considering the total mass of hydrogen converted to helium and heavy elements during the bright PG phase. If the phase lasts a time Δt, the average bolometric luminosity is

$$L \simeq 0.01 Mc^2 \frac{\Delta X}{\Delta t}, \qquad (1)$$

where ΔX is the fraction of hydrogen converted to heavy elements. PP*a* take $\Delta X = 0.02$ and $\Delta t = 3 \times 10^7$ yr, leading to $L/M \sim 200$ ergs s^{-1} g^{-1} for PGs, a value $\sim 10^3$ times the luminosity-to-mass ratio for our Galaxy today. If we assume that the PGs produce the present helium abundance as well,[1] then $\Delta X \sim 0.25$ (W; see also PP*b*). Weymann makes this assumption, with $10^7 < \Delta t < 1.7 \times 10^9$ yr, giving values of L/M in the approximate range 50–7000 ergs s^{-1} g^{-1}.

Two possible corrections to estimates of this sort should be mentioned. (1) Some of the heavy elements (and possibly helium) created by fusion may be trapped in collapsed objects. If we ignore this material, which does not get returned to the interstellar medium, we underestimate the energy output per gram of heavy elements returned to the interstellar gas, and therefore underestimate L. (2) We also underestimate L by ignoring supernovae, and any nonthermal emission processes during collapse.

We will not attempt to make these corrections: we note only that ignoring them is conservative in the sense that we thereby underestimate L.

Tinsley has taken a different approach to predicting L and Δt: she evolves the stellar population of galaxies in time. From her papers, we derive estimates of 10^8 yr $\lesssim \Delta t \lesssim 4 \times 10^8$ yr, leading to luminosities 20–100 times present luminosities. Values of this ratio for elliptical galaxies tend to be approximately twice those for spiral galaxies.

We have cited these estimates of L only to give an impression of the heightened luminosity of PGs: when we come to compare our observational limits with the models, we will leave both ΔX and Δt as free parameters.

c) *Linear Diameter and Radial Luminosity Dependence*

Only W and PP*a* deal with this question, and reach quite opposite conclusions. In the former, it is assumed that the radial dependence matches that of NGC 3379 (Miller and Prendergast 1962). As a consequence, one-half the luminosity is contained within a radius of 3.2 kpc. Basing their arguments on the results of Eggen *et al.* (1962), PP*a* argue that star formation must occur early in the collapse phase ($t_f \approx t_m$) before much central concentration has occurred (see also Sandage *et al.* 1972). They adopt 30 kpc as the linear diameter of a typical massive PG and make the further assumption that the brightness distribution is uniform across the image of the galaxy. This difference is an important one: for the values of $z(t_f)$ of particular interest, a 30-kpc PG will subtend $\sim 10''$ (Davis 1973; PP*a*), whereas the centrally concentrated PGs of W will appear essentially stellar or only slightly "soft."

In this connection we note that collapse to a disk structure, expected on dynamical grounds for initially oblate or rotating protogalactic clouds (Oort 1970; Field 1974), would produce PGs without strong central concentrations. One would then expect to observe PGs with a range of axial ratios.

d) *Spectrum*

The most detailed studies of the spectra of PGs are those of Tinsley (T2*b*, T3*b*). Unfortunately, her projections of galactic spectra to epochs earlier than 10^9 yr

[1] Now thought to be a poor assumption: the helium is probably primordial (Peebles 1971).

are uncertain (Tinsley, private communication). In addition, her work is not carried to emission wavelengths less than 1700 Å, despite the fact that the peak luminosity of PGs is likely to lie at shorter wavelengths. Other workers (W, PP*a*, and TC) take a more approximate approach, essentially treating the PGs as blackbody sources. PP*a* adopt 30,000° K as a color temperature: as TC point out, however, this value is almost certainly too low. The work of Ezer and Cameron (1971) on H-He stars suggests 10^5 ° K as a more realistic value.

One important modification to a straightforward blackbody spectrum may be the existence of Lyman continuum absorption below $\lambda = 912$ Å (PP*a*). At 10^5 ° K, a representative value for the Lyman discontinuity in stellar spectra is 1.6 (Thorstensen 1974). Following Tinsley (1973*a*), we assume that the interstellar gas in PGs will be fully ionized. We therefore adopt two model spectra, to which we will refer in our analysis of the observational results: *model 1:* blackbody spectrum, $T = 10^5$ ° K, with *no* absorption below 912 Å; *model 2:* blackbody spectrum, $T = 10^5$ ° K, with a Lyman discontinuity $I(912+)/I(912-) = 1.6$ and $1/\nu^3$ absorption for $\lambda < 912$ Å (PP*a*). For purposes of comparison with DW, we also consider *model 3:* a blackbody spectrum with no absorption, but with $T = 3 \times 10^4$ ° K.

e) *Number of Primeval Galaxies*

Finally we must consider the number of PGs per comoving coordinate volume. Both W and PP*a* arbitrarily assume that only massive galaxies go through the PG phase. For PP*a*, $\eta_0 = 8 \times 10^{-3}$ Mpc^{-3}; W adopts $\eta_0 = 0.03$ Mpc^{-3}.

f) *Example*

To provide a rough guide to the possible range of observable parameters for PGs, let us adopt a specific cosmological model and a set of assumptions about the intrinsic properties of PGs. We adopt $H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = \frac{1}{2}$, and $z(t_f) = 5$. For the PGs we take $\Delta X = 0.02$, $\Delta t = 3 \times 10^7$ yr, and a linear diameter of 30 kpc, as in PP*a*; $\eta_0 = 10^{-2}$ Mpc^{-3}; and model spectrum (3). Then PG would appear with red magnitudes $m_R \leq 19.7$ mag and an angular diameter of $\sim 10''$. From an observational point of view, the most important result is that one would expect $\sim$2000 PG images with $m_R \leq 19.7$ mag per square degree!

g) *Early Observational Results*

Before turning to the results of the present search for such objects, we ask what limits previously published data can place on PG models. The most useful set of observations are those of the extragalactic component of the brightness of the night sky (Lillie 1968; Roach and Smith 1968; Harwit *et al.* 1966). These results have been used by Peebles and Partridge (1967) to set limits on the mass-to-light ratio of matter in the Universe. More relevant to our present concern is the work of Thorstensen (1974), who has shown that the models of TC will produce a nightsky brightness in excess of the observed upper limits unless $t_f < 10^8$ yr.

The very recent work of Shectman (1974) on the small-scale anisotropy of the cosmic light is not directly useful in a search for PGs because he assumes that galaxies are clumped: the clumping may not have had time to develop by $t_f \sim 10^8$ yr. However, if PGs are present with an areal density of $\sim$2000 per deg^2, his spatial power spectrum should show an upturn at $\sim$2600 rad^{-1}, beyond the high-frequency limit of his power spectrum.

III. PHOTOELECTRIC SEARCH USING A CHOPPING PHOTOMETER

In 1968 the present author started a search for isolated PG images using a photoelectric photometer. Because the results have been superseded by the more sensitive photoelectric work of DW and the photographic work described in the following section, the design and results of the early photoelectric search will be presented only briefly. In this section, the principle of the chopping photometer will be discussed, since it was later employed in modified form by DW. Details of the apparatus may be discussed in a separate publication.

a) *Experimental Design*

The nature of the apparatus was largely determined by the predictions of the PP*a* model: the photometer was designed to discover faint sources with angular scales $\sim 10''$ and an areal density of $\sim$1000 per deg^2 or above. The search was carried out in the red and near-infrared (6200–7800 Å), a wavelength region appropriate for a search for PGs having $z \sim$ 5–8. A single red-sensitive phototube was employed.

The search for faint extended objects was conducted by comparing the total flux from two adjacent areas of the night sky, each of 0.42 arcmin^2. A chopping wheel was employed for this purpose. A nonzero differential signal implied the existence of a bright image in one of the two areas. Included in the design was a means of discriminating between extended images, those of angular diameter $\gtrsim 3''$ (such as PG candidates), and stellar objects. The discrimination was achieved by chopping the sky at a higher spatial frequency to identify the small stellar images.

b) *Results*

The search for PGs was carried out with the use of the 50-inch (1.3-m) telescope of the Kitt Peak National Observatory in 1970 June and July. Regions selected for the search were chosen so they could be observed within 45° of the zenith during our runs. The small areas chosen for careful study were selected from the Palomar prints: we selected areas free of stellar or diffuse images down to the plate limit on both the blue and red plates. The coordinates of the areas studied appear in columns (3) and (4) of table 1. The galactic latitudes (col. [5]) of the areas were lower than we might have wished because the searches were made in the summer. Lower-quality data from a trial run appear

TABLE 1

REGIONS SEARCHED, AND UPPER LIMITS ON FLUX AND ON MAGNITUDES

Area (1)	Date of Runs (2)	α(1950) (3)	δ(1950) (4)	b^{II} (5)	l^{II} (6)	Limit (μfu) (7)	m_R Limit (mag) (8)
1.	1970 June–July	$16^h19^m20^s.4$	49°09′10″	+45°	75°	34	19.5
2.	1970 June–July	18 20 32.5	49 21 51	+25	78	57	18.9
3.	1970 June–July	18 20 29.2	49 33 47	+25	78	44	19.2
4.	1969 May	12 30 59.3	33 39 53	+85	160	210	17.5

on the last line of table 1. The observational results were converted to flux densities and red magnitudes by using observations of standard stars. In making this conversion, a rough correction for atmospheric extinction was made. The final results appear as *upper limits* on the flux: the values in columns (7) and (8) of table 1 represent the amplitude *plus* one standard deviation of the mean (i.e., they are formally upper limits at the 70% confidence limit).

c) *Discussion*

Our results indicate that no bright objects (stellar or diffuse) were detected at a level of $m_R \lesssim 18.9$ mag in a total area of 3.8 arcmin². Of course, *stellar* images of this magnitude would have been visible on the Palomar prints (hence the technique for discriminating between stars and extended objects was not really needed). An *extended* red object with angular diameter 10″ and total magnitude of 18.9, however, would have a surface brightness of only 23.6 mag per arcsec², and would probably have escaped detection on the Palomar prints.

Finally, one 0.42 arcmin² area was scanned twice for each run. Here the sensitivity was somewhat better. We can set the following limits on the flux over three such small areas: $f \leq 37$ μfu or $m_R \gtrsim 19.4$ mag (1 μfu = 1 microflux unit = 10^{-32} W m^{-2} Hz^{-1}).

IV. SEARCH FOR PRIMEVAL GALAXIES ON PHOTOGRAPHIC PLATES

The search was carried out on *B*, *V*, and *R* plates of Selected Area 57 made by Ivan King and kindly lent by him to the author.

The plates were obtained with the 120-inch telescope at Lick Observatory in 1965 and 1966. They cover a useful area of 360 arcmin² (a small area containing an obvious cluster of galaxies was excluded from the analysis). SA 57 is centered at $\alpha = 13^h07^m$, $\delta = 29°34'$, or $b^{II} \approx 90°$. The figures for the exposure times (and seeing) for the three plates are: *B*, 45 min (1″.6); *V*, 60 min (1″.5); and *R*, 45 min (0″.8). The plate limits for virtually certain identification of *stellar* objects were: *B*, 22.6 mag; *V*, 21.8 mag; *R*, 21.7 mag. The spectral responses are shown in figure 1.

a) *Search Technique*

First, all the plates were blinked, and the positions of all nonstellar images on any plate were noted. In this fashion 233 nonstellar images were located (compared with ~280 stars in the same 360 arcmin² area). The vast majority of these images were faint objects of small angular diameter, typically 3″.

Next, several faint nonstellar images, together with several faint standard stars with known magnitudes, were microphotometered to determine approximate plate limits for *nonstellar* images. The selected images were clearly above the plate limit. The direct measurements appear in column (2) of table 2: they are accurate to ~20 percent in flux or 0.2 mag. Limiting magnitudes for images of larger angular diameter (cols. [3], [4], and [5]) were estimated from these results by assuming that the limiting flux for an extended image is proportional to the angular diameter of the image, θ (Baum 1962). Clearly, this is an approximation which is strictly valid only if the image is of uniform surface brightness (see discussion in § II) and if the plate response is linear.[2] The values in the final column represent surface brightnesses [flux/$\pi(\theta/2)^2$] of about 3 percent of the night sky.

The range of angular diameters in table 2 was chosen to accord with PP*a*. Recall that they suggest 10″ as a characteristic value for θ, and in the worst

[2] The method employed was checked by photometering a larger image with θ ~ 8″, clearly visible on the plates. The measured magnitude m_v was 21.0 ± 0.3 mag, actually fainter than the plate limit we calculated.

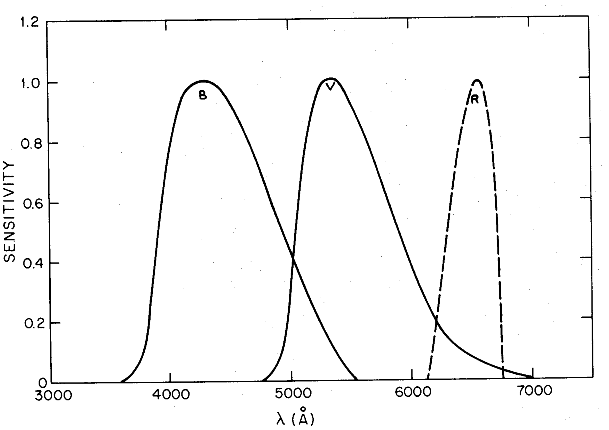

FIG. 1.—Spectral response of the three plate-plus-filter combinations, used in the photographic search for PGs.

TABLE 2

CALCULATED PLATE LIMITS FOR DIFFUSE IMAGES

PLATE	2″–3″ (measured) mag	$\theta = 5''$ mag	$\theta = 5''$ μfu	$\theta = 10''$ mag	$\theta = 10''$ μfu	$\theta = 15''$ mag	$\theta = 15''$ μfu
B.........	22.2	21.4	11	20.65	21	20.2	32
V.........	21.4	20.6	16	19.85	32	19.4	48
R.........	21.3	20.5	16	19.75	32	19.3	48

NOTE.—The calculated results are based on scans of several faint images of ~2″–3″ diameter.

case θ is less than 18″ for the redshift range of interest (Davis 1973).

The limiting magnitudes found for each plate and each value of θ have been converted to upper limits on the flux by using the observations of 3C 295 by Oke (1971) and Sandage (1973). Since the former measured flux and the latter photoelectric B, V, and R magnitudes, a conversion is possible. Sandage's B and V magnitudes match the B and V sensitivities of these plates well (see fig. 1): his values for 3C 295 are $B = 21.2$ mag, and $V = 19.74$ mag (taken from his table 2, assuming a 7″.6 aperture). Sandage's R magnitude has an effective wavelength of ~6700 Å, some 200 Å longer than the effective wavelength of the R plate. We have therefore corrected his R magnitude by +0.2 mag. With this correction, the photographic red magnitude of 3C 295 is taken to be 18.3 mag, and this value is used to effect the conversion.

Finally, a careful examination was made of each of the 233 nonstellar images in an attempt to determine if they were PGs. A set of criteria, listed below, was established to try to isolate PG candidates from faint foreground galaxies. The criteria were based mainly on the work of PP*a*. (1) Angular diameter $\gtrsim 5''$. (2) Approximately uniform color and surface brightness across the visible image. This criterion was chosen to help eliminate nearby spirals with red nuclei and also nearby ellipticals. Both criteria 1 and 2, we note, are model dependent (see § II). (3) Diffuse images with large color excesses $|B - V|$ or $|V - R|$ *of any sort* were considered PG candidates. A very wide latitude was used in applying this criterion for the obvious reason that we know neither the intrinsic spectra nor the redshift of the PG. (4) Finally, obvious foreground galaxies were rejected.

Since these criteria are model dependent, it may be useful to the reader to know how many images were rejected by applying the criteria. The vast majority of the diffuse images were rejected by criterion 1. Only 21 of the 233 diffuse images had angular diameters of 5″ or more on any of the plates. Of these, 12 objects well above the plate limit were rejected by criterion 4, and five more by criterion 2. We are thus left with four candidate PGs over an area of 360 arcmin^2.

b) *Conclusion*

It is clear that PGs of the sort suggested by PP*a* are not present on these plates with anything like the predicted numbers. Since no more than four candidate PGs were present, we conclude on the basis of Poisson statistics that, at the 90 percent confidence limit, the number of detectable PG images of angular diameter greater than 5″ in the area searched was less than or equal to 8. We will thus adopt an upper limit of 80 such images per square degree or $2.6 \times 10^5\ \mathrm{sr}^{-1}$ in our analysis of the observations: we claim that there are less than $2.6 \times 10^5\ \mathrm{sr}^{-1}$ PG candidates brighter than the magnitude limits given in table 2.

c) *Smaller Images*

Finally, we ask whether many of the faint diffuse images of $\lesssim 3''$ angular diameter might have been more centrally concentrated PGs of the sort suggested by Weymann. Of these smaller images, roughly 10 were very red ($m_B - m_V \gtrsim 2.0$ mag). These have redder apparent colors than most foreground galaxies of $z \lesssim 0.5$ (Schild and Oke 1971), and are thus conceivable high-redshift PG candidates. Again, the number is small compared with the model predictions.

Another approach to this question is to ask how many ordinary foreground galaxies we would expect on the plates down to the limiting magnitudes of table 2. Extrapolating the results of Hubble and Mayall as given by Rowan-Robinson (1972), we find ~400 as an expected number.[3] Clearly, it is possible that all the faint diffuse images on the plate were foreground galaxies, not PGs.

d) *Overlapping Images*

If the epoch of the PG phase is very early ($z > 10$), images of the PGs may overlap (see PP*a*). Thus the PGs might form a more or less continuous background. Such a background would be very difficult to detect photographically. Some limits, however, may be placed on small-scale fluctuations in the brightness of the night sky by the photometric work reported in the companion paper (DW).

V. DISCUSSION OF RESULTS

In this section, we attempt to assess the limits our results place on the many models for PGs. Here we discuss only the photographic search: the photoelectric work described in § III has been superseded by the similar, but more sensitive, search of DW.

[3] We assume $m_{pg} = m_B = 22.0$ mag as our limiting magnitude.

a) Apparent Bolometric Luminosity of Primeval Galaxies

For purposes of comparison between our results and PG models, we assume that all galaxies whose present mass exceeds $10^{11}\,M_\odot$ went through the PG phase. For most cosmological models, as we shall see, this assumption ensures $N > 2.6 \times 10^5\ \mathrm{sr}^{-1}$. If $M \geq 10^{11}\,M_\odot$, then from equation (1),

$$L \gtrsim 5.7 \times 10^{55}\,\frac{\Delta X}{\Delta t}\ \mathrm{ergs\ s^{-1}}\,, \tag{2}$$

where Δt is *in years*.

We next calculate the apparent bolometric luminosity of PGs using the standard formula (Weinberg 1972):

$$l = \frac{LH_0{}^2q_0{}^4}{4\pi c^2}\{q_0z + (q_0 - 1)[(1 + 2q_0z)^{1/2} - 1]\}^{-2}\,, \tag{3}$$

where z is the redshift corresponding to t_f. The quantity lh^{-2} is plotted for several values of ΔX and Δt in figures 2, 3, and 4. Note that it scales directly with

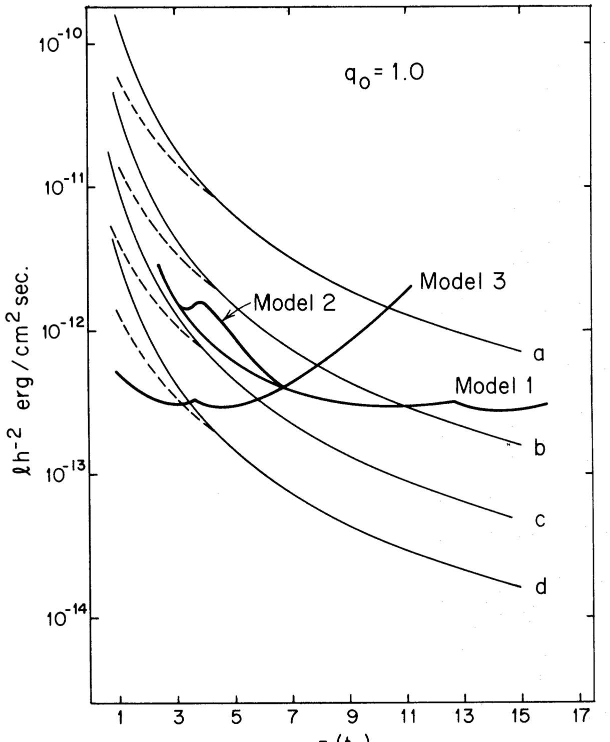

FIG. 2.—Computed luminosity of PG images for $q_0 = 1$, and observational upper limits, as a function of the redshifts corresponding to the time of formation, $z(t_f)$. The light lines are computed bolometric luminosities for 4 sets of PG parameters (see text for details). The dashed light lines show the correction discussed in the Appendix. Observational upper limits are plotted as heavy lines for three different assumptions about the PG spectrum (see § II). For model 2, the observational upper limits are the same as for model 1 for $z \gtrsim 7$. Note that the region *above* the heavy line for each model is excluded.

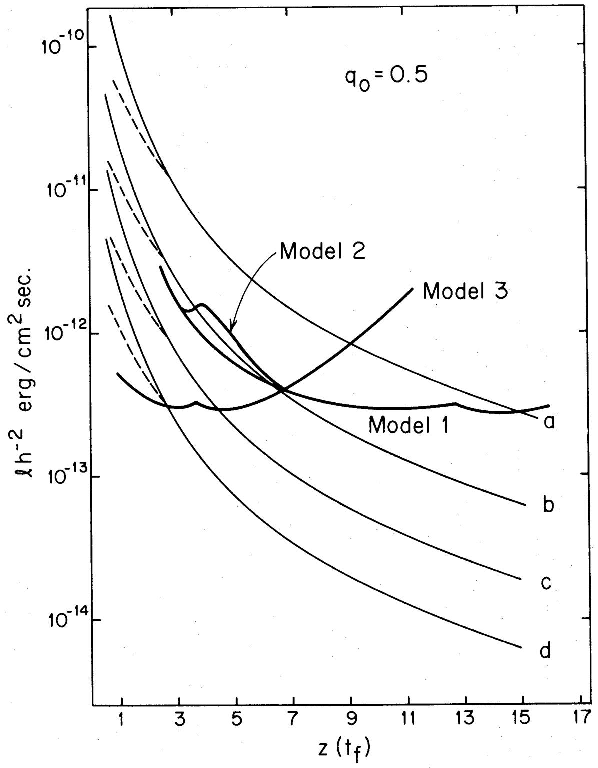

FIG. 3.—As for fig. 2, but for $q_0 = \frac{1}{2}$

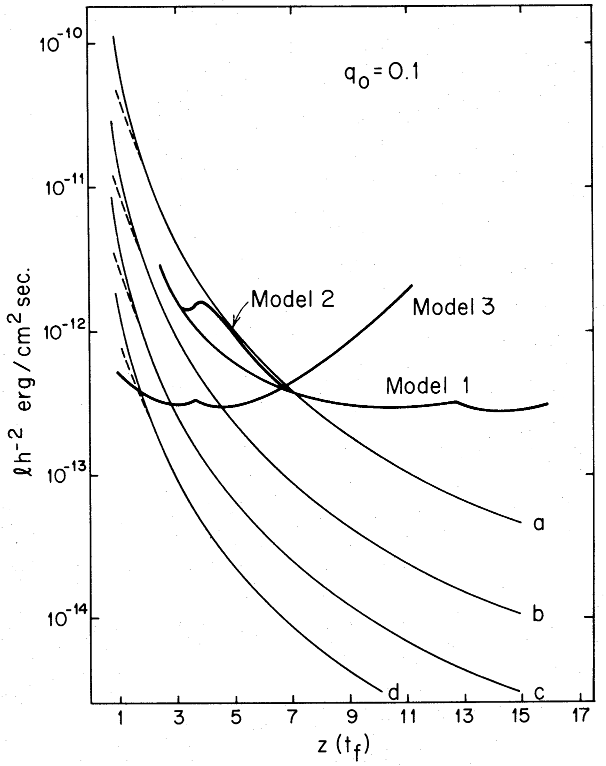

FIG. 4.—As for fig. 2, but for $q_0 = 0.1$

$\Delta X/\Delta t$, so curves for other values of ΔX or Δt may be constructed readily.

The curves were computed for the following models:

a) $\Delta X = 0.30$; $\Delta t = 10^8$ yr: a model which produces helium as well as heavy elements.

b) $\Delta X = 0.02$; $\Delta t = 3 \times 10^7$ yr: fits the assumptions of PP*a*.

c) $\Delta X = 0.02$; $\Delta t = 10^8$ yr.

d) $\Delta X = 0.02$; $\Delta t = 3 \times 10^8$ yr.

b) *Observational Limits on l*

These are found from the following relation:

$$l(z) = \frac{f_i W_i}{\epsilon_i(z)}\,,$$

where f_i is the observed upper limit on the flux, taken from the final (most conservative) column of table 2 for the ith plate; W_i is the effective bandwidth for each plate, and ϵ_i is an efficiency factor which measures the fraction of the bolometric luminosity which lies within the bandwidth of each plate. This quantity naturally depends on the redshift and on the PG spectrum, and was found from convolving the redshifted spectrum and the plate responses of figure 1:

$$\epsilon_i = \frac{\int_0^\infty S[\lambda/(1 + z)]P_i(\lambda)d\lambda}{\int_0^\infty S[\lambda/(1 + z)]d\lambda}\,.$$

Here $S[\lambda/(1 + z)]$ is the redshifted spectrum of a PG (following one of the three models discussed in § II) and $P_i(\lambda)$ is the wavelength response of the ith plate.

The observational upper limits so calculated appear in figures 2, 3, and 4 as solid lines, one corresponding to model 1 and one to model 3 of § II. The best limit at low redshifts ($z \leq 12$ for model 1 spectrum) is set by the blue plate; the best limit at higher redshifts by the red plate. The corresponding curve for model 2 is generally congruent with the curve for model 1, except in the range $3 \leqslant z \leqslant 7$ where the Lyman absorption edge and continuum pass through the B spectral band.

c) *Number of PG Images*

We must next ask whether we might have missed PG images well above the plate limit simply because there were too few of them on the plates (less than 8 on the plates, or $N < 2.6 \times 10^5$ sr^{-1}). If we retain the assumption that only galaxies whose mass exceeds 10^{11} $M_\odot$ go through the PG phase, we do encounter the problem that N falls below 2.6×10^5 sr^{-1} for some cosmological and PG models. For instance, with $h = q_0 = 1$ and $\Delta t = 10^7$ yr, $N < 2.6 \times 10^5$ sr^{-1} for values of $z(t_f) \leq 4$. To avoid this problem, we will proceed by relaxing the assumption that only galaxies of mass greater than 10^{11} $M_\odot$ go through the PG phase. Only a modest relaxation is needed. As we show in the Appendix, it is only necessary to assume that all galaxies whose mass exceeds 3.7×10^{10} $M_\odot$ were PGs in order to ensure that $N > 2.6 \times 10^5$ sr^{-1} for *any* cosmological model or PG model considered in this paper.

However, if we alter the mass limit for PGs, we also lower the values of L and l calculated from equations (2) and (3). As demonstrated in the Appendix, these corrections are important only for low values of z. The corrections, which are necessary for $h = 1.0$ only, have been made as dashed lines in figures 2, 3, and 4. Finally, we note that the corrections have virtually no effect on the conclusions of this paper.

d) *Conclusions*

Our negative results indicate that galaxies formed at epochs corresponding to $z(t_f) \gtrsim 4$–8 if they went through a highly luminous phase as suggested by PP*a* (model spectrum 3; curve *b*). For most cosmological models, it appears that the PG phase—if it resembled the models presented in § II—preceded the epoch of enhanced quasar and radio-source formation ($z \sim 2$–4) suggested by Schmidt (1972) and Sunyaev (1971).

If PGs are required to produce helium as well as heavy metals ($\Delta X \sim 0.30$), the epoch of formation must be still earlier, $z(t_f) > 7$.

e) *Comparison with Davis and Wilkinson*

The value of these results is considerably enhanced when they are combined with those in the companion paper of DW. A comparison with their work is most easily accomplished by plotting the experimental upper limits established in this paper on their figures 7, 8, and 9. See DW for discussion.

f) *Extinction by the Intergalactic Medium*

The effect of extinction on our results may generally be ignored, since the optical depth due to Thomson scattering is less than unity for $z < 7$.

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APPENDIX

MASS LIMITS ON PGs NECESSARY TO ENSURE $N > 2.6 \times 10^5$ PER STERADIAN

Our photographic search is not valid unless N, the number of galaxies per solid angle, exceeds 2.6×10^5 sr^{-1} (§ IV). This requirement sets constraints on η_0, the present number density of galaxies. The two are related by (Weinberg 1972)

$$N = \eta_0 \Delta t c^3 H_0^{-2} \frac{1}{(z+1)} \times \left\{\frac{z}{q_0} + \frac{q_0 - 1}{q_0^2}[(1 + 2q_0 z)^{1/2} - 1]\right\}^2 . \quad (A1)$$

A value of η_0 may be derived from the results of Kiang (1961), assuming a mass-to-luminosity ratio of 10 for massive galaxies. The number density of galaxies whose mass exceeds $10^{11}\ M_\odot$ is $\sim 3 \times 10^{-3}$ Mpc^{-3}. Substituting this value in equation (A1) shows that N will fall below 2.6×10^5 sr^{-1} if Δt and z are both small. To ensure $N > 2.6 \times 10^5$ sr^{-1}, we must increase η_0, which implies we must consider less massive galaxies.

We proceed as follows:

1. Δt is fixed at 10^7 yr, the *lowest* value suggested by any model discussed in § II. This is clearly a conservative assumption, since $N \propto \Delta t$.
2. For each value of q_0 and h taken in this paper, equation (A1) is solved for that value of η_0 which will ensure $N \geq 2.6 \times 10^5$ sr^{-1}.
3. Using Kiang's (1961) paper, we then ask how far down the mass spectrum it is necessary to go to ensure that we have a large enough value of η_0. The results appear in table A1. Note that we need not change the mass limit by more than a factor of 3 even in the worst case. The modified mass limits of table A1 were used to correct the values of lh^{-2} plotted in figures 2, 3, and 4.

TABLE A1

MASS NEEDED TO ENSURE $N > 2.6 \times 10^5$ PER STERADIAN*

	$q_0 = 1.0$		$q_0 = 0.5$		$q_0 = 0.1$	
$z(t_f)$	η_0, 10^{-3} Mpc^{-3}	Implied Mass Limit, $10^{11}\ M_\odot$	η_0, 10^{-3} Mpc^{-3}	Implied Mass Limit, $10^{11}\ M_\odot$	η_0, 10^{-3} Mpc^{-3}	Implied Mass Limit, $10^{11}\ M_\odot$
			$h = 1$			
1........	19	0.37	13.7	0.45	9.4	0.55
2........	7.1	0.65	4.4	0.85	2.3	>1
4........	3.0	0.95	1.55	>1	0.55	>1
6........	1.8	>1	0.87	>1	0.25	>1
			$h = \frac{1}{2}$			
1........	4.75	0.85	3.42	1.0	2.35	>1
2........	1.75	>1	1.1	>1	0.57	>1

* Or more than eight PGs on the plates.

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R. B. Partridge
Haverford College, Haverford, PA 19041