SEARCHES FOR PRIMEVAL GALAXIES — PAST, PRESENT, AND FUTURE

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ABSTRACT. Most models of galactic evolution include a high luminosity epoch of bright star formation at a redshift $2 < Z < 100$. Past searches have failed to detect galaxies in their "primeval" state, but recent advances in detector technology will soon enable much improved searches that will very seriously constrain the evolutionary models. Using the CCD detectors on the Space Telescope offers the opportunity for a thousandfold improvement over present search limits. We review here several models of primeval galaxies and comment on their observability in present and future experiments.

I. WHAT IS A PRIMEVAL GALAXY?

The evolution of galaxies is a subject of central importance in extragalactic astronomy and cosmology. The work of Butcher and Oemler (1976) suggests that in the recent past ($Z \sim .5$) galaxies in clusters tended to be bluer, presumably because they contained more gas to form blue stars. Apart from this direct evidence for rich cluster members, there is little present constraint on the evolutionary history of normal galaxies. Number counts of galaxies versus magnitude may eventually provide constraints on galactic evolution for $Z < 1$, but at the present time, problems of uncertain luminosity functions and K corrections confuse the picture, as discussed by Ellis at this conference. What indirect evidence there is suggests the halo of our galaxy formed within one free fall time (Eggen, Lynden-Bell, and Sandage, 1962) and that the initial star formation rate was considerably higher in the past. Hence primeval galaxies (PG's) should have been quite luminous and may be detectable today, even if their formation epoch is $Z > 5$.

Extensive model calculations by Tinsley (1977, 1978), Tinsley and Larson (1978), Larson (1976) and others satisfactorily describe the colors and luminosities of galaxies of all types observed locally. Evolving these systems backwards in time provides evolutionary predictions that could be directly tested. The detection of primeval

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galaxies or lack of detection at a suitable limit, would serve to seriously constrain these models and thereby improve our understanding of galactic history.

In this talk I shall consider a primeval galaxy to be the progenitors of galaxies such as giant ellipticals or large spirals like our Milky Way. There is no doubt that there exist "young" galaxies in our local region, objects such as the dwarf peculiar galaxy II Zw 40 which is totally dominated by young blue stars. Presumably this object was an intergalactic cloud recently perturbed and gone unstable (Searle and Sargent, 1972). The progenitors of large galaxies may also have resembled gigantic H II regions at one time (Sunyaev, Tinsley, and Meier, 1978); it is these objects we designate as "primeval" galaxies, because they belong to the earliest age of galactic evolution.

II. HOW BRIGHT AND HOW MANY?

Details of the early evolution of galaxies, and therefore of the detailed appearance of primeval galaxies is of course highly speculative. Nevertheless there are a number of relatively model independent predictions that are of considerable interest.

The standard scenario of a primeval galaxy is a collapsing protogalaxy, with halo stars forming in a time short compared to one free gall time, and the disk stars forming after the inelastic collapse of the gaseous disk.

The characteristic time scale of the primeval galaxy is its collapse time which will be 10^8-10^9 years, and depends on the maximum expansion size of the protogalactic cloud. In the standard scenario, the bright phase begins when the clouds reach their maximum extent after one collapse time, corresponding to $Z \sim 20 - 200$ in an $\Omega = 0$, $H_o = 50$ km s^{-1} Mpc^{-1} universe, or to $Z \sim 3 - 16$ in an $\Omega = 1$, $H_o = 100$ km s^{-1} Mpc^{-1} universe. The length of the bright phase depends on the star formation rate, and can reasonably be expected to last one collapse time.

Old disk stars are not particularly metal poor, so it is reasonable to suppose that the first generation halo stars Pop II.5-III converted $\Delta X \sim 0.01$ of their hydrogen to metals. The energy conversion efficiency for this process is .007, and presumably the bulk of this energy will be radiated. If the present density of the remnants is ρ_L, then the integrated sky brightness B from all the PG's will be given as (Peebles, 1971)

$$B = \frac{0.007 \, \rho_L \, c^3 \, \Delta x}{4\pi \, (1+z)} \text{ ergs } s^{-1} \text{ cm}^{-2} \text{ ster}^{-1}$$

$$= \frac{8 \times 10^{-5}}{1+Z} \left(\frac{\Omega_L}{0.1}\right) \left(\frac{\Delta x}{.01}\right) \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ ster}^{-1}$$

where Ω_L is the fractional closure density of this once luminous material and Z is the redshift at which the bright phase occurs. We are here using $H_o = 50$ km $\sec^{-1}$ Mpc^{-1}. If we identify the once luminous remnant with the now dark massive halo around spiral galaxies and providing the virial mass of clusters, then $\Omega_L \sim .1$ is a not unreasonable estimate.

The best experimental limits are given by the ingenious experiment of Dube, Wilkinson, and Wickes (1977) which sets a 3σ upper limit of $B \leq 3 \times 10^{-5}$ ergs s^{-1} cm^{-2} $ster^{-1}$ at 5100 Å. Because the emission spectrum is expected to be reasonably flat to the Lyman cutoff, this result implies that galactic halos, if they are comprised of burned out stars, must have formed prior to Z = 2.

If primeval galaxies are to be seen individually, how abundant are they expected to be? If we assume all large galaxies went through the bright phase and that their present density is $n_o \sim .002$ Mpc^{-3}, then the number per square degree expected in an $\Omega = 1$ universe is

$$N \sim 2400 \ (1+Z) \left(\frac{\Delta t}{10^8 \text{ yrs}}\right) \text{deg}^{-2}$$

where again Z is the epoch of high luminosity and Δt is the timescale of the bright phase, which should roughly match the dynamical timescale of the galaxies. Thus it is not necessary to search large regions of the sky; it is much preferable to search a small region very deep.

III. PAST FAILURES, FUTURE HOPES

There have been several past attempts to detect individual primeval galaxies, all of which failed (Davis and Wilkinson, 1974; Partridge, 1974). These searches were based on the models of Partridge and Peebles, (1967a, 1967b) which predicted large fuzzy images (∿ 10") not too centrally concentrated but with very low surface brightness. The resulting upper limits on flux (at ∿ 7000 Å) and number density are plotted in Figure 1. Because the upper limits were large, the null results set no serious constraint on evolutionary models.

These earlier attempts were based on use of point detectors or red sensitive photographic plates. The ideal detector for such a program, and indeed for almost all astronomical programs, is a panoramic detector with high efficiency and negligible internal noise. Such devices are now becoming a reality; CCD's offer the chance for

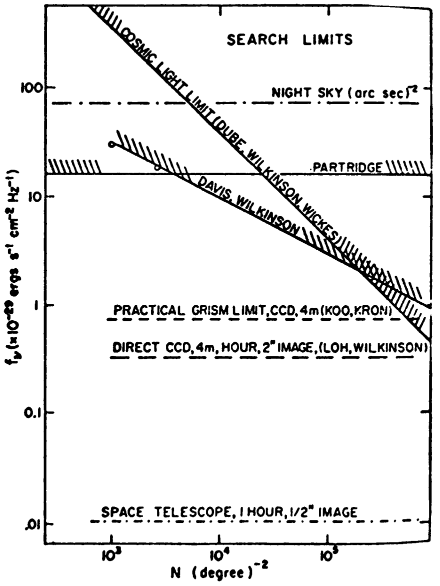

Figure 1. Present and expected flux and number density limits for searches of Primeval Galaxies.

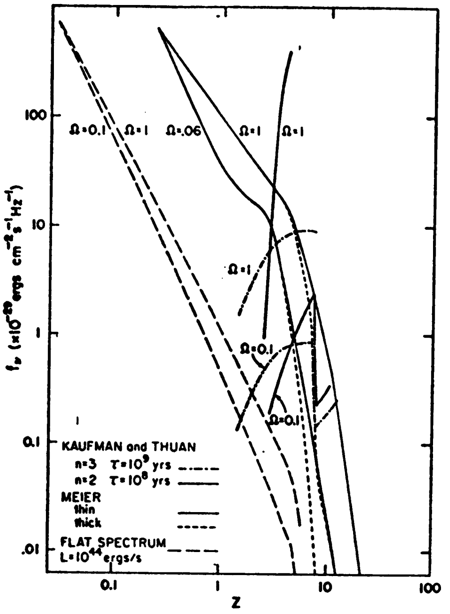

Figure 2. Expected flux at 7000 Å for several model primeval galaxies as a function of redshift. Each model is presented in the case of high and low density universe.

dramatic improvements in the search for primeval galaxies. Indeed at least two groups are currently trying to do just that. Shown in Figure 1 is the expected limit for detection of 2" images with signal to noise = 3, 1000 Å bandwidth, in one hour using the JPL CCD on the KPNO 4 meter (Loh and Wilkinson, 1979). Koo and Kron (1979) have used this same CCD for deep grism photographs. Their goal is to search for either Ly α emission or Lyman continuum break, and they estimate a practical detection limit of 1% of the night sky for a Ly α line. These limits are drawn in Figure 1. The Space Telescope facility offers further opportunities for detection of primeval galaxies because the sky background will drop four magnitudes in the red, and the seeing will improve to subarcsecond limits. Shown in figure 1 is the expected detection limit for 1000 Å bandwidth, signal to noise = 3, in one hour and 1/2 arcsecond images (Wilkinson, 1979).

IV. WILL PRIMEVAL GALAXIES BE DETECTED?

The limits above are impressive, but will they be good enough? I believe primeval galaxies will be detected at these limits, but they may not be recognized. Shown in Figure 2 are expected flux levels versus Z for several different, but typical, models. First consider a modest galaxy like our own with enough blue stars to increase its bolometric luminosity to 10^{44} erg/sec and to give an approximately flat spectrum to the Lyman break. The incident flux versus redshift (at 7000 Å) is shown for $\Omega = 1$ and $\Omega = 0.1$. Such an object would be readily detectable on the Space Telescope to redshifts ~ 6.

Meier (1976a) has examined several evolutionary models of Tinsley and Larson; shown in Figure 2 is the incident flux at 7000 Å for a 10^{11} $M_\odot$ model collapsing from an initial radius of 30 kpc and undergoing rapid star formation (Larson, 1974). Such a model might result in an elliptical galaxy today. Presented are the cases $\Omega = 1$ and $\Omega = 0.06$, both for an optically thin and optically thick interstellar medium. These models use a Salpeter initial mass function and follow the evolutionary tracks of the stellar population. What is plotted is the apparent flux versus redshift of formation. Increasing the initial radius of collapse would increase the free fall time and decrease the initial star formation rate, but because the epoch is later, at smaller Z, the apparent luminosity is not dramatically decreased. All of these models are centrally concentrated with 50% of the emission occuring within 8 kpc, so these primeval galaxies would appear almost stellar in ground based observations.

Models of massive primeval galactic halos have been explored by Kaufman and Thuan (1977). They characterize the stellar birth rate with the form $B(m,Z) \propto m^{-n} e^{-t/\tau}$ where m is the stellar mass of the star and t is time since formation. Again they follow a galactic evolution code, and have considered the interstellar medium to be optically thin. The typical free fall time for these models is 10^9 years, as they collapse from a radius of 100 kpc. Their mass is of order 3×10^{11} $M_\odot$. Plotted in figure 2 are evolutionary trajectories of several of these models starting at their expected formation epoch with n, τ, and Ω varied within their reasonable range. This type of primeval galaxy will again be centrally concentrated, but with a 1/r brightness profile out to 100 kpc, so they will appear distinctly fuzzy.

V. WILL WE RECOGNIZE A PRIMEVAL GALAXY IF WE SEE ONE?

It is apparent from comparison of Figures 1 and 2 that these models of PG's should be readily detectable on the Space Telescope, and very likely detectable from the ground today. Many alternative models have been proposed, but the models of Fig. 2 give a general picture of the expected range. It is entirely possible that galactic disks formed slowly by infall and never underwent a bright phase. However, to prevent dissipation, galactic halos and elliptical galaxies almost surely underwent rapid star formation in a time scale of one collapse time or less. If these objects are not detected by the Space Telescope, the epoch of the bright phase will be pushed beyond $Z = 10$.

How will we recognize a faint image as a PG? A primeval galaxy detected at 27^m may be nearly stellar and without spectral information it will be very difficult to distinguish it from a relatively nearby dwarf elliptical galaxy. The signature of a PG is that it should have the spectrum of an H II region, with weak metal lines and strong Ly α emission, plus a likely cutoff at the Lyman continuum. The width of the emission lines should not exceed the velocity dispersions in galaxies, $\sim$ 300 km/sec. Thus spectroscopic searches such as being undertaken by Koo and Kron will be very significant.

Candidates for primeval galaxies should exhibit no polarization or variability. They may be weak non-inverted radio sources, and should be weak X-ray sources. If they are extended, the spectral features should be the same in the core as in the outer fuzz.

It is possible that some QSO's are really PG's. Indeed Meier (1976b) has suggested that the spectra of OH471 and 4C05.34 strongly resemble his models of PG's. QSO's with suitable narrow emission lines are good candidates for primeval galaxies, and if so they should appear fuzzy in good seeing. Mackay (1979) has taken Ly α filter photographs of several high redshift QSO's in good seeing, which have revealed nothing extending larger than 0.2". In the fields of these QSOs in broadband (500 Å bandpass) photographs no objects with unusual colors were detected down to $m_B \sim 23$.

Perhaps the past searches for primeval galaxies were premature. Soon, however, it will be quite realistic to expect to detect galaxies at these large redshifts. The detection and positive identification of primeval galaxies would provide invaluable data for understanding the dynamical and evolutionary processes of stellar systems.

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DISCUSSION

Spinrad: The UV spectra of HII regions are, apparently, very different from that of QSOs; they have weak emission lines, not strong Lyα, CIV and CIII of QSOs and Seyferts. So primeval galaxy spectra, if like HII regions, may not be very spectacular.

Davis: Perhaps their non-spectacular nature will be the distinguishing element. That doesn't make it easy for the spectroscopist, however.

Wolfe: There are some QSOs (3C 48, 3C 279, etc.) which have extended images with spectra resembling HII regions: the lines are narrower than typical QSO emission lines. Thus, these look like the objects you are talking about. But their redshifts are small, $z \sim 0.5$. How do they fit into your theory?

Davis: Presumably, these are too rare to be the progenitors of bright nearby galaxies. They may be "young" galaxies which for some reason have delayed the onset of star formation.

Boldt: Would there be significant X-ray emission associated with these protogalaxies?

Davis: They will be weak X-ray sources because of their O stars and supernovae remnant shells, but they should not be strong X-ray sources like QSOs.

Rees: You showed a diagram which indicated that the space telescope would offer a great improvement in sensitivity compared with a CCD or a ground-based 4-m telescope. Would this improvement really be so significant if the intrinsic angular size of a photogalaxy exceeded $0\overset{''}{.}5$?

Davis: The increased sensitivity of the space telescope is partly due to decreased sky background, which amounts to 4 magnitudes in the red.

This accounts for most of the difference between ground-based and space telescope CCD limits.