PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Detectability of Young Galaxies [and Discussion]

Beatrice M. Tinsley and D. Meier

Phil. Trans. R. Soc. Lond. A 1980 **296**, 303-308
doi: 10.1098/rsta.1980.0173

Phil. Trans. R. Soc. Lond. A **296**, 303–308 (1980) [303]
Printed in Great Britain

The detectability of young galaxies

By Beatrice M. Tinsley
Yale University Observatory, Box 2023 *Yale Station, New Haven, Connecticut* 06520, *U.S.A.*

Possibilities for detecting primaeval galaxies are reviewed. The best prospects for detection are giant elliptical galaxies, in a stage of rapid star formation about 10^{10} years ago. These primaeval galaxies would probably be quasi-stellar in angular size. They could have easily detectable magnitudes if the most luminous stage occurs at red shifts $z \lesssim 5$, and if internal dust does not absorb most of the ultraviolet–visual light. Although it is not clear whether very young giant elliptical galaxies have yet been found, excess populations of blue galaxies in clusters (discovered by Butcher & Oemler) and in the field (discovered by Kron) are almost certainly in early stages of active star formation.

1. Introduction

Earlier papers in this volume concentrate on the growth of galaxies from perturbations in the early Universe, asking how objects of galactic size and shape could develop. Here I consider a different question: given the present stellar populations in galaxies, what would the first stages of star formation have looked like? By looking back in time to large enough red shifts, can we detect these primaeval stages? If successful, a search for primaeval galaxies (p.gs) would determine the epoch at which early perturbations reached the critical stage of fragmenting into ordinary stars.

The idea of searching for p.gs originated with Partridge & Peebles's (1967*a*, *b*) seminal papers on their possible properties, appearance as individuals, and collective contribution to the diffuse background light. Recent reviews of the subject include those of Larson (1976), Tinsley (1978*a*) and Sunyaev *et al.* (1978) on which this brief summary is largely based.

Why do we hope to see p.gs at red shifts many times greater than those at which familiar, nearby galaxies would certainly have faded from sight? The predictions depend on extrapolating from present to past stellar populations of galaxies, using plausible (although necessarily tentative) assumptions. The light from most present-day galaxies is dominated by old red giant stars that must have formed at least several billion years ago. At formation, these same stars would be faint F–G dwarfs, so the hope of seeing p.gs is predicated on the assumption that a full mass spectrum of stars, extending up to bright blue OB stars, formed at the same time. In galaxies with predominantly old stars now, this early burst would have been especially bright. Galaxies that are still actively forming stars, however, must have made stars inefficiently at early times, so they would have been less bright relative to their present luminosities. Extending these arguments to quantitative estimates of how present-day stellar populations and colours could have arisen, one predicts that elliptical and S0 galaxies were probably several magnitudes brighter during their first stages of star formation, early-type spiral galaxies have never been much brighter, and late-type spirals were always fainter in the past than they are now (Tinsley 1978*b*). The p.gs discussed here are therefore the precursors of E and S0 galaxies, and, because S0s were possibly just ordinary spirals until fairly recently (see, for example, van den Bergh, this symposium), the most luminous p.gs were probably young ellipticals.

2. Clues from nearby galaxies

Nearby galaxies would be most valuable in the search for p.gs at large red shifts if we could find truly young systems forming at this late date. Candidates for such objects have been discussed by Burbidge *et al.* (1963), Searle & Sargent (1972), Larson (1976), and others cited in these papers. Properties that would distinguish young galaxies are a chaotic shape and a population of exclusively young stars. However, the Magellanic Clouds show that very old stars (old globular clusters, for example) can exist in irregular systems, and it is very easy for young stars to hide an underlying old population in more distant galaxies. Morphologically normal galaxies, with Hubble types ranging from E through Irr I, have colours consistent with ages *ca.* 10^{10} years (Tinsley 1968; Searle *et al.* 1973; Larson & Tinsley 1978), and most of them are too red to be younger than *ca.* 5×10^{9} years. On the other hand, there are some morphologically peculiar galaxies that are abnormally blue. Some of these *could* be young, but in all cases the colours are equally consistent with 90% or more of the stellar mass being 10^{10} years old; the old stars can be completely masked in optical light by a small minority formed in a recent burst.

Whether or not any nearby peculiar galaxies are really young, the extreme cases serve as valuable examples of sites with a very high star formation rate (s.f.r.). Some galaxies that may be undergoing strong bursts have been discussed in this context by Larson (1976). Many such galaxies have recently been found to be intense infrared sources, and, assuming that the infrared radiation is starlight thermalized by dust grains, one can estimate the s.f.r. (Struck-Marcell & Tinsley 1978). Examples are M82 with an s.f.r. of *ca.* 6 $M_\odot$ per year, and NGC 5128 with an s.f.r. of *ca.* 1 $M_\odot$ per year in its dust band (based on the infrared luminosity reported by Telesco (1978)). Neither of these galaxies is especially blue, so they lead one to suspect that p.gs at large red shifts might be too dusty to be optically striking objects.

Properties of the Milky Way and regions of external galaxies with rapid star formation show that the whole electromagnetic spectrum, from γ-radiation to radio wavelengths, is affected by a very young stellar population and the interstellar material from which stars form. Some possibilities for the entire spectrum have been discussed in detail by Sunyaev *et al.* (1978), and the main features predicted are the following: there is a large infrared peak near 100 μm, due to stars hidden behind dust, and a sudden break at 912 Å, due to the absorption of Lyman continuum photons by hydrogen; OB stars and H II regions provide an optical–ultraviolet continuum with characteristic stellar absorption lines and gaseous emission lines; H II regions and supernova remnants contribute thermal and non-thermal radio continua; molecular clouds give significant CO line emission at 2.6 mm; and X-rays come from binaries analogous to Cyg X-1. Of course, the relative proportions of these components cannot be predicted at all accurately since they are very sensitive to the relative quantities of young stars and dust and neutral, ionized and molecular interstellar gas. Various papers on the appearance of p.gs (see references in Sunyeav *et al.* 1978) have emphasized different possibilities, ranging from unobscured very blue starlight to pure infrared radiation from dust. If nearby star-forming galaxies are any guide, the intrinsic colours of p.gs could cover this whole range.

3. Predictions for large red shifts

At what red shift (z) would a giant elliptical galaxy have reached its peak s.f.r. and luminosity? As discussed by Larson this symposium), estimates of the time scale for star formation in a p.g. range from a minimum of a little more than a free-fall time, up to several thousand million years if the star formation occurs during collisions of subsystems that have taken several orbits to merge. The red shift could therefore range from several tens down to $z \approx 2$, with recent models preferring lower values, $z \approx 5$. The latter estimates are propitious for the detectability of p.gs, because their optical apparent magnitudes are predicted to be very faint at greater red shifts. This is due not only to a simple dimming with distance, but also to enormous K-corrections if light emitted below the Lyman limit falls into the observer's bandpass. For example, the B (or photographic J) bands will receive very little light if $z \gtrsim 4$. Other strong effects of red shift on the appearance of p.gs at various observed wavelengths are discussed by Meier (1976*b*) and Sunyaev *et al.* (1978).

Both the red shift and the cosmological model determine the angular size of a p.g. of given proper diameter. If the density is well below critical, p.gs will be semistellar in appearance at $z > 1$, provided most of the star formation at the brightest moment occurs inside a diameter less than about 10 kpc. For this reason, Meier (1976*a*, *b*) and Longair & Sunyaev (1977) have suggested that p.gs could be mistaken for quasars; these authors and Sunyaev *et al.* (1978) discuss criteria for distinguishing p.gs from genuine quasars (very small non-thermal sources), such as optical non-variability and characteristic spectral features. Such a small angular size is expected for primaeval elliptical galaxies only if their peak s.f.r. occurs in a region as condensed as the nuclei of present-day ellipticals. This behaviour is predicted by Larson's (1974) collapse models (see Meier 1976*b*), and it is plausible if star formation occurs during mergers of subsystems (Tinsley & Larson 1979; Larson, this symposium). Earlier models for p.gs (beginning with Partridge & Peebles (1967*a*)) had suggested much larger linear and angular diameters, on the supposition that stars would form before the collapse of the protogalaxy, but this scenario now seems less plausible.

The most important factor in the detectability of a p.g. is of course its apparent luminosity. It is easy enough to estimate the intrinsic bolometric luminosity from the predicted s.f.r.: for example, both collapse and merger models for the formation of an elliptical of $10^{12}\,M_\odot$ predict a peak s.f.r. of *ca.* 1000 $M_\odot$ per year, which would have $L_{\text{bol}} \approx 5\times10^{12}\,L_\odot$. The critical questions concern internal extinction and K-dimming: this light could appear almost entirely in the infrared, peaking at 100 $(1+z)$ μm, if the p.g. is very dusty; and, even if it is not, a red shift $\gtrsim 10$ would make detection at any optical wavelengths very unlikely. In an optimistic case, a dust-free p.g. with the s.f.r. just mentioned would have $M_{\text{v}} \approx -25$; at a red shift of, say, $z = 3$, its apparent visual magnitude would be *ca.* 22, right in the range of quasar magnitudes.

4. Have primaeval galaxies been found?

Most searches for p.gs have been aimed at finding individual objects. Partridge (1974) and Davis & Wilkinson (1974) looked for extended images, on the supposition that star formation would precede the collapse of a protogalaxy. These studies gave null results, which may have been because p.gs are in fact very condensed (§3). Meier (1976*a*) pointed out some quasars whose properties made them promising candidates for p.gs: they are optically non-variable, and have sharp cutoffs at the Lyman limit at the emission-line red shift. However, subsequent studies have shown that these objects have emission lines that are too wide to originate in the interstellar medium of a p.g. The search for p.gs among objects at red shifts *ca.* 2–5, especially among slightly fuzzy quasars, must continue.

Another approach is to see whether the extragalactic background light has a greater intensity than one could account for without very luminous, unresolved, p.gs (Partridge & Peebles 1976*b*). The latest observations (Dube *et al.* 1977; Spinrad & Stone 1978) give upper limits that do not allow *all* galaxies to have been very bright primaevally (unless the red shift moves the region below the Lyman limit up to visual wavelengths). However, such a scenario is probably inconsistent with the present colours of galaxies (§1); more plausible models, in which only early-type galaxies have bright initial bursts, predict an intensity below the empirical limits for *any* red shift of galaxy formation (Tinsley 1978*b*). Greater sensitivity, to a component of the night-sky intensity that is far below extraneous foreground contributions, will be needed if this test is to yield constraints on primaeval elliptical galaxies.

Counts of galaxies present a more promising approach, because models suggest that p.gs could make a striking difference to the number–magnitude relation (Tinsley 1978*b*). If the bright stages of early-type galaxies are invisible, other stages of galactic evolution lead to little difference from the counts that one would expect with no evolution at all; but if the bright p.gs are at suitable red shifts (and are not too dusty) for detection, they would contribute pronounced features in the counts. Recent sets of deep galaxy counts differ as to whether any such features are seen. As described by Ellis (this symposium), the counts of Peterson *et al.* (1979) extend smoothly to a J magnitude of *ca.* 24.5, and are consistent with plausible galaxy evolution but no bright p.gs. However, Kron's (1978) counts show a sharp excess at $J \approx 23$–24, and a very blue distribution of colours at faint magnitudes. Since the two studies used different methods of defining magnitudes and of identifying very faint galaxy images, the diverse results are not inconsistent (Kron 1979). Kron's survey could in fact have found very young galaxies, although red shifts of his blue objects near $J = 24$ will be needed for a firm interpretation. In any case, Kron's distribution of magnitudes and colours are clearly inconsistent with models allowing no galactic evolution; he has certainly found that the faint population of galaxies includes intrinsically bluer and brighter objects than the nearby population.

An earlier discovery of very blue galaxies was made by Butcher & Oemler (1978*a*). They found that two rich, centrally concentrated clusters of galaxies at $z \approx 0.4$ contain a large population of bright blue galaxies; this is in striking contrast to morphologically similar nearby clusters, where essentially all the bright galaxies are red (Butcher & Oemler 1978*b*). It appears that the precursors of the present red cluster members were blue because of very vigorous star formation, as recently as *ca.* 4×10^9 years ago.

5. Conclusion

Galaxies in early stages of rapid star formation have almost certainly been found, as an excess population of blue objects in the field and in clusters. It is not yet clear, however, that any of these are really the long-sought bright primaeval ellipticals. Whether these will ever be identified depends primarily on their red shifts and their content of interstellar gas and dust. With luck, giant p.gs may be found among objects thought to be quasars, with red shifts of *ca.* 2–5 and very high intrinsic luminosities at optical and u.v. wavelengths. But if very young ellipticals are as dusty as some nearby galaxies with strong bursts of star formation, they may appear only as infrared stars.

I wish to thank R. G. Kron for discussions about his galaxy counts. This work was supported in part by N.S.F. Grant AST 77-23566 and the Alfred P. Sloan Foundation.

References (Tinsley)

Burbidge, E. M., Burbidge, G. R. & Hoyle, F. 1963 *Astrophys. J.* **138**, 873.
Butcher, H. & Oemler, A. 1978*a* *Astrophys. J.* **219**, 18.
Butcher, H. & Oemler, A. 1978*b* *Astrophys. J.* **226**, 559.
Davis, M. & Wilkinson, D. T. 1974 *Astrophys. J.* **192**, 251.
Dube, R. R., Wickes, W. C. & Wilkinson, D. T. 1977 *Astrophys. J.* **215**, L51.
Kron, R. G. 1978 Ph.D. thesis, University of California at Berkeley.
Kron, R. G. 1979 In the press.
Larson, R. B. 1974 *Mon. Not. R. astr. Soc.* **166**, 585.
Larson, R. B. 1976 *Comments Astrophys.* **6**, 139.
Larson, R. B. & Tinsley, B. M. 1978 *Astrophys. J.* **219**, 46.
Longair, M. S. & Sunyaev, R. A. 1977 In *Radio astronomy and cosmology* (*I.A.U. Symp.* no. 74) (ed. D. L. Jauncey), p. 353. Dordrecht: D. Reidel.
Meier, D. L. 1976*a* *Astrophys. J.* **203**, L103.
Meier, D. L. 1976*b* *Astrophys. J.* **207**, 343.
Partridge, R. B. 1974 *Astrophys. J.* **192**, 241.
Partridge, R. B. & Peebles, P. J. E. 1967*a* *Astrophys. J.* **147**, 868.
Partridge, R. B. & Peebles, P. J. E. 1967*b* *Astrophys. J.* **148**, 377.
Peterson, B. A., Ellis, R. S., Kibblewhite, E. J., Bridgeland, M. T., Hooley, Y. & Horne, D. 1979 (In preparation.)
Searle, L. & Sargent, W. L. W. 1972 *Astrophys. J.* **173**, 25.
Searle, L., Sargent, W. L. W. & Bagnuolo, W. G. 1973 *Astrophys. J.* **179**, 427.
Spinrad, H. & Stone, R. P. S. 1978 *Astrophys. J.* **226**, 609.
Struck-Marcell, C. & Tinsley, B. M. 1978 *Astrophys. J.* **221**, 562.
Sunyaev, R. A., Tinsley, B. M. & Meier, D. L. 1978 *Comments Astrophys.* **7**, 183.
Telesco, C. M. 1978 *Astrophys. J.* **226**, L125.
Tinsley, B. M. 1968 *Astrophys. J.* **151**, 547.
Tinsley, B. M. 1978*a* In *The large-scale structure of the Universe* (*I.A.U. Symp.* no. 79) (ed. M. S. Longair & J. Einasto), p. 343. Dordrecht: D. Reidel.
Tinsley, B. M. 1978*b* *Astrophys. J.* **220**, 816.
Tinsley, B. M. & Larson, R. B. 1979 *Mon. Not. R. astr. Soc.* **186**, 503.

Discussion

D. Meier (*Institute of Astronomy, Cambridge, U.K.*). I should like to make a few brief comments concerning the paper given by Dr Tinsley. Figure 1 is an illustration from Sunyaev *et al.* (1978), which shows the predicted optical–ultraviolet spectrum of a primaeval galaxy (p.g.) assuming no reddening by dust. The optical part is from a scan of Mkn 33 (G. Neugebauer *et al.* (1976) *Astrophys. J.* **205**, 29), a very blue galaxy with an apparently high star formation rate. The ultraviolet part is synthesized theoretically from stellar population models of young galaxies and emission line models of H II regions (G. A. Shields & L. Searle (1978), *Astrophys. J.* **222**, 821). One can see why at first a primaeval galaxy may appear spectroscopically similar to a quasar. There is strong ultraviolet continuum radiation (from hot massive stars) and strong line emission (from ionized gas in the forming galaxy). However, there are some differences which could distinguish a p.g. from a quasar. First, the emission line widths would be typical of the dispersion velocity in a galaxy – a few hundred kilometres per second rather than the 10^4 km s^{-1} seen in quasars. Secondly, there will be absorption lines in the atmospheres of hot stars (not shown here) with line widths similar to the emission lines and at a red shift $z_{abs} = z_{em}$.

All p.gs should have a Lyman continuum cut-off due to interstellar absorption (in the p.gs themselves) and consequently will be invisible in filter bands of wavelength $\lambda > (1+z)$ 912 Å, regardless of intrinsic luminosity! Another possibility, which is uncertain at present, is that Si IV and C IV emission may be weak or absent since hot stars may produce less excitation than a quasar central source. I shall be obtaining some IUE spectra of objects like Mkn 33 in the near future to test these theoretical predictions.

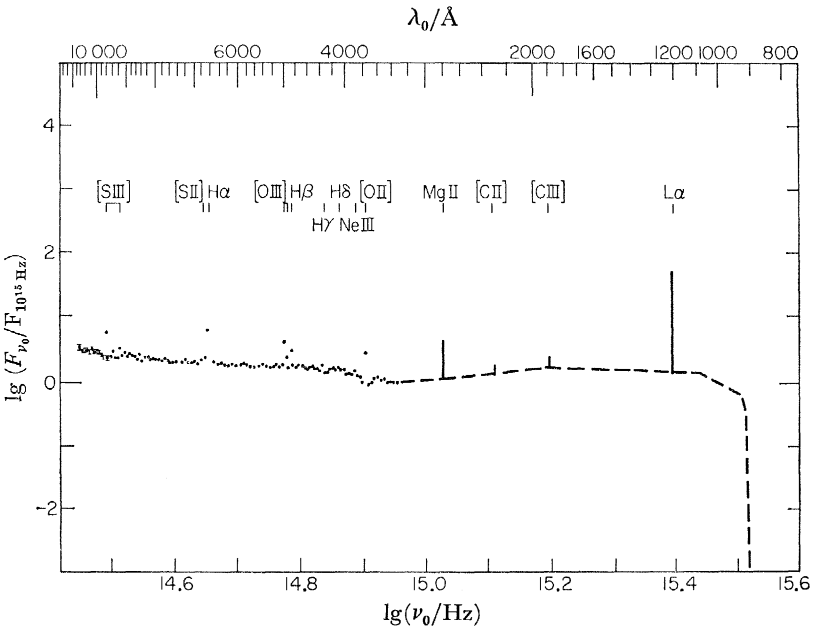

FIGURE 1

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES