MODELS FOR THE FORMATION AND EVOLUTION OF SPHERICAL GALAXIES

RICHARD B. LARSON
Yale University Observatory, New Haven, Conn. 06520, U.S.A.

Abstract. Detailed dynamical model calculations based on a conventional collapse picture of galaxy formation, and conventional assumptions concerning star formation and stellar evolution, are found to be able to reproduce satisfactorily the basic structural and photometric properties of elliptical galaxies. The quasar phenomenon may be identifiable with the formation of the nucleus of a giant elliptical galaxy.

Because the basic structural properties of elliptical galaxies must have been largely determined at the time of formation, they can be properly accounted for only by fairly detailed dynamical models describing the galaxy formation process. Also, various cosmological studies and the interpretation of objects like the quasars require a knowledge of how galaxies form and evolve with time. For these reasons, an attempt has been made to construct models of the formation and evolution of spherical galaxies, with the hope that the results will apply also to elliptical galaxies which are not too highly flattened. The basic hydrodynamical method used in these calculations is that developed earlier in *Monthly Notices Roy. Astron. Soc.* **145**, 405, 1969, with the incorporation of the effects of stellar mass loss and heavy element production and of some new assumptions for the star formation and gaseous dissipation rates. The photometric properties of these models have been computed as a function of time and radial coordinate by B. M. Tinsley. This work will be described in detail elsewhere, e.g. *Monthly Notices Roy. Astron. Soc.* **166**, 585, 1974, and therefore only a brief summary of the salient features of the models is presented here.

In a typical case, the calculations begin with a spherical protogalaxy of mass $10^{11}\ M_\odot$ and radius 50 kpc; in contrast to the calculations described by Gott in this volume (p.181), we assume here that the protogalaxy is initially entirely gaseous. The gas is assumed to possess large-scale internal turbulent or streaming motions whose dissipation through collisions allows the system to become highly centrally condensed; the dissipation time scale is assumed to be approximately equal to the local dynamical time scale for the system. The gas is continually transformed into stars during the collapse, and it is assumed that the characteristic time scale for star formation is also approximately equal to the dynamical time scale, the justification being that star formation may be triggered by the compression or shock fronts produced when large-scale gas streams collide. The evolution of the galaxy is followed for 10^{10} yr, after which time the residual gas content is reduced to only a few times $10^6\ M_\odot$. With reasonable choices for the parameters of the model, the resulting projected stellar density distribution gives a close fit to the observed surface brightness distribution in typical elliptical galaxies like NGC 3379. Assuming a conventional Salpeter stellar mass spectrum, the models also reproduce satisfactorily other ob-

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served properties of typical elliptical galaxies, such as the nuclear velocity dispersion ($\sim 200\ \mathrm{km\ s^{-1}}$), the mass-to-light ratio (~ 20), the approximate metal abundance ($Z \sim 0.02$) and the $B-V$ colour (~ 0.97).

An important general prediction of these models is a steep metal abundance gradient in the nuclear region, qualitatively similar to the abundance gradients observed by McClure, Spinrad, and others. The abundance gradient is produced by the continuing inflow of residual gas through an already formed background of stars, which causes the heavy elements lost from the stars to be swept inward and concentrated at the centre of the galaxy. A further important result is that the metal abundance distribution in the nuclear region approaches an approximate steady state, so that most of the stars at any point are formed with nearly the same metal abundance, and relatively metal-poor stars are quite rare. Thus the observed scarcity of metal-poor stars in the solar vicinity, which is difficult to account for with conventional 'one zone' models of galactic evolution, can be explained naturally by a dynamical picture in which the galactic disk is built up by the continuing inflow of gas into a region in which an approximate steady-state metal abundance has been established. These results, together with the results mentioned above for the structure of the models, provide strong support for the conventional collapse picture of galaxy formation and show that more exotic models, such as galaxy formation by ejection from a nuclear source, are not required to account for any of the observed properties of typical elliptical galaxies.

The total star formation rate in the present models reaches a maximum at a time about $1.0\text{–}2.5 \times 10^9$ yr after the big bang, corresponding to a redshift of the order of $2-5$, with considerable uncertainty. For a model of mass $10^{11}\ M_\odot$ the maximum star formation rate is of the order of $10^2\ M_\odot\ \mathrm{yr}^{-1}$ and the corresponding maximum stellar luminosity is of the order of $3 \times 10^{11}\ L_\odot$; these numbers scale with the mass and so could be 1 to 2 orders of magnitude higher for massive elliptical galaxies. Thus, forming galaxies are predicted to have redshifts and luminosities comparable with those of quasars. This result, together with the fact that during the later stages of the galaxy formation process the residual gas and star formation activity become more and more strongly concentrated in the nucleus of a galaxy, suggests that the quasar phenomenon may be identifiable with a stage of the galaxy formation process when residual gas is concentrating at the centre to form a highly condensed nucleus. The present models do not directly account for the non-thermal nature or the variability of quasar radiation, but they provide a natural justification for those quasar models which postulate that large numbers of pulsars or similar condensed objects are formed in a dense ambient gas in the nucleus of a galaxy. This is expected to occur in a forming galactic nucleus, since a high rate of star formation in the nucleus will result in a high rate of supernova and pulsar production.

In models where the boundary is allowed to expand with time, the inflow of gas into the nuclear region may continue at an appreciable rate for up to 10^{10} yr or longer, owing to the long time required for the outermost layers of the protocloud to collapse. Thus it is possible that, in some cases, star formation and related activity may continue or recur in the nucleus of a galaxy long after the formation of the bulk of the galaxy is completed. This may help to explain why nuclear activity is observed in a number of presumably old galaxies at relatively small redshifts.

DISCUSSION

Rickard: From your diagram of the growth of metals as a function of time, one can see that the metal abundance *decreases* in the later stages in the *outer* region of the protogalaxy. What is the reason for this?

Larson: This effect is found also in some of the non-dynamical models of other authors and is due simply to the fact that, after the initial phase of rapid star formation and metal enrichment, most of the gas in the outer region is supplied by mass loss from relatively old low-mass stars which do not contribute additional metals; thus the metal abundance of the ejected gas is essentially the average metal abundance with which the halo stars were formed, and this is significantly smaller than the peak value.

G. de Vaucouleurs: As an observational test of your models, would you expect the fraction of E galaxies with emission lines in their nuclei to increase with distance (look-back time)? Or the ratio [N II]/Hα to be expected to vary appreciably in the last 10^9 yr?

Larson: The models predict that the amount of gas in a galaxy decreases as a function of time, and one would thus expect to see, at least on the average, more gas and stronger emission lines in galaxies at larger redshifts. One might also expect some variation with time in the emission line ratios; in particular, a relative strengthening of nitrogen lines due to the continuing production of nitrogen. However, my models do not yet provide predictions for individual elements.

Cox: Have you included the energy input to the residual gas by supernovae? I think Mathews and Baker (*Astrophys. J.* **170**, 241, 1971) found that, with such low gas densities, the gas cannot radiate the energy input and an outflow of galactic wind occurs.

Larson: These models do not include the supernova energy input, and that is one of the main deficiencies which I hope to correct. It may be that some or all of the residual gas is blown out during the later stages of evolution. It may also be that intense quasar activity in a forming galactic nucleus could have interesting effects in blowing gas out of the system and possibly setting a limit to further gas inflow and star formation; these are problems that remain to be investigated.

Disney: Would you please comment on the sensitivity of the results to the assumed initial conditions? Are not computations dominated by free-fall strongly dependent on the initial conditions, in particular the initial density distribution?

Larson: In hydrodynamic collapse calculations for interstellar gas clouds and protostars, it has generally been found that the results are not strongly dependent on the details of the initial conditions, e.g. the initial density distribution, and I think that the same conclusion holds here. From experiments with the models, it seems that the structure of the resulting galaxy is determined more by the physical processes occurring during the collapse, particularly the gaseous dissipation and star formation processes, than by the details of the initial or boundary conditions. However, these latter do affect the time scale of the collapse and the rate of continuing inflow of residual protogalactic gas throughout the evolution of the galaxy.

Wright: Your result of QSO luminosities and redshifts after the collapse of a protogalaxy follows, I believe, simply because the free-fall time for reasonable protogalactic densities corresponds to a value of $z \approx 2$. At an A.A.S. meeting two years ago (*Bull. Am. Astron. Soc.* **4**, 267, 1972) I noted this result but concluded it was simply an amusing coincidence since I didn't believe that the extremely spherical collapse needed to get a very small emitting region was realistic.

Larson: It is, of course, hardly likely that real collapsing protogalaxies would be strictly spherical; probably the situation would be chaotic and irregular, and to the extent that my models are applicable at all they would provide only a smoothed, spherically symmetrized representation of the complicated and chaotic real situation. Nevertheless, the observed presence of highly condensed nuclei in elliptical galaxies is an indication that, even though the collapse may not be closely spherical, protogalaxies *are* able to develop highly condensed cores; thus I think that the spherical collapse models are not completely without reality. It is true that the region of active nuclear star formation in the models is one to two orders of magnitude larger than the 10 pc size which one infers for the region of intense activity in quasars, but again it should be kept in mind that the models describe only a smoothed average of the condensation and star formation processes which in reality are probably highly inhomogeneous and confined to atypically small, dense regions; it is plausible that quasar activity would be most prominent in such regions.