THE PAST HISTORY OF STAR FORMATION IN GALAXIES

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1. THE "STANDARD SCENARIO" - AN IDEALIZATION

It is generally believed that most galaxies have similar ages, and that the age differences of their most visible stellar populations are due to a diversity of evolutionary stages. The presence of old stars in even late-type galaxies rules out an age sequence increasing from irregulars through S0's; dynamical constraints prevent transitions of isolated disc systems into ellipticals; and the gas contents of typical galaxies provide enough fuel for a long life of star formation at current rates (Baade, 1963; Roberts, 1963, 1975; King, 1971; Sandage, 1975). More specifically, models for the evolution of photometric properties show that integrated colors of galaxies are consistent with the following hypothesis:

> Normal galaxies have the same age and stellar initial mass function (IMF), and have monotonically decreasing star formation rates, but the time scale for star formation to decline varies along the sequence of morphological types

(Tinsley, 1968; Searle et al., 1973; Larson and Tinsley, 1974). I shall refer to this hypothesis as the "standard scenario" for the evolution of galaxies. Its interest is twofold: in correlating star-formation time scales with structure in a way that calls for dynamical explanation, and in providing an idealized "smooth background" to the complicated real scene of star formation in galaxies. This paper will address the second point.

The colors of ordinary galaxies agree remarkably well with the predictions of this idealization, as illustrated simply by UBV colors in Figure 1. The data points are for a sample selected on the basis of morphological "normality", as detailed in Larson and Tinsley (1978; to be referred to as LT). The line is an eye-estimated mean, and it corresponds closely to the theoretical 2-color locus of models conforming to the standard scenario. Indicated on the figure are limiting

E. M. Berkhuijsen and R. Wielebinski (eds.), Structure and Properties of Nearby Galaxies, 15-21.

https://doi.org/10.1017/S0074180900143621 Published online by Cambridge University Press

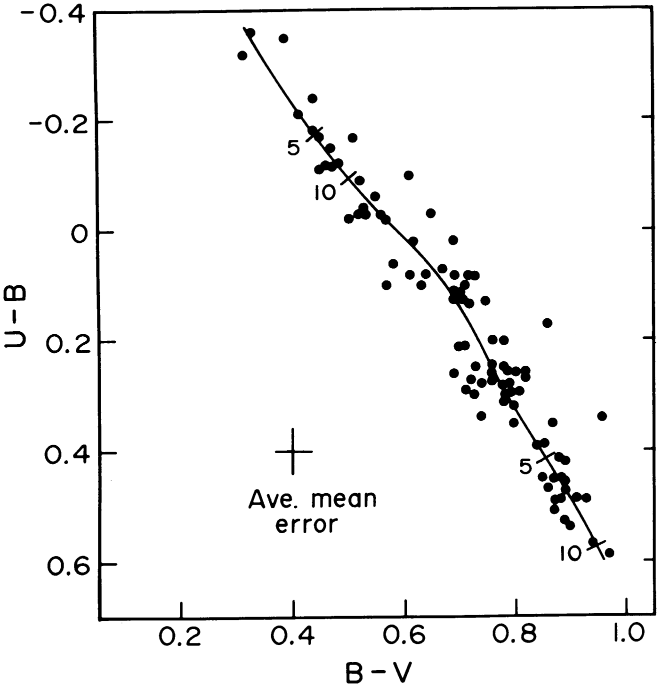

Figure 1. Colors of morphologically "normal" galaxies; cross marks indicate limiting colors of monotonic models with ages 5 and 10×10^9 yr.

colors for such models with ages 5 and 10×10^9 yr; the blue limit at each age is for constant star formation, the red limit is for a brief initial burst, and models with monotonically decreasing rates (of any time-dependence) have intermediate colors. It can be seen that few points deviate by more than the observational errors from the mean line, in accordance with our hypothesis. (The data points have not been adjusted for metallicity differences, which tend to scatter colors parallel to the mean line and probably account for the unusually blue top few points [LT].) Only stars above about 0.4 $M_\odot$ contribute significantly to the light, but if galaxies have the same IMF for less massive stars, the models predict that their mass-to-luminosity ratios should increase with color along the mean line by an overall factor ∿ 10. This indeed seems to be the case (Sargent and Tinsley, 1974; LT).

In spite of such successes, the standard scenario is obviously not a unique explanation of the broad photometric properties and gas contents of normal galaxies. The next section discusses some of the growing evidence that it is at best a very oversimplified view of galactic evolution.

2. SOME VARIANTS FOUND IN NEARBY GALAXIES

2.1. Variations in the initial mass function

The IMF is known to vary, at least on small scales within galaxies. Freeman (1977) has reported values of the power-law slope (x) in globular clusters and young LMC clusters ranging from 0.2 to > 3! Field stars in the solar neighborhood have $x \sim 1.3$ for most masses, and ~ 0.3 between 0.5 and 1 $M_\odot$, but there are wide variations among small-scale regions of star formation (associations and open clusters). Van den Bergh (1976) and Schweizer (1977) have noted an unusual paucity of O stars in the star-forming knots in NGC 4594, and Larson (1977) has discussed evidence that the most massive stars may form only in regions of large-scale dynamical disturbance or shock fronts. On the other hand, the data in Figure 1 are not consistent with entire normal galaxies having x as great as 3 or as small as 0.2 for stars above 1 $M_\odot$; and the giant-dominated spectra of elliptical galaxies and the central bulges of spirals show that $x \lesssim 1$ for their stars of 0.5 - 1 $M_\odot$ (Whitford, 1977; Tinsley and Gunn, 1976). Thus in spite of localized variations that are of great interest for understanding star formation, the IMF of nearby field stars may be a valid average for most galaxies.

2.2. Non-monotonic star formation rates

Ongoing bursts of star formation greatly affect the colors of some galaxies (Searle et al., 1973; Huchra, 1977; LT). Moreover, sudden enhancements in the star formation rate seem to be correlated with violent dynamical interactions: LT found that interacting galaxies have a much wider color distribution than the sample in Figure 1, and that the most anomalous colors can be interpreted as due to conversion of up to 5% of the mass of a system - i.e. the whole interstellar gas content of a typical spiral - into stars in times as short as a few times 10^7 yr. Bursts of this strength may not be very rare. Toomre (1977) and Vorontsov-Velyaminov (quoted in discussion after Toomre's paper) have estimated that 15% or more of all galaxies have undergone collisions or mergers in their lifetimes. Examples of systems with colors suggesting that a large burst of star formation occurred a few times 10^8 yr ago are NGC 2623 (Arp 243) and NGC 7252 (Arp 226), which Toomre cites as prospects for ongoing mergers because of their extensive tails. It is startling to realize that after only $\sim 10^9$ yr galaxies like these will resemble ordinary ellipticals in both morphology and colors! Some nearby peculiar galaxies such as M82 and NGC 5128 may be undergoing bursts of star formation induced by encounters with clouds of intergalactic gas (Larson, 1976a; Solinger et al., 1977), which again may be a fairly common interruption to the smooth conversion of a galaxy's gas supply into stars. In summary, the frequency of present-day interactions and the short time scale for obvious effects of these to die away indicate that many so-called normal galaxies could have had very disturbed pasts. Star formation may, in many cases, be "monotonic" only in averages over judiciously chosen time intervals.

https://doi.org/10.1017/S0074180900143621 Published online by Cambridge University Press

2.3. Age differences

A number of candidates for young galaxies have been discussed in the literature (Sargent and Searle, 1971; Larson, 1976a), but in all cases 90% of the mass could be in old stars masked by the "terrific splash" (Baade, 1963) of a younger burst, and the chaotic appearance could be due to interactions. There are, however, significant large-scale age differences among stellar populations within galaxies. For example, Demarque and McClure (1977) find that almost all disc stars in the solar neighborhood are $\lesssim$ 1/3 times as old as some globular clusters, and more generally, collapse models (Larson, 1976b) predict that star formation should reach its peak rate much later in the outer parts of discs than in the central regions. Only in integrated light that includes the central bulge are galaxies likely to appear coeval.

3. THE OUTLOOK

Altogether, the apparent success of the "standard scenario" in accounting for integrated UBV colors of most galaxies (Fig. 1) is due to the insensitivity of these colors to parameters other than the total age and the star formation rate in the last 10^9 yr (LT). Population syntheses based on far more detailed photometric data are, unfortunately, not decisively more sensitive to details of past evolution (although they can reveal some interesting components of a galaxy's population). Two general problems are: (1) the light is dominated by stars in late stages of evolution that are poorly understood and insensitive to the ages of their precursor stars; and (2) colors and spectral features are sensitive to chemical abundances, which vary in overall level and in relative proportions of heavy elements (Faber, 1977). Obviously, collisions and other vagaries play havoc with attempts to predict chemical abundances using evolutionary models! We shall therefore have to rely on detailed observations of nearby galaxies to tell us about complications that are smoothed over beyond detection in most cases.

In spite of its superficiality, the simple picture provided by the standard scenario for galactic evolution remains valid and suggestive in that correlations among properties of typical galaxies are consistent with the main variable along the Hubble sequence being the time scale for star formation. Details that are accessible for only a few galaxies point to the frequent occurrence of large deviations from such features of the idealized picture as a monotonic star formation rate, isolated evolution, or an invariant IMF, and some of the most interesting problems ahead are to document and understand such deviations.

I am indebted to Dr. Morton S. Roberts for presenting this paper at IAU Symposium No. 77. This work was supported in part by the National Science Foundation (Grant AST76-16329) and by the Alfred P. Sloan Foundation.

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DISCUSSION FOLLOWING PAPER I.2 WRITTEN BY B.M. TINSLEY

BIERMANN: I would like to mention that at Bonn we have made both theoretical calculations and radio continuum observations for Markarian

https://doi.org/10.1017/S0074180900143621 Published online by Cambridge University Press

galaxies. The evidence supports the viewpoint that bursts of star formation play an important role in the evolution of galaxies (Astron. Astrophys.: 1977, 60, 353).

VAN DEN BERGH: The interstellar gas in NGC 5128 is loaded with dust and the HII regions in it emit strong [NII]. This suggests that the gas in this galaxy contains material that has been processed in stars i.e. it is probably not pristeen intergalactic material. Note that NGC 5128 is an isolated object so one would not expect to observe material swept out of SO galaxies such as is found in rich clusters.

GALLAGHER: I think that you have to be careful about the abundances in the gas in NGC 5128. There is a band of gas across NGC 4278 (Knapp, Kerr and Williams 1977, preprint), but little dust is seen. This suggests that star formation in accreted gas could provide the heavy elements, even though the gas was initially metal poor.

M.S. ROBERTS: We should be cautious in invoking intergalactic HI since we have yet to find such gas except for apparent tidal remnants and the gas in the Sculptor group. The latter is much more complex than described in the discovery paper by Mathewson et al.

VAN DEN BERGH: MULTI-COLOUR OBSERVATIONS OF NGC 5128 (= CENTAURUS A)

In cooperation with R.J. Dufour ultraviolet, blue and yellow plates obtained with the CTIO 4-m telescope have been combined to produce both real-colour (Dufour and Martins 1976, J. Appl. Photogr. Eng. 2, 93) and false-colour photographs of NGC 5128. Each plate used for this work was calibrated using both sensitometer spots and photoelectric UBV photometry at over one hundred positions within NGC 5128 (van den Bergh 1976, Ap.J. 208, 673). Inspection of the real- and false-colour photographs and of composite images produced with the KPNO Image Picture Processing System shows the following:

(1) The main body of NGC 5128 has a brightness profile that obeys de Vaucouleurs' $\sigma \propto R^{-1/4}$ law for elliptical galaxies.

(2) The outer isophotes of NGC 5128 are quite highly flattened and have an axial ratio $b/a \sim 0.7$. The major axis of these isophotes is almost perpendicular to the equatorial dust band.

(3) Active star formation along the edges of this dust band manifests itself by the presence of numerous blue stars, clusters and associations. Some of the reddened stars embedded within the dust band have a distinctly orange colour on true-colour prints. The integrated UBV colours of points within the dust band show that large numbers of hot young stars must be embedded within dust clouds.

(4) The distribution of young stars (see Figure 1) and of HII regions, which were observed with the Yale 1-m telescope, are most easily understood in terms of star formation within a doughnut-shaped volume. This suggests that the dark band that appears to cross NGC 5128 is, in reality, the front side of a ring or disk of absorbing material.

(5) No optical radiation is seen at the positions of the inner lobes of the radio source Centaurus A.

Fig. 1. Ultraviolet plate (103aO + UG2) of NGC 5128 obtained by Dufour in seeing 1-2" with the CTIO 4-m telescope.

ELVIUS: Could the Hα regions (and regions of star formation) which are supposed to be seen through the bulge of NGC 5128 perhaps be connected with the dust clouds seen projected against the bulge?

VAN DEN BERGH: It is always difficult to interpret a three-dimensional structure that is seen on a two-dimensional picture. Continuity arguments and the absence of young stars associated with the "high latitude" dark clouds suggest that the high latitude HII regions and young stars lie behind the main body of NGC 5128, i.e. they form the backside of a ring- or doughnut-shaped region of star formation.

OORT: Have you an explanation of the north-south asymmetry in the number of dark patches projected on the bulge of NGC 5128?

VAN DEN BERGH: I have no idea.