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STAR FORMATION RATE HISTORY OF GALAXIES

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STAR FORMATION RATE HISTORY OF GALAXIES

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Abstract

This paper reviews recent observations of the history of star formation in galaxies, and their implications for models of galaxy formation and evolution.

1 Introduction

Observations of stellar populations in galaxies have begun to reveal in quantitative detail the evolutionary patterns that underlie the Hubble sequence. Data on the star formation histories of galaxies are relevant to a wide range of broader questions: What is the star formation history of the universe, past and future? When did galaxies form, during the final stages of a primeval collapse, or as a continuous or episodic process? What is the evolutionary nature of the Hubble sequence, and what are the physical mechanisms that dictate the present-day Hubble type of a galaxy? Was Hubble type imprinted at birth, or can it be deterined or at least modified by infall, mergers, or secular dynamical evolution within the galaxy? Do low-mass galaxies evolve in a way that is distinct from more massive galaxies? What is the role of starbursts in the global evolution of galaxies?

Thanks to recent advances in both ground-based and space-based instrumentation we are advancing on these fundamental problems on several fronts. Observations of the resolved stellar populations in the Galaxy and the Local Group provide detailed information on the birthrate histories of disk, bulge, halo, and dwarf galaxy populations. Observations of more distant galaxies in integrated light provide cruder information on the systematic trends in star formation history with galaxy type, mass, and radius within individual objects. Observations of galaxies at high redshift are allowing us to observe the past history of star formation directly. These complementary approaches provide an evolutionary picture which can be compared with the expectations from different classes of galaxy formation and evolution models.

In this review I summarize recent progress in observations of star formation histories of galaxies [24], and discuss the implications for galaxy formation and evolution models. Section 2 summarizes observations of resolved stellar populations in the Local Group, while Section 3 describes recent work on the systematics of star formation histories in more distant galaxies. In Section 4 I discuss the results in the context of the traditional closed-box evolution model and contemporary hierarchical infall/merger models. The latter topic is addressed in more depth in a companion review [25].

2 Probing the Fossil Record: Resolved Stellar Populations

The resolved stellar populations in Local Group galaxies provide detailed information on the stellar birthrate histories in a range of populations and galaxy types. They also provide the foundation for testing the less direct indicators of star formation rates and histories in more distant objects.

2.1 The Galaxy

Probably the most exciting (and controversial) work in the last several years concerns the distribution of stellar ages in the Galactic bulge and halo. CCD photometry can provide color-magnitude diagrams for globular clusters with internal precision of 0.01 mag or better, sufficient in principle to measure *relative* cluster ages with an accuracy of $\sim$1 Gyr. This makes it possible to test whether the Galactic globular clusters form a coeval system, and constrain the time scale for the formation of the spheroid.

Recent reviews of this work are given elsewhere [4]. The most convincing evidence for a finite time scale for star formation in the Galactic spheroid comes from differential measurements of pairs of globular clusters with nearly identical compositions but different horizontal branch morphologies— so-called "second parameter" clusters. These comparisons often reveal age differences of up to 3–5 Gyr. The studies to date have often focussed on clusters with the most extreme second parameter effect, so it not certain whether this age spread applies to the halo as a whole or rather represents an extended tail of spheroid formation [4]. However the observations do appear to rule out a single rapid halo collapse on a free-fall timescale [14], and favors the more extended formation picture of Searle and Zinn [43]. There is longstanding evidence from spectral synthesis observations of elliptical galaxies for even more extended star formation in some objects [16].

The Galactic disk shows a very different star formation history, as revealed by several stellar age indicators, including isochrone fitting of stars near the main sequence turnoff, chromospheric dating of late-type stars, and cooling ages of white dwarfs [41], [31]. Although some details remain uncertain, such as the detailed time dependence of the stellar birthrate, the role of starbursts, and the age of the oldest disk stars, the observations are all consistent with a roughly constant star formation rate (SFR) over the history of the disk, with the long-term SFR not varying by more than factors of 2–3. A convenient way to parameterize this history is in terms of the ratio of the current disk SFR to the average past rate, which I denote as b [41]. Values of b near unity correspond to disks with nearly constant SFRs, low values of b would apply to galactic spheroids or disks in which most star formation took place in the past, while a starburst galaxy would be characterized by $b \gg 1$. For the Galactic disk the observations are consistent with $b \simeq 1 \pm 0.5$ [41], [31]. This result already is interesting because the present-day gas fraction of the disk is much lower, $\sim$0.2, yet the SFR today appears to be near the past average value.

2.2 Other Local Group Galaxies

Breakthroughs in CCD imaging and PSF fitting techniques have also made it possible to extend the same types of stellar population studies to the other galaxies in the Local Group. To date the most complete studies have been made of the Magellanic Clouds and several dwarf spheroidal galaxies. These data reveal star formation histories which are strikingly different from either the spheroid or disk of our own Galaxy.

The best studied galaxy outside of the Milky Way is the LMC. Recent deep CCD observations of the field population show evidence for a large increase in the star formation rate (SFR) in the last 4 Gyr [1], confirming the general results from previous photographic surveys. The work suggests that the global SFR in the LMC was quite low during at least the first half of its lifetime, and the most active epoch of star formation has peaked only in the past few Gyr. The LMC also contains a population of massive star clusters that is quite distinct from the Galactic globular or open cluster populations. CCD observations of the populous clusters reveal a bimodal age distribution, with virtually all of the clusters being either younger than 3 Gyr old or older than 12 Gyr [10]. The metal abundance distributions show a similar bimodality. The presence of young "blue globular clusters" appears to be a common property of late-type galaxies, and may be connected to similar differences in the giant HII region populations as functions of galaxy type [26]. The reasons for the absence of 3–15 Gyr old clusters in the LMC are unclear. Massive clusters may not have formed during that period— after all the field stars also show a recent peak in the SFR— or it is possible that some event $\sim$3 Gyr ago disrupted any clusters that may have been present (while preserving the massive old halo clusters). In

any case both the field and cluster populations in the LMC show evidence for a star formation history that was unlike that in any major population in the Galaxy. Data on the SMC are less complete, but suggest a history that is different from either the Galaxy or the LMC [10], [18].

The dwarf spheroidal galaxies in the Local Group tell yet a different story [11]. Studies of several objects (e.g., Sculptor, Fornax, Ursa Minor, Carina, Leo I) show evidence of a composite stellar population, with both a very old ($\tau \geq 13$ Gyr) metal-poor component, and an intermediate age (roughly 5–10 Gyr old) population. The relative fractions of old and younger stars, and the age of the younger component itself appear to be different in each of the galaxies. Among the most interesting cases is Carina, which shows a color-magnitude diagram with an extended main sequence turnoff and at least two distinct horizontal branches, corresponding to ages of ~6 and >10 Gyr [45]. HST observations of Leo I show a turnoff that may extend as young as 1–2 Gyr [32]. In most cases there is evidence for discrete bursts of star formation rather than continuous formation as is typical of the Galactic disk. None of these galaxies is currently undergoing star formation, and none appears to possess enough interstellar gas to form stars today. Thus the transformation of many of these galaxies to early-type systems has been a relatively recent event.

With such a variation between the star formation histories of the individual members of the Local Group— it is probably a fair statement that no two systems studied to date have the same history— one must be cautious about drawing general inferences, but some important trends are apparent. While the general picture of old spheroid and constant-SFR disk may apply reasonably well to the spirals of the Local Group, it fails completely in describing the star formation histories of the lower mass members of the Local Group. Galaxy mass appears to be at least as important a variable as Hubble type in dictating the evolution of a galaxy. The bursting, rapidly evolving histories of the dwarf spheroidal (aka "dwarf elliptical") galaxies probably are more closely related to those of gas-rich dwarf irregulars than to those of giant elliptical galaxies.

3 Studies of Integrated Light: Systematic Trends

For external galaxies only rudimentary information on the star formation history is available. The integrated light is dominated by a combination of young main sequence stars and older disk giants, so the integrated colors and spectra are determined primarily by the ratio of the present to past SFRs (i.e., b). However the more distant galaxies offer the full range of morphological types, environments, and physical properties, so that systematic trends can be studied, and one can begin to explore the physical mechanisms which regulate the global SFR [23]. Several methods have been applied to measure b for large samples of spirals, including modelling of integrated colors in the visible and ultraviolet, and use of integrated Hα emission-line fluxes to measure the SFRs directly [24]. This discussion will emphasize spirals, for which the most information are available.

3.1 Trends With Hubble Type

Figure 1 shows the distribution of the birthrate parameter b for a sample of 210 Sa–Irr disks [27]. Intercomparison of different methods shows that values of b for individual galaxies are uncertain at roughly the factor-of-two level, due to systematic effects of reddening, extinction, the IMF, and short-term variations in the SFR, but this is sufficient to study the quantitative trends in b along the Hubble sequence. The star formation history shows a strong systematic dependence on type, with $b \sim 1$ in the disks of late-type galaxies (Sbc and later), decreasing to $b < 0.05$ in Sa disks (many of the latter measurements are upper limits). This confirms the general observation, manifested in the Hubble classification itself, that the spiral sequence is one of increasing SFR per unit mass and increasingly extended star formation [22], [17], [41], [27].

The birthrate histories in Fig. 1 have been corrected for the effects of bulge contamination, using published surface photometry, so the values of b shown apply to the disks alone. Consequently the pronounced changes in the integrated spectra and stellar populations of spirals along the Hubble

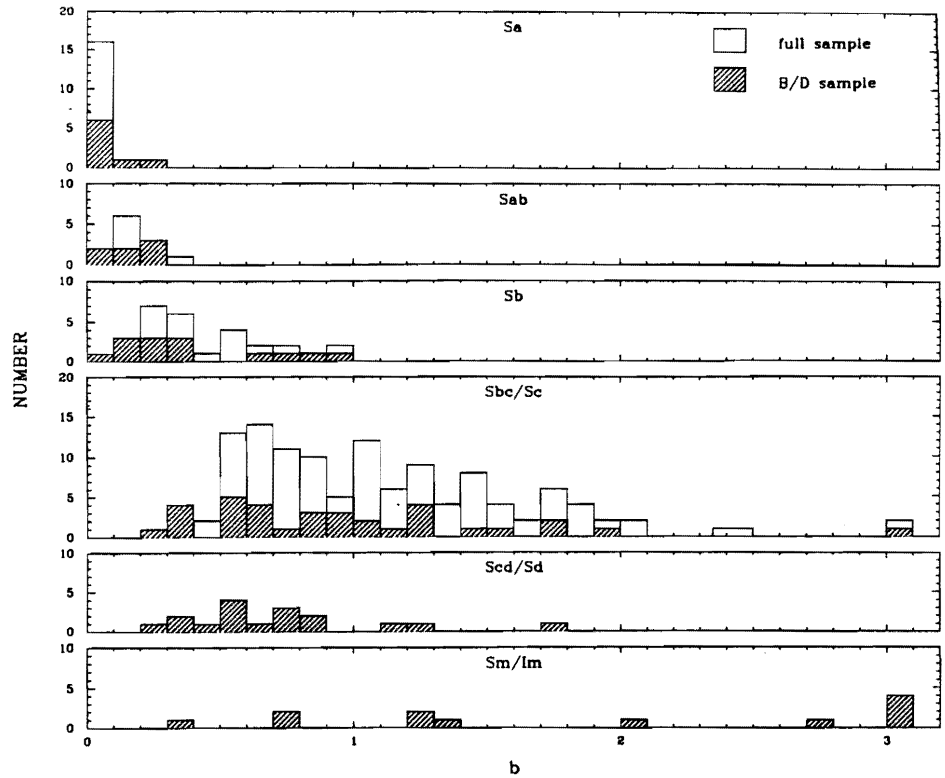

Figure 1: Distribution of birthrate parameter b in disks, subdivided by Hubble type.

sequence are due overwhelmingly to changes in the *disk* star formation histories, with changes to the bulge/disk ratio being much less important. For example between types Sa and Sc the fractional contribution of young stars to the integrated disk population changes by at least a factor of 20, whereas the disk luminosity fraction changes by only a factor of two [44]. The sequence of spiral galaxies photometric and spectral properties would be nearly the same even if their bulges were invisible, though bulges of course may play a pivotal role in causing these changes to disk populations. I return to the physical interpretation of these trends later.

3.2 Trends with Galactocentric Radius

The radial dependence of the star formation history within disks can provide important clues to the physical origin of the type-dependent trends. For example most disk formation and evolution models predict a pronounced "inside-out" evolution due to the higher surface densities and shorter dynamical times at small radii [28]. Until recently little was known about the actual radial variation of the star formation history in spirals, but the advent of wide-field CCD and infrared array cameras now makes it possible to address this problem [12], [46]. Figure 2 shows a composite plot of $B-K$ color profiles for 86 face on spirals, displayed as a function of surface brightness (so radius increased to the right), and grouped by de Vaucouleurs T-type [12]. The galaxies show a wide dispersion in color at any type, and a trend toward bluer colors with later type, consistent with Fig. 1. Most of the disks also show significant color gradients, with bluer colors at larger radii. Similar gradients have been observed by other authors [46], [33].

Several effects can combine to produce color gradients, including a radial variation in the star formation history, gradients in reddening, and metal abundance gradients. Modelling by de Jong [12] suggests that all three effects are important, and this makes it difficult to accurately measure the magnitude of the variation in b. However an independent study by Ryder & Dopita offers strong evidence for radial birthrate gradients, based on a comparison of Hα and I-band scale lengths for 30

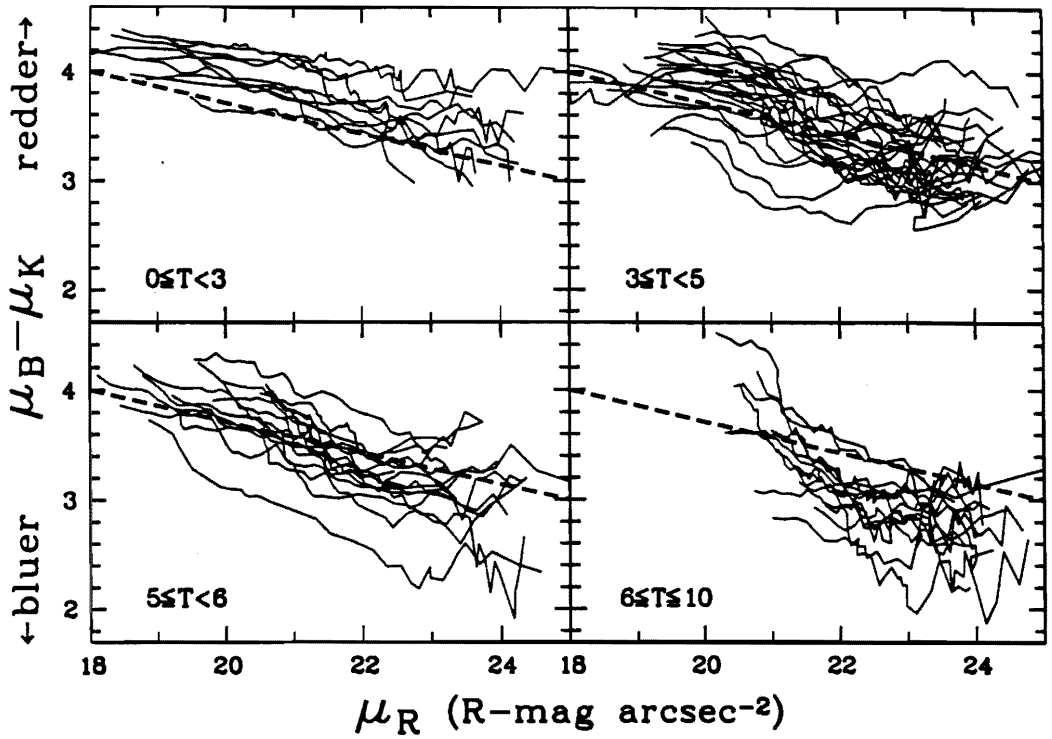

Figure 2: $B - K$ color distributions in spiral galaxies, plotted as functions of surface brightness, and subdivided by RC3 type, from de Jong.

southern spirals [38]. They find that the young disks (Hα) are considerably more extended, typically by ~50% as compared to I. These results are consistent with the colors discussed above, and imply that b increases by factors of up to a few over the extent of the active star forming disks. Note however that these gradients are small in comparison to the order-of-magnitude changes in b observed along the Hubble sequence.

3.3 Trends With Redshift

It is now becoming possible to apply these same techniques to distant galaxies at cosmologically significant redshifts, in order to observe the evolution in the stellar birthrate directly. A thorough discussion of this very active field is beyond the scope of this review, but I briefly describe a few recent results to illustrate the potential power of this approach. Proper reviews of this subject can be found elswhere [15].

Systematic redshift surveys of field and cluster galaxies over the redshift range $z \sim 0$–1 have been ongoing for the past decade. Modelling of the number counts, broadband colors, and spectra of these objects has revealed evidence for substantial evolution in both field and cluster populations. However the absence of morphological information on galaxies beyond $z \sim 0.2$ has made it difficult to associate these distant populations with their corresponding descendents among present-day galaxies. However the superb imaging capabilities of the *Hubble Space Telescope* now makes it possible to compare the star formation properties of the distant and nearby populations directly.

An example is shown in Figure 3, which compares the distributions of the birthrate parameter b for spirals in the $z = 0.41$ cluster CL0939+4713 with those of nearby rich clusters and the nearby field. I generated these approximate distributions by using our synthesis models for b as a function of corrected $B - V$ color [27], as applied to published colors for CL0939+4713 from *HST* observations by Dressler *et al.* [13] and for nearby clusters from the compilation of Butcher & Oemler [8]. The

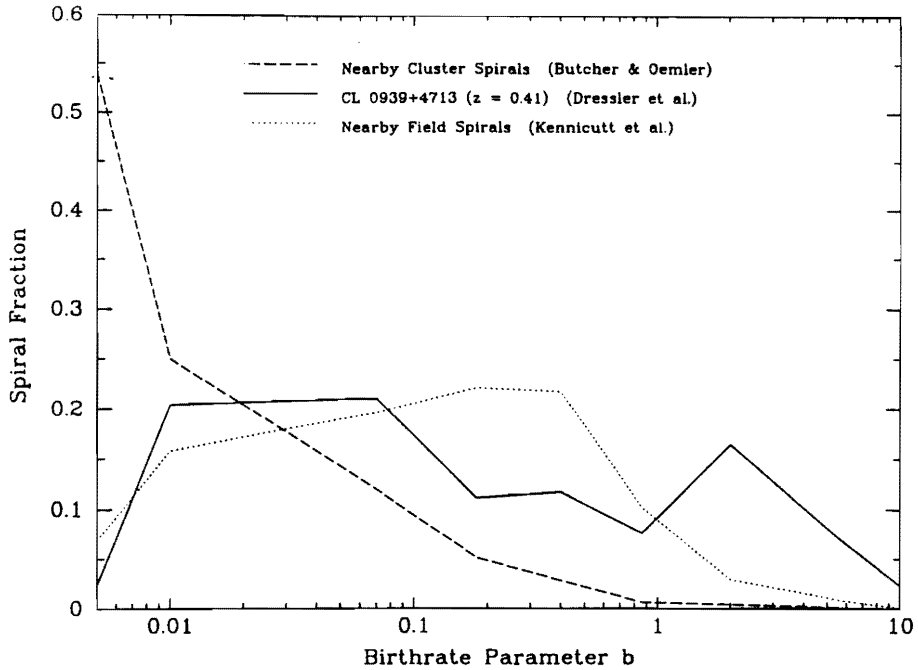

Figure 3: Comparison of approximate distribution of birthrate parameter for spiral galaxies in the distant cluster CL0939+4713 compared with nearby rich clusters and nearby field spirals. Note the logarithmic birthrate scale.

distribution of b for field spirals was taken directly from our own study [27]. The comparison shows a quantitative depiction of the well-known Butcher-Oemler effect, namely a strong excess of blue star forming galaxies at high redshift. The data show that most of the B-O effect is not due to an excess of starbursting galaxies— indeed the cluster population at $z = 0.41$ bears a remarkable resemblance to the *present-day* field spiral population— but rather it is due to an abrupt curtailment of star formation in cluster spirals in the past several Gyr [13]. This is an example of a spiral population that evolves quite differently from the smooth exponential evolution that usually assumed for disks, presumably because of changes induced by the cluster environment. While only very preliminary this comparison illustrates how we should be able to apply these techniques to directly study the evolution of the stellar birthrate with cosmic time in different classes of galaxies.

4 Implications for Models of Galaxy Formation and Evolution

4.1 Conventional Interpretation: Passive Closed-Box Model

These birthrate histories are usually interpreted in the context of a passive closed-box model, in which the stellar birthrate is assumed to decline slowly with time (usually parameterized with an exponential time dependence). This model implicitly assumes that most disks accreted their material at early epochs, and that the differences in subsequent evolution along the Hubble sequence are due to physical differences in the properties of these proto-disks.

The simplest version of this picture treats disks as systems with identical ages and IMFs, varying only in the e-folding time of the SFR. Such models have been used to synthesize the colors, Hα emission, ultraviolet continua, and integrated spectra of nearby galaxies [22], [27], [7], [6]. A schematic illustration of this scenario by Sandage [40] is shown in Figure 4. This simplistic model is remarkably successful at reproducing the integrated spectra of galaxies over a wavelength range extending from

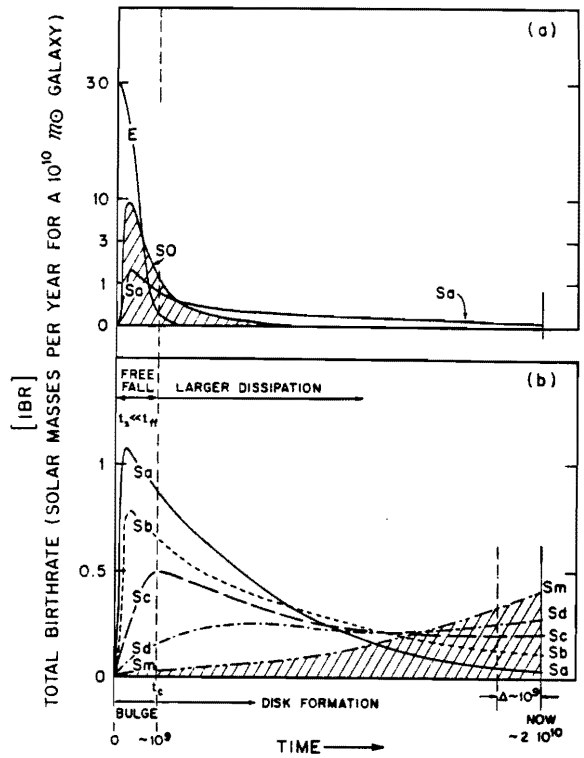

Figure 4: Schematic interpretation of the observed star formation histories of disks, from Sandage.

the ionizing UV to the near-infrared. The same model predicts a relatively modest evolution in the photometric properties of intermediate to late-type spirals with lookback time, which appears to be consistent with the statistics of luminous spirals from redshift surveys and the statistics of Mg II absorption-line galaxies.

Given these successes why should one be dissatisfied with the closed-box picture at all? Perhaps the most disconcerting problem is the lack of any physical basis for why the disk star formation histories should vary so strongly with parent galaxy type [27]. The parameter thought to be most important for regulating the SFR locally is gas density, and one is tempted to associate the rapid evolution of early-type disks with higher initial densities. However the characteristic scale lengths and surface densities of disks show no strong dependence on Hubble type in the range S0–Sc. Furthermore if the timescale for star formation were dictated by the local density, we should expect to observe very strong radial gradients in stellar populations within disks— the inside-out evolution predicted by many models— but in fact the radial variations in b appear to be much *smaller* than the type-to-type trends. Hence gas density does not appear to be the primary driver of the star formation history, at least not in the context of a closed-disk model. Closed-box models also have well-known difficulties in reproducing the observed metal abundance distributions and radial abundance gradients in disks.

Hence we are forced to conclude that either the closed-box assumption is invalid, or that a physical mechanism other than the Schmidt gas density law is responsible for the strong changes in star formation timescale along the Hubble sequence. Early-type spirals possess large central bulges, and the bulges might influence the disk SFR in several ways: by increasing the angular rotation speeds in the inner disks and stimuating star formation; by raising the threshold density for star formation at later epochs; or by inducing strong spiral density waves at early times. Or the differences may be connected to the systematic trend toward higher galaxy mass among early-type systems. Yet another mechanism which has attracted some attention is secular dynamical evolution of spirals, for example the formation of a bulge from a bar instability [34]. This could transform a spiral from a late to an earlier Hubble type within the context of a closed-evolution model.

4.2 Revisionist Interpretations: Infall, Captures, Mergers

In a hierarchical model of galaxy formation one would not expect galaxies to evolve as closed systems at all, and indeed it is conceivable that the present-day Hubble type of a spiral could be largely dictated by its disk accretion or merger history. Here we discuss models for accretion-driven spiral galaxy evolution, including infall models, in which the accretion of gas is continuous, and merger models, in which disks grow by the capture of discrete clumps of gas and stars.

Infall can solve several of the problems alluded to earlier, extending the star formation timescales of late-type galaxies and more readily explaining the abundance distributions and gradients in disks. However recent observations appear to limit the amount of infall to rates which are well below the present-day SFRs in massive spirals. HI measurements reveal no large reservoirs of cold gas, and the inflow rate from high-velocity clouds in the Galaxy is several times smaller than that needed to sustain the current SFR [30]. Perhaps the strongest limit comes from the soft X-ray luminosities of spirals [48]. *ROSAT* observations of nearby spirals yield diffuse X-ray luminosities that are several times smaller than the values expected from a cooling flow if the infall rate were equal to the gas depletion rate from star formation. Hence an extreme spherical infall model appears to be ruled out. However some fraction of the star formation could be fueled by infall or by a radial inflow of HI from the outer disk.

These constraints can be avoided if the accretion of gas takes place in discrete events, such as by the merger of a spiral with a companion or satellite galaxy. Indeed such hierarchical growth is a fundamental consequence of many galaxy formation models [48], [21]. A serious problem with this picture however is the observed thinness and dynamical coldness of disks. Numerical simulations show that much of the dynamical friction loss in a merger is converted into thermal energy of the disk. Tóth & Ostriker have estimated that no more than 4% of the mass of the disk within the solar radius could have been accreted in the last 5 Gyr [47]. These results appear to rule out recent mergers of *stellar* systems (e.g., satellite galaxies) as the predominant mechanism for assembling disks, but these limits may not apply to the accretion of largely gaseous (dissipative) material.

A very exciting development in this field has been the discovery of numerous examples of disks with distinct kinematic subsystems in stars and/or gas, which must represent the products of at least two discrete accretion events. Polar ring galaxies represent the best known and perhaps the best studied examples of multiple kinematic subsystems in spirals [49]. Multiple kinematic components in a coplanar disk are more difficult to detect, but two spectacular instances of such disks are now known. The disk of the edge-on S0 galaxy NGC 4550 is comprised of two counterrotating components with nearly identical masses and scale lengths [37]. In the normal Sb galaxy NGC 7217 20–30% of the disk stars are in a retrograde cold disk [29]. The most frequently observed instances of counterrotation involve gas disks counterrotating with respect to the stars [2]. In most instances the gas is confined to low-mass nuclear disks, but in at least two cases, NGC 4526 [3] and NGC 3626 [9] the counterrotation extends over the entire disk and the gas masses are of order $10^8 - 10^9\ M_\odot$. NGC 4826 (M64) represents yet another class of system in which the rotation of the gas disk reverses itself, at a radius of $\sim$1 kpc, coincident with its prominent dust lane [5]. These galaxies demonstrate that it is possible to form a stable counterrotating disk without violating the disk heating constraint. Such systems may form from two distinct generations of disk accretion and star formation, or by an extended period of infall in which the angular momentum of the accreted material undergoes a rapid change [35], [29].

Evidence for actual infalling gas in nearby spirals comes from a variety of sources [39]. High-velocity HI clouds with masses of up to $2 \times 10^8\ M_\odot$ have been detected in M101, NGC 628, and NGC 6946 [20]. High-resolution HI observations of other objects reveal large-scale kinematic structures in the form of massive arms and arcs of gas that may still be settling into disks. Infalling ionized gas has been observed in the early-type spirals NGC 4258 and NGC 4826 [36]. Dynamical modelling of mergers suggests that a steady infall of gas can persist for billions of years after a merger [19].

The many examples described above indicate that episodic accretion does play a significant role in disk evolution, and that significant accretion can take place without disrupting or overheating the disks. However these types of subsystems probably comprise no more than a few percent of the

present-day mass of disks. Rix and Kuijken (private communications) have completed surveys for stellar counterrotation of the type seen in NGC 4550 for ~30–40 S0 and spiral galaxies and have failed to detect counterrotation in any, implying upper limits of a few percent on the fraction of retrograde stars. Similar fractions are derived from polar rings [49]. Counterrotating gas disks may be more common, but the masses involved are rarely more than a few percent of the total disk mass. These numbers are reminiscent of the limits based on disk heating derived for the Galactic disk [47].

These results may have important implications for current models of galaxy formation. In an $\Omega = 1$ CDM model most L^* galaxies experience major halo mergers over the past few Gyr [21], and even if only a fraction of these events lead to stellar/gas disk mergers the predictions would appear to be in conflict with the observations described above. On the other hand in an $\Omega = 0.2$ model most of the galaxy assembling occurs at early cosmological epochs, and the fraction of recent mergers, of order a few tens of percent or less, is in reasonable accord with the observations of disks. While hardly conclusive this example illustrates the importance of disk galaxies in constraining the merger rate and the nature of the galaxy formation paradigm.

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