THE STAR FORMATION HISTORY OF LOW REDSHIFT SPIRAL GALAXIES

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Abstract.
Recent results on the star formation histories of nearby spiral galaxies do not conform to the classical view of how such systems evolve. Bulges have a range of light-weighted ages and are probably strongly influenced by the inner disks. Disks probably do not have a smoothly monotonic, exponential star forming history but do show a remarkable degree of regulation over time scales with a ratio of 1000:1. UV observations are especially valuable in probing dynamical control of star formation in disks on time scales of 50-500 Myr.

INTRODUCTION

The star forming history of nearby spiral galaxies is a subject which probably hasn't received the attention it deserves. One problem is intrinsic: spirals contain two distinct but interacting components, a bulge and a disk, with very different dynamical properties and star formation histories (SFH's). They are correspondingly more complex than elliptical or pure-disk systems. Another difficulty is technical: because nearby spirals subtend large angles on the sky, it is hard to obtain global information on them, especially spectroscopy. In this sense, it is actually easier to study high redshift systems. Only recently has global spectroscopy become available for a large sample of nearby spirals (e.g. [1]). A final impediment is more sociological. Many astronomers tend to regard spirals as a "solved problem", apparently because there are robust methods of estimating the *current* star formation rate (SFR) in spirals. But this is not at all the same thing as determining the star formation *history* over a Hubble time.

Consequently, information is actually growing faster about spirals at high redshifts than about their low redshift counterparts. Even so, I cannot hope to provide a comprehensive review of low redshift studies, especially those of the Galaxy itself. For that subject, let me just refer to the fine reviews in [2–5]. Instead, I will give here a selective review of some work which bears on the viability of our basic prejudices concerning the evolutionary history of other large spiral galaxies.

I PROBING THE STAR FORMATION HISTORY OF SPIRALS

The classical picture of spiral evolution derives largely from the seminal paper of Eggen et al. [6] and the early consensus on stellar populations developed at the Vatican Conference [7]. Spiral bulges were thought to have formed rapidly, early, and nearly synchronously, independent of their environments. After the bulge stabilized, little gas remained to fuel later star formation (much may have been expelled by winds). Disks were imagined to have formed later, under more quiescent circumstances in which significant amounts of gas survived for long periods. This was thought to be smoothly consumed in a process with a time scale which varied from system to system but which was usually taken to have an monotonically decreasing, exponential time dependence (e.g. [8]). In this picture, bulges may influence disks, especially through control of the rate of gas consumption in the disk [9], but disks should not have significant influence on bulges.

How well does the evidence for spiral systems which are too distant for the study of individual stars agree with the classical picture? Though structure and kinematics provide some insights into history, the most useful information is found in the integrated spectral energy distribution (SED) of the galaxies. But this is less easy to extract than is often supposed. The SED of a single generation of stars is only logarithmically sensitive to its age. That is, conventional measures (Q) of the SED such as colors or line indices tend to scale as $Q \sim a + b \log t$, where a and b are constants. This means that we should imagine the history of a galaxy as a set of bins of *constant size in* $\delta \log t$ stretching from the present to a lookback time of ~15 Gyr. The SFH is then described by the mass of stars formed in each bin. The $\log t$ binning implies that much less information will be available on the details of the early SFH than on more recent times. The size of the bins, and hence the detail which can be discerned in the SFH, is governed by the amount of stellar population information (not equivalent to spectral information) present in our SED measures. That in turn is determined by the number of data points, the spectral resolution, the wavelength baseline covered, and the photometric precision of the measures [10].

With this perspective, it is evident that the most ubiquitous type of SED information available, namely broad-band colors, can provide only limited constraints on the SFH. Two colors, e.g. $U-B$ and $B-V$, yield at most only two logarithmic resolution cells over the last 15 Gyr. Many different types of histories can be consistent with a given pair of broad-band colors. That is, broad band colors are often degenerate with respect to the SFH. Examples of color degeneracy for SFH's characterized by smooth functions, bursts, and quenching have been discussed in [11–13].

One of the first studies to characterize SFH's of spirals this way was that of Gallagher et al. [14]. They analyzed galaxy histories on three very different timescales. The mean SFR over a Hubble time was determined from the total mass of the galaxies. The mean SFR over the past few Gyr was estimated from the integrated B-band (λ4400) luminosity. And finally, the mean SFR over the lifetime of massive ionizing stars was probed by the strength of the Hα emission line. Since the ionizing flux from a population with a standard IMF declines by a factor of 10 after only 5 Myr, Hα effectively probes the instantaneous current SF rate. Gallagher et al. found that the SF rates for irregular galaxies were nearly constant over these three epochs but that spirals seemed to have experienced an early burst of star formation (or contained dark matter). Most other studies of spiral galaxies do not provide much more information on histories than this kind of few-epoch comparison.

II HISTORIES OF SPIRAL BULGES

A straightforward prediction of the classical picture is that the bulges of different spirals should have very similar properties (apart from metallicity effects), characteristic of very old populations, and may differ substantially from their surrounding disks. There is considerable debate as to whether this is true of the nearby bulges in which one can study individual stars (e.g. [15]). For other galaxies, the evidence seems to contradict this expectation.

The first discussion of this subject was presented by Morgan and his collaborators [16,17], who had earlier demonstrated that spiral bulges were not pure Pop II systems as had been proposed by Baade in 1944. Morgan found that most small bulge spirals (types $\gtrsim$ Sbc) have strong spectroscopic signatures (F–G spectral types) of nuclear star formation over the past $\sim$ 2 Gyr. The relative youth of the spectra is inversely related to the overall prominence of the bulge (L_{bulge}/L_{tot}). Later quantitative analysis of SED's by Turnrose [18] confirmed this result in late type spirals. An alternative interpretation of these bulges as very old but metal poor systems similar to globular clusters was excluded by high S/N spectra and colors [19–21].

Strictly speaking, the youthful stars found in these studies lie within the volume of the bulges but are not necessarily part of the dynamical bulge itself. It would be important to test their spatial distribution. However, it does seem clear they are a long-lived phenomenon, unrelated to recent starbursts for instance, and that they are not simply the product of normal disk-like star formation extended to the galaxy centers.

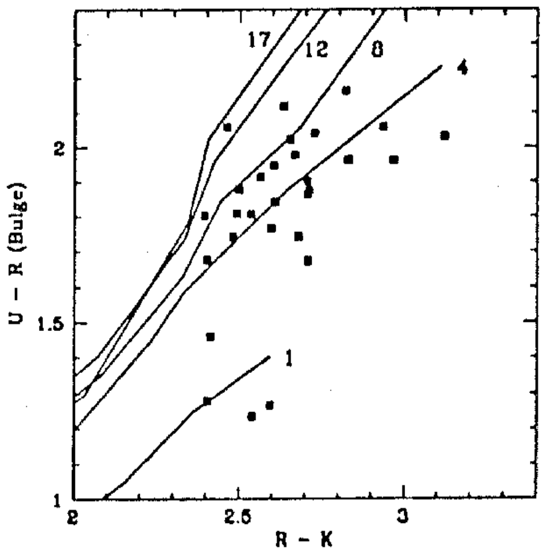

FIGURE 1. Two-color plot for spiral bulges from [26]. In the classical picture, bulges should show a small range of color consistent with large ages. That is clearly not the case here. Synthetic isochrones (lines), labeled by ages in Gyr, are from recent models [27], and indicate a large age range for the bulges here.

The bulges of earlier type galaxies (Sa–Sb) are outwardly more homogeneous; most were classified as having "K"-type spectra by Morgan, for instance. Photometrically and spectroscopically, however, they exhibit more scatter than do E/S0's, and there are some clear cases of young populations [22–25]. A difficulty is that the effects of dust extinction are particularly important here, where the intrinsic range of SED may be smaller.

Recent multicolor CCD observations of spiral bulges permit an improved treatment of extinction. Peletier & Balcells [26] minimize the dust effects by using special synthetic apertures. They claim that earlier work on the homogeneity of spiral bulges was strongly influenced by extinction, which tended to produce red, "old" colors. They find a significant range in bulge SED properties using several optical/IR colors in a sample of 30 S0–Sbc objects. They also find that the bulge-disk color differential is small in a given galaxy. They conclude that the histories of bulges and disks are not independent and that the mean age differential between bulges and disks is small, $\delta \log t \lesssim 0.1$. The range in bulge colors (see Fig. 1) implies a large range (1–15 Gyr) in *light-weighted* bulge ages. Fagatto et al. [28] have independently examined the problem of extinction in bulges and reach similar conclusions about the range of bulge ages based on intrinsic colors.

The "Morgan effect" therefore suggests that spiral bulges are not uniform structures, that their stars were not produced at a single early epoch, and that bulges and disks probably influence one another. There is no doubt that spiral bulges can form at very early epochs (Dressler, this conference). After formation, however, external circumstances such as mergers or stripping can clearly induce a wide variety of evolutionary histories (e.g. [12,29–32]). The spiral bulges being discussed here may have been influenced more by *internal* processes in which disk material is secularly converted into bulge material by dynamical interactions with the bulge potential well [33]. The moderate starbursts identified in nearby barred spirals (Kenney, this conference) demonstrate that the sheer gas processing rate necessary to build bulges on short time scales (a few Gyr) is available at the present epoch. The resulting changes in galaxy structure, perhaps even in Hubble type, may contribute to the dispersion seen in the Hα-color correlation discussed below. There is also good *kinematic* evidence that in many cases disk material is being converted to bulges. This was reviewed by Kormendy [34], who states, "By type Sc, I do not believe that any galaxies contain true [i.e. classical] bulges."

Could some bulges form late, e.g. at the intermediate redshifts $z \sim 0.5$ suggested if the dating in Fig. 1 is correct and does not result from secular evolution? Probably they could. Evidently, the mild starburst activity involved in current-day bulge building as described by Kenney does not result in galaxies which look very peculiar. The same would be true of initial bulge formation if the central star formation rate were less than $\sim$10 $M_\odot$ yr^{-1}. Such systems would have bright centers or inner disks but would not necessarily be seriously disrupted objects like those associated with massive starbursts. The best available cases of earlier ($z > 2$) galaxy formation show surprisingly modest rates of star formation near or below this level (Madau, this conference).

III HISTORIES OF SPIRAL DISKS

A Ionized Gas and Star Formation Regulation

Is the star formation history of spiral disks the smooth, monotonic function expected in the classic picture? My own view is that the functional form of the SFH in spirals hasn't been determined yet, but that nonetheless emission line data does imply the existence of strong global regulation in spiral disks. There would seem to be good reason to doubt this. One of the remarkable results to emerge from the rapidly increasing volume of digital images of resolved galaxies in the Local Group is the widespread evidence for *strongly discontinuous* star formation histories in the form of bursts or accretion events. This was anticipated nearly 20 years ago by Butcher's [35] study of the LMC field, and the most beautiful recent example is the multiburst Carina system [36]. Most objects showing such discrete episodes of star formation are small galaxies—low luminosity or dwarf. These are easily disturbed by larger neighbors and are more likely to suffer quenching of star formation by expulsion of their

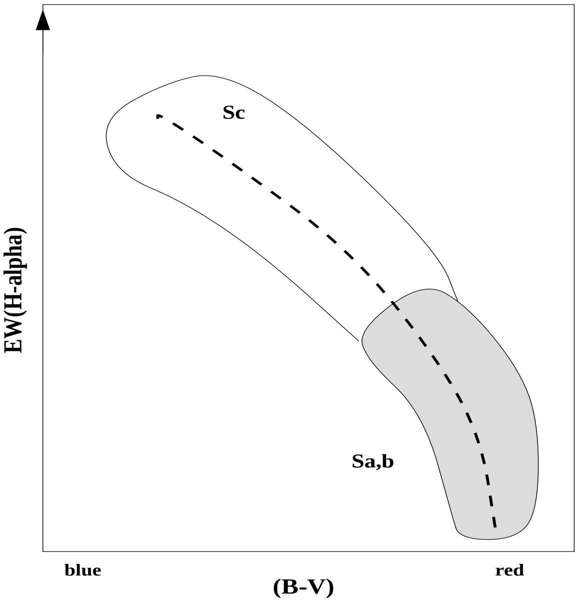

FIGURE 2. Schematic correlation between the global equivalent width of Hα and (B–V) color in spiral galaxies, after [42]. The dashed line shows a typical fit with an exponentially-declining SFR.

interstellar media following a star forming episode. But size is not the determining factor, since the Milky Way disk itself shows evidence of at least 3 discrete bursts of star formation near the Sun over the past 9 Gyr (reviewed in [5]). Of course, we do not know over what fraction of the total disk such events might remain coherent. The superposition of many incoherent bursts, smoothed over the time resolution of our analysis techniques, may be nicely monotonic.

Evidence for global regulation comes mainly from ionized gas studies. This subject has not changed much since the earlier review by Kennicutt [37], but I approach it from a somewhat different angle here. There is a good correlation between the prominence of Hα or other strong emission lines and the integrated color or spectral type of bright spiral galaxies. This was evident, for instance, from the spectroscopic survey of Humason et al. [38] and from early photoelectric studies [39]. The definitive work on this subject is by Kennicutt and collaborators [40–42]. The composite Hα-(B–V) correlation from these studies is shown in schematic form in Figure 2; both quantities refer primarily to the disks, not bulges, of the galaxies. There is significant scatter within each morphological class and at any color, but the general correlation is quite good.

This correlation has conventionally been interpreted in the context of exponentially-declining star formation histories. The e-folding times needed are in the range 1 Gyr–∞, and the fits are generally good, as suggested in the figure. But this diagram is actually *not* a good test of the *shape* of the star formation history. The Hα equivalent width is a measure of the current SFR compared to the mean past rate, and while (B–V) responds to the mean rate over the past few Gyr, it is quite insensitive to the detailed structure in SFR(t) over that period. In other words, a wide variety of non-exponential SFH's could be consistent with the observed correlation.

The inappropriateness of the monotonically declining exponential SFH is emphasized by another well-established result from the Kennicutt studies. Using several indicators of the mean past SFR, one can compute b, the ratio of the current SFR to the mean past SFR. In many galaxies of type Sbc or later, $b > 1$ [42]—i.e. the disk is presently experiencing enhanced star formation possibly like the irregularities detected in nearby resolved galaxies.

Even if the correlation of Fig. 2 does not establish the shape of the SFH, it does demonstrate a remarkable degree of regulation in the global star formation rates because the two axes in the diagram measure star formation rates over time scales which differ by a ratio of about 1000:1! The correlation implies that the SFR over the past 5 Myr (as measured by Hα) can be used to infer the SFR during the past 500-5000 Myr. The fact that there is any correlation at all implies a strong degree of global regulation in disk SFR's. The correlation cannot be produced unless a large fraction of the disk participates. My impression is that the kind of coherence necessary to explain Fig. 2 is not realistically achieved by existing theoretical models for star formation in disks. If so, then I think the problem merits being called the "regulation mystery".

B UV Studies of Disk Histories

The vacuum-UV provides an important opportunity to extend our probes of the SFH to timescales intermediate between those discussed so far (either very short or very long), namely 50-500 Myr, which are the times over which the 1000–3000Å light of a single generation of stars will decay.

UV brightnesses can be used to estimate the mean SFR over the past few 100 Myr [43–45]. Since this is derived from the stellar continuum, rather than from ionized gas, it is an important complement to the emission line methods. Extinction by dust is often cited as an impediment to UV continuum methods, but gaseous ionization, being driven by the Lyman continuum, is comparably sensitive to dust. Good correlations have been found in spiral disks between UV-derived global SFR's and μ, the total gas surface density (H I plus H_2) which show that SFR $\sim \mu^{1.6}$ [46] . The correlations with either atomic or molecular gas alone are less good. In terms of the time dependence of star formation, one can compare the emission line to UV continuum measures to examine changes over the last ~100 Myr [43] or derive UV-optical colors to compare time scales of a few 100 and a few 1000 Myr [44,45].

Of particular interest for the regulation problem are imaging studies where

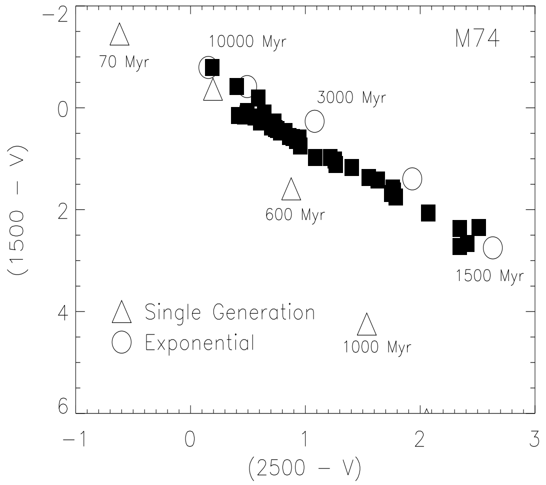

FIGURE 3. UV surface photometry of the Sc M74 obtained by UIT plotted in a UV/optical 2-color diagram, after [51]. Galaxy data are solid squares, with smaller radii to the right (redder colors) and larger to the left. Triangles and circles are single generation models and exponentially-declining models, labeled by age and e-folding time, respectively.

the UV structure of galaxies can be spatially resolved and gradients can be analyzed. The FOCA and UIT experiments have produced multiband UV continuum maps of a number of prominent spirals, including M33, M51, and M81 [47–50]. From our Astro-1/UIT images, we have studied gradients in the SFH across the face of the Sc I galaxy M74 [51]. Most of the far-UV light does not originate in young, compact H II regions but rather from a more diffuse, presumably older, component. We have compared surface photometry in two UV bands and one optical band to various models (Figure 3). There is a large change in UV color with radius. We believe this is neither a metallicity nor extinction effect, nor does it simply reflect the run of the current SFR or gas density with radius. Instead, it measures changes in the history of the SFR. The entire disk has undergone star formation during the past $\sim$ 500 Myr, but the inner regions have experienced more rapidly declining star formation than the outer regions. If the models are taken at face value, then no part of the disk has experienced a constant SFR (corresponding to an e-folding time of ∞), and the SFR has declined more steeply than an exponential.

What is surprising about the diagram is not that the SFH changes with radius but that it exhibits such a remarkably organized pattern of change. The smooth change with radius removes some of the ambiguity affecting SFH interpretations based on global quantities. For instance, it excludes strong recent bursts of star formation superposed on a strictly old population, which might explain any single point on the M74 locus but can't plausibly reproduce the whole well-behaved correlation. Different galaxies, e.g. M33 and M81, present

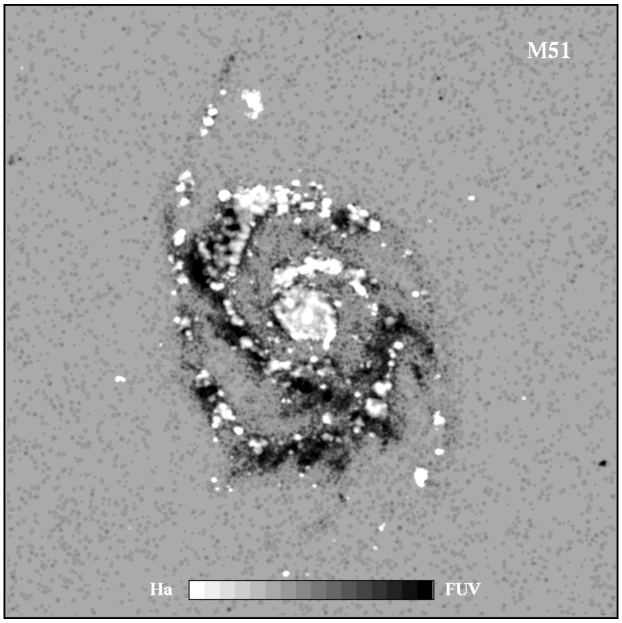

FIGURE 4. An Hα-far-UV difference map of M51 based on Astro-2/UIT images with FWHM $\sim 4''$. The grey scale displays the logarithmic difference between the two bands, with lighter areas being relatively brighter in Hα. The perturbing companion galaxy (NGC 5195) at the top of the image is completely absent in the far-UV.

different disk loci in such diagrams [51]. These have not yet been interpreted, but they are probably important clues to the regulation mechanism.

Such UV maps of the SFH over the past ~ 1000 Myr can be used to relate star formation to dynamics. It is presumably density wave forcing and radiation and gas pressure feedback from young regions that act to produce these examples of star formation regulation. The time scale sampled by the UV is particularly relevant to density wave effects since the period between density wave passages for material in spiral disks is ~ 50–500 Myr. Using Hα and UV maps, the relationship of star formation on short and intermediate timescales to density waves, molecular and atomic gas, far-IR radiation, and other relevant properties can be examined in detail. A nice example is the nearby Sc spiral M51. Figure 4 shows an Hα/far-UV difference image of M51 derived from our Astro-2/UIT data [52,53]. A similar map with lower resolution was published by the FOCA group [54,55]. One can see how the ~ 50–100 Myr year old populations are usually spread farther downstream from the density wave than the ~ 5 Myr-old, Hα bright populations. There are significant differences in the population pattern with position in the galaxy, however, which are presumably related to the tidal interaction which is strongly influencing the density wave structure (e.g. [56]).

If we think of galaxy evolution in Darwinian terms, it may not be surprising that star formation in large spiral disks is well regulated. Because cool interstellar gas at the densities which prevail in spiral galaxies is explosively unstable to star formation in the presence of strong pressure gradients, the thin, relatively quiescent disks we see in current epoch spirals are selected for their survival characteristics. However, I think we don't understand very well *how* the regulation is enforced or how it is to be reconciled with the discontinuous star formation histories revealed in smaller galaxies and even in the Milky Way disk.

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