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STAR FORMATION COHERENCE IN SPIRAL GALAXIES [1]

J. S. Gallagher
Dept. of Astronomy, 5534 Sterling, University of Wisconsin, Madison, WI 53706-1582, USA
and
Paul A. Scowen
Dept. of Physics & Astronomy, Arizona State Univ., Tyler Mall, Tempe, AZ 85287-1504, USA

RESUMEN

El ancho equivalente de Hα en emisión proporciona una poderosa herramienta de diagnóstico evolutivo para galaxias, al permitir comparar las tasas de formación estelar recientes con las de los pasados Giga años. Existen variaciones substanciales en los anchos equivalentes de Hα de las espirales con similares colores ópticos, sugiriendo que las variaciones a corto plazo, en la tasa de formación estelar, son comunes. Esto puede deberse a una variedad de factores y en este trabajo se explora el papel que los procesos de formación estelar, coherente en gran escala, pueden tener al producir variaciones a corto plazo de la tasa de formación estelar. Ilustramos algunas de estas posibilidades con nuevas imágenes de la galaxia Sc gigante M101 obtenidas con el *Telescopio Espacial Hubble.*

ABSTRACT

The Hα emission line equivalent width provides a powerful evolutionary diagnostic for galaxies by comparing recent star formation rates (SFRs) to those during the past several Gyr. Substantial variations exist in Hα equivalent widths for spirals of similar optical color, suggesting that substantial short-term variations in SFRs are relatively common. These could result from a variety of factors and in this paper we explore the role which coherent star formation processes on large scales might play in producing short-term SFR variations. We illustrate some of these possibilities with new *Hubble Space Telescope* imaging observations of the giant Sc spiral M101.

Key words: **GALAXIES: SPIRAL — GALAXIES: EVOLUTION — H II REGIONS**

1. INTRODUCTION

In this paper we exploit H II regions as tracers of the locations and levels of recent star forming activity with the goal of understanding short term variability in galactic star formation rates (SFRs). Since we cannot see individual galaxies evolve, we rely on statistical properties of samples of galaxies to determine how SFRs vary. We use Hα luminosities of galaxies L(Hα) to measure current SFRs. The meaning of "current" in this context is not trivial to define, but probably lies between the time scales for supergiant H II complexes to evolve ($\leq 10^7$ yr) and galactic dynamical time scales of $\approx 10^8$ yr (e.g., Gallagher, Hunter, & Tutukov 1984).

Our approach is based on the idea that star forming regions have characteristic coherence times which define a single star-forming event. This is consistent with the standard view of star formation as a locally episodic process. The coherence time is also related to the size of a star forming region; larger time scales allow larger complexes to form stars (Elmegreen et al. 1994)

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The next section of the paper reviews observational evidence for short-term fluctuations in the SFRs of giant spiral galaxies. Unlike the situation for dwarf irregular galaxies, where ample evidence exists for large amplitude star bursts (e.g., Gallagher & Gibson 1993), the evolution of spirals over short time scales is less well explored. In § 3 we consider the scales of star formation in spiral galaxies and illustrate these points in § 4 with images of M101 obtained with the Wide Field Planetary Camera 2 on the *Hubble Space Telescope*. Results are discussed in § 5.

2. STAR FORMATION RATES IN SPIRAL GALAXIES

What are perhaps the simplest models of galactic evolution have star formation laws which depend only on the gas density ρ_g via a Schmidt relationship, $SFR = A\rho_g^n$ where A is a constant and $n \approx 2$. In such a model, if the gas is not influenced by star formation and assuming the simplest one-zone approximation in which the total stellar + gas mass density remains constant, the SFR declines smoothly with time. Deterministic evolutionary models have been very successful in describing some of the most basic features of galactic stellar populations (e.g., Sandage 1986; Kennicutt 1992), but are obviously incomplete in some areas; e.g., the existence of starbursts (Sandage 1963; Larson & Tinsley 1978). Thus the current quandary: how well do the monotonically declining SFR models describe the current behavior of galaxies?

An early and excellent formulation of this issue was provided by Searle, Sargent, & Bagnuolo (1973) who discussed the statistical effects which might be associated with the discrete nature of star formation. The Searle et al. model galaxies contain N discrete "cells" which can independently form stars. Small galaxies have few cells, and are subject to large statistical excursions in the number of actively star-forming cells and thus in the global SFR. Large galaxies have many cells and little statistical noise in their SFRs. Statistical models were extended by including the possibility of star formation in one cell stimulating activity in surrounding locations (Seiden & Gerola 1982). The propagating star formation models also show that large SFR fluctuations should be most common in small galaxies.

These models appear to agree with many observations. Among isolated galaxies, large ranges in the current SFR are most obvious in small dwarf galaxies and this aspect of SFR fluctuations has received considerable attention (see Melnick 1992 for a recent review). Conversely, the statistical models predict that giant, normal galaxies should have relatively small amplitude variations in short term SFRs.

What is the observational situation for giant galaxies? Broad band optical colors depend on SFRs averaged over time scales of $\geq 10^8 - 10^9$ yr, and these are consistent with smooth evolutionary models for the majority of giant spiral galaxies (Larson & Tinsley 1978; Kennicutt 1983). When averaged over times that are longer than internal dynamical times scales the recent SFRs of most galactic disks have been relatively constant or slowly declining with characteristic e-folding times of several Gyr (Roberts 1963; Gallagher et al. 1984; Kennicutt 1992).

We can use Hα emission to examine the SFR on time scales of < 0.1 Gyr. This information is contained in the Hα emission line equivalent width, which is a color that compares the power output from stars with ages of about 5 Myr with those produced during the past few Gyr. In smoothly evolving galaxy models the Hα equivalent width closely correlates with $B - V$ color (Kennicutt, Tamblyn, & Congdon 1994). Hα global equivalent widths are available for a good sample of normal spiral galaxies (e.g., Kennicutt & Kent 1983; Romanishin 1990). These data show the predicted trend in which the emission equivalent width increases with bluer colors, but they also have large scatter. At intermediate colors of $0.4 \leq B - V \leq 0.7$, the Hα emission equivalent width varies by nearly a factor of ten (Kennicutt et al. 1994).

This amount of dispersion is surprising because it is seen in giant spirals such as Sc systems, which should be the epitome of smooth recent SFRs. Kennicutt & Kent (1983) commented on this issue, "The dispersion in emission among galaxies of a given color is still substantial, and it probably reflects the combined contributions of extraneous effects [starburst nuclei, dust absorption, etc.], along with real variability..." Additional factors such as gas supply and the possibility of past starbursts may also be important. In this paper we consider the role of large star-forming units in producing short term SFR variations in galaxies without nuclear starbursts. For example, in a statistical model it could be possible for the size and luminosity of star formation cells to increase with galaxy size, in which case the number of cells will always remain small and statistical SFR variations can occur even in luminous galaxies.

3. SCALES OF STAR FORMATION

Sizes or other global attributes of star complexes are difficult to measure. For example, suppose that a wave of star formation propagates at constant speed v_{sf} around a galactic disk at radius R_G over a distance comparable to R_G. There is a maximum age t_{young} of stars that we can observationally recognize to have been recently formed; older stars simply blend into the general field of the disk. The linear scale of this star-forming region will be measured as $D_{sf} \approx v_{sf} t_{young}$. In the normal case where $t_{young} \ll R_G/v_{sf}$, D_{sf} underestimates the size of the entire star-forming event. Because we are limited to detecting stars with ages less than t_{young}, we are unable to observationally trace where this particular wave induced star formation at times before t_{young}. In this case D_{sf}, is set by empirical constraints rather than the true physical scale of the star forming event, as in a classical density wave spiral arm (e.g., Kaufmann et al. 1989). On the other hand, if we observe an isolated, non-propagating star formation event, then D_{sf} can be a reasonable estimate of both the complex size and the

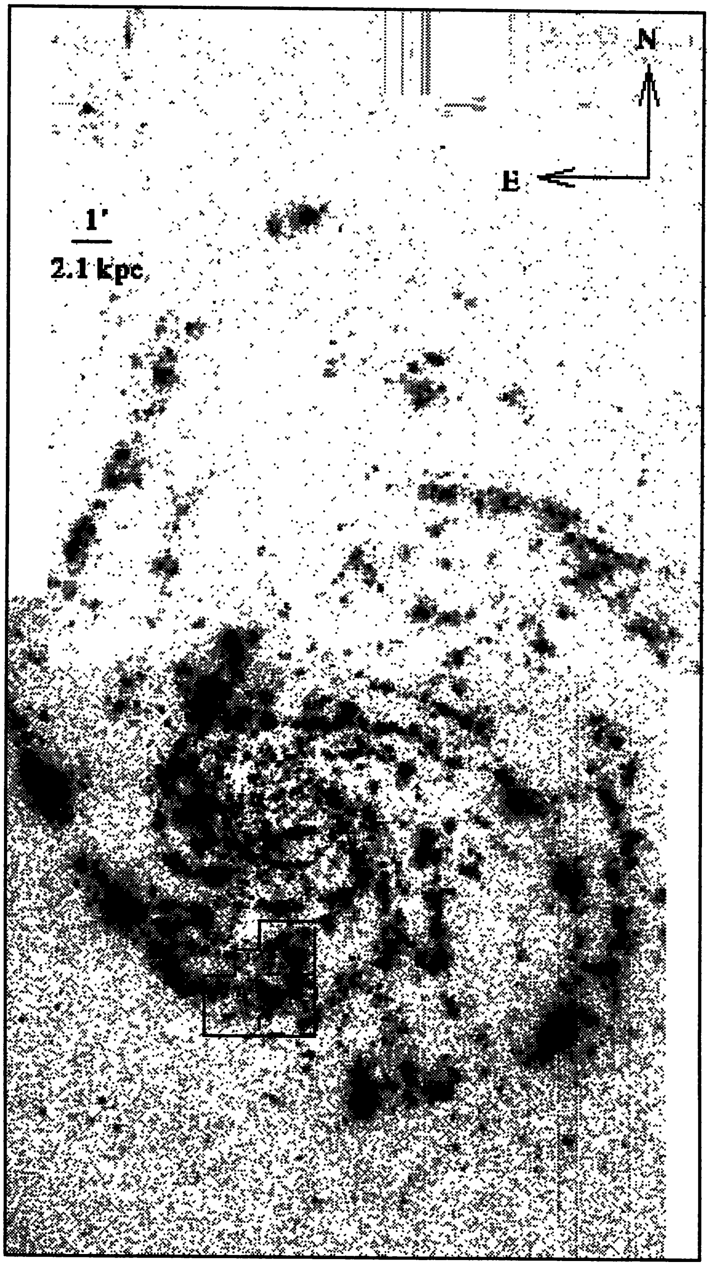

Fig. 1. The location of the WFPC-2 field is shown on this narrow band Hα image of M101 from Scowen et al. (1992).

scale of the physical event which produced it. In general we see that we will tend to underestimate the scales of processes which organize star formation on large scales and thereby underestimate galactic star formation coherence times.

The most direct approach utilizes H II regions as a measure of star formation scales (e.g., Hunter 1982). Advantages of this technique include a clear distinction of young regions from their surroundings and a good observational ability to select specific regions. The down side is that the lifetimes of H II regions may be less than the star forming coherence time within large complexes. As a result, ***H II regions alone may not display the full evolution of some star complexes.*** This point was recognized by McKibben, Nail, & Shapley (1953) who found that a large fraction of young stars in the Large Magellanic Cloud (LMC) are located in large groups which they called constellations. Payne-Gaposchkin (1974) extended this work via a clever application of variable stars as a means to determine the spatial patterns of star formation over the past 0.1 Gyr in the LMC. She also found that star formation is coherent up to a kpc scale.

A parallel and eventually more extensive study was carried out by Ambartsumian's group (e.g., Shakhbazyan 1968) and later by Efremov (1978, 1979). This work showed that large "star complexes" are common features of late-type galaxies; star formation is organized on scales that are larger than individual OB associations or H II regions in spiral and irregular galaxies. Furthermore, based on the argument given above, we expect the observations will tend to ***underestimate*** the scales of coherent star forming events.

Elmegreen et al. (1994) investigated the sizes star complexes in late-type galaxies based on the superb photographs in Sandage & Bedke (1988). A correlation was found between the size of the complex measured in blue light, D_c, and host galaxy luminosity, $D_c \propto L_g^{0.3}$. If we assume that the surface brightnesses of star complexes are roughly constant, then we can crudely estimate that complex luminosity will scale as $L_c \propto D_c^y$ where we take $y = 1.5$ as compromise between geometries. We then find

$$L_c/L_g \propto L_g^{-0.5}.$$

This implies that the effects of individual star complexes should become less important with increasing galaxy luminosity, but that the fall-off is slow. We also recognize that not all luminous, young star complexes are large. Luminous compact OB clusters also exist (Melnick 1992; O'Connell, Gallagher, & Hunter 1994) and so the assumption of constant surface brightness is questionable. But even so, the peak luminosities of giant star complexes are typically $\approx 1\%$ of the parent galaxy L_B (Wray & de Vaucouleurs 1980).

We are fortunate to be investigating L(Hα) in galaxies where we can observe the behavior of a wide range of types of H II regions. Kennicutt et al. (1989) measured the luminosity function of H II regions and found variations between galaxies. In some galaxies the number of H II regions with luminosities in the range L(Hα)$dl(H\alpha)$ scale as L(Hα)^s with $s \leq 2$. This implies a a formal divergence in the total luminosity integrated over all H II regions, L(Hα), due to luminous H II regions. In practice there is no divergence because the number of luminous H II regions is small, but this effect demonstrates that the most luminous H II regions are significant contributors to L(Hα) in some spirals. For example, in M101 and NGC 2403 the first ranked H II region produces about 20% of the L(Hα). The statistical variations in L(Hα) associated with giant H II complexes therefore remain important even in luminous, giant spirals, while the blue light contributions from these regions are small.

The effects of giant H II regions will be multiplied if their production is clumped in time. This pattern is seen in M101, where about 30% of L(Hα) comes from the outer spiral arm containing the giant H II region NGC 5461 as well as other luminous H II complexes. The organized formation of giant H II complexes enhances the global Hα emission equivalent width by factors of two, compared to a similar galaxy without such regions.

4. TYPICAL DISK NEIGHBORHOOD IN M101

Although giant H II regions are significant contributors to the L(Hα) in many spiral galaxies, more mundane star complexes have similar sizes (Elmegreen et al. 1994). This leads us to a brief consideration of the internal evolution of star complexes by taking advantage of recently acquired images of a normal mid-disk region of the giant Sc spiral galaxy M101. These data were taken with the Wide Field Planetary Camera II on the ***Hubble Space Telescope*** by the WFPC-2 Investigation Definition Team. Our preliminary comments presented here are based on images in the F547M filter, which is a continuum band, and the F656N, which is a narrow band filter including Hα and some of the [N II] emission. A complete description of these data will be published elsewhere (Scowen et al. 1995).

Figure 1 shows the WFPC-2 field on the ground-based Hα narrow band image of M101 from Scowen, Dufour, & Hester (1992). Here we examine only the WF3 CCD field which is in the lower right corner of the field in the box. This area includes the base of a major spiral arm which in turn contains a large star complex.

The Hα and continuum images are shown in Figures 2 and 3. We suggest that the main Population I components in this region are an example of a young Efremov (1979) star complex. The dominant feature in the continuum is a large OB star cloud which contains only a few H II regions. It is young enough to still be optically very luminous and yet old enough that most but not all of its associated H II regions have dispersed. This combination of conditions suggests an age of 10–30 Myr.

In the Hα image we see that the primary H II regions in this area fall along a roughly vertical swath which defines the peak of the spiral arm. The arm front is not sharply defined, as H II regions can be found both ahead of and behind the arm.

The combination of Hα and continuum images, which is shown in Figure 4 (Plate 1), suggests that the large star cloud and two nearby H II regions are joined by dark lanes, and thus may be a single entity. This

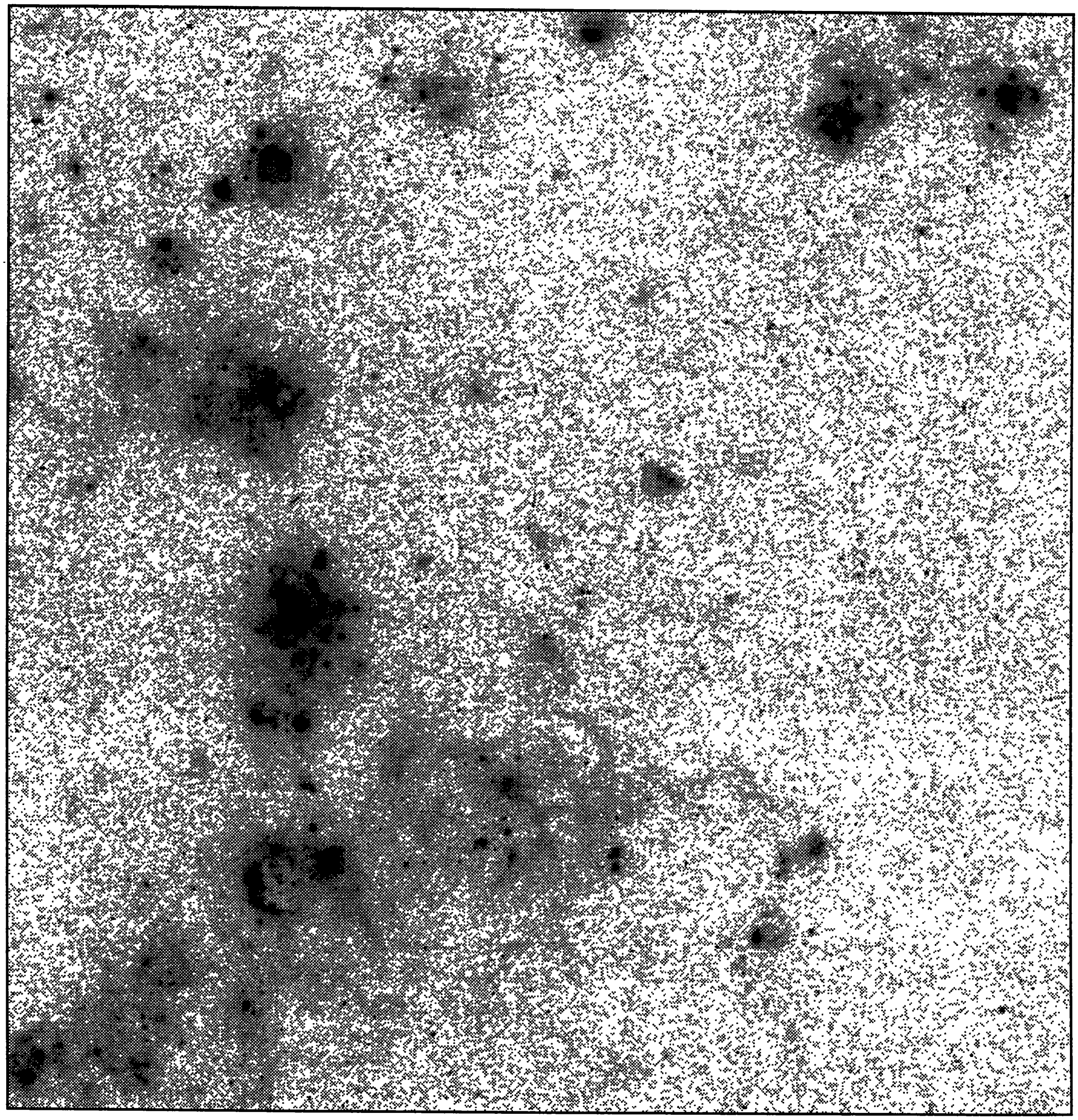

Fig. 2. Narrow band Hα WFPC-2 image of M101 covering a field of about 2.7 × 2.7 kpc^2 in the lower right of the box in Figure 1.

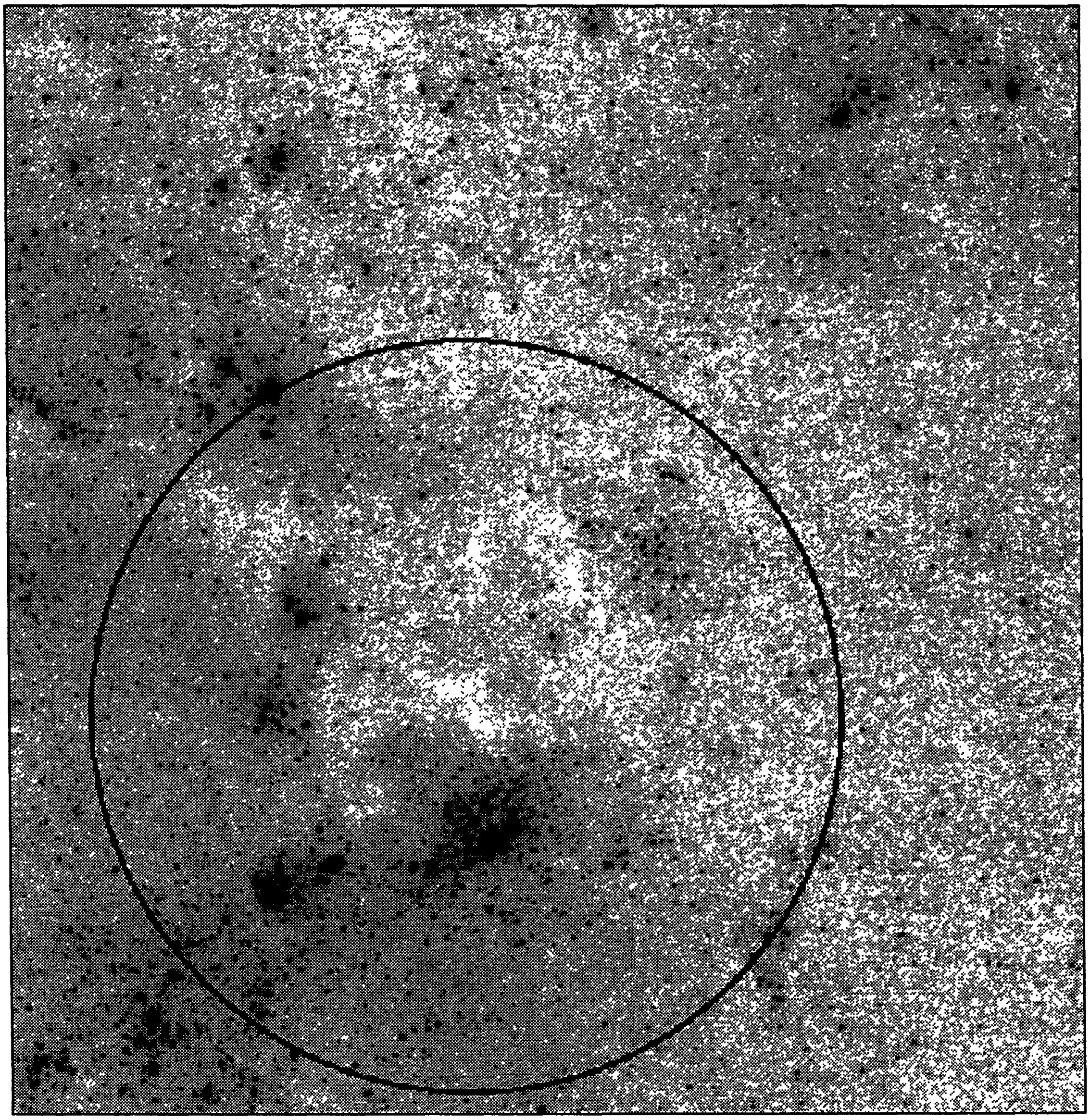

Fig. 3. M101 WFPC-2 field at the same location as in Figure 2, but in a visual continuum band. The approximate location of a possible young star complex is marked with a circle whose diameter is 48″.

complex is about ≈ 40″ across, or about 1.5 kpc, and thus is comparable in size to giant H II regions in the outer disks of spirals and in irregular galaxies (Hunter & Gallagher 1985; Kennicutt 1987).

The identification of this region as a young star complex is uncertain —at this point we are assuming that the spatial coincidence of components is the key feature. The future evolution of this region is also unclear. If it remains together, then the dark nebulae suggest that substantial raw material exists to support further star formation. Important physical processes will likely include star formation propagation, gravitational effects, and molecular cloud "shuffling" within the complex (see Elmegreen 1992). This mode of evolution can occur at a relatively leisurely pace, leading to an extended lifetime of active star formation.

In this picture the difference between a giant H II complex and more mundane star complexes is due to variations in the degree of star formation coherence and intensity within the complex. Intense star formation occurring across a giant molecular cloud complex over times comparable to the lifetimes of hot O stars produces the spectacular burst of Hα luminosity of a giant H II complex. Note that for cloud sizes of $\approx$1 kpc, these events require that v_{sf} $\approx$100 km s^{-1}! A normal star complex producing stars during 50 Myr with a similar total yield of high-mass Population I stars would produce stars at about one tenth of the giant H II complex rate and thus have a proportionally lower peak L(Hα).

5. DISCUSSION

Late-type galaxies of all sizes have significant variations in the global emission line equivalent width of Hα at a fixed $B-V$ color. We interpret this behavior as resulting from short-term variations in SFRs, which do not average out in large galaxies as predicted by simple statistical models. Some of this variability arises from the coeval presence of giant H II complexes in the main disks of galaxies, which substantially boost the global galactic L(Hα) and thus the integrated Hα emission equivalent width while changing total $B-V$ colors by only a few percent.

One example of correlated formation of giant H II regions is provided by M101, where three giant H II regions are simultaneously present on the east side of the outer galaxy. Most of the outer giant H II regions in M101 are associated with spiral arms. While spiral arms may aid in the formation of giant H II regions by collecting gas into massive gas cloud complexes, they are not necessary. For example, giant H II regions are common in irregular galaxies without spiral structure (Hunter & Gallagher 1985). This view is also consistent with observations showing that while spiral arms are often seen to *organize* star formation on large scales, they do not trigger or greatly enhance global star formation rates (Elmegreen & Elmegreen 1986).

High angular resolution observations obtained with the *Hubble Space Telescope* support models in which massive stars often form in large star complexes with sizes of up to 1 kpc. The degree of star formation time coherence within complexes evidently varies, with giant H II regions arising from those complexes where star formation occurs over times of a few Myr. More typical star complexes form over tens of Myr. However, it is not clear whether those regions with high peak SFR differ from similar mass but more slowly evolving star complexes in terms of their *total* production of new stars, as discussed by Hunter at this meeting.

Given that star formation is intrinsically a local process (see Hunter 1992), why do smooth galactic evolution models work at all? The current data agree remarkably well with predictions of smooth models over time spans of several Gyr (e.g., Gallagher et al. 1984; Kennicutt et al. 1994). This result is perhaps a signature of the important role played by the interaction between star formation and the parent galaxy which produces an "ecology" or which controls the birth and evolution of star complexes. The variability of the Hα emission strengths in galaxies then can be viewed as a reflection of the inevitable interplay between the local exuberance of star formation and the degree of long term stability imposed on these processes by the physics of galactic environments.

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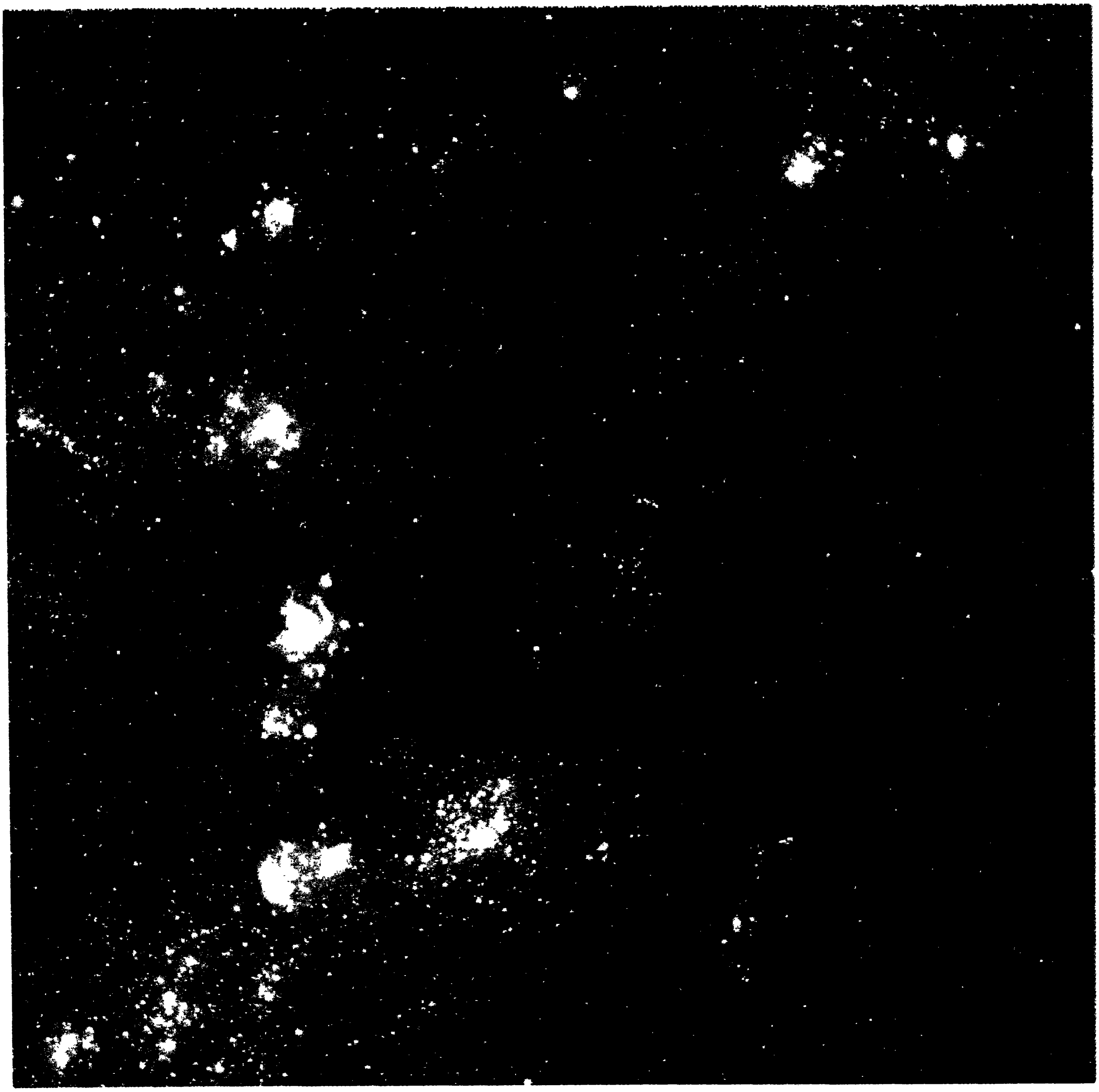

Figure 4. (Plate 1). This false color image combines the Hα and continuum bands in the inner disk of M101. The observations were made with the NASA/ESA *Hubble Space Telescope* using the WFPC-2 by the WFPC-2 Investigation Definition Team. The field of view is about 2.7×2.7 kpc^2 and the angular resolution is 0.1″ (3.6 pc). Note the presence of sub-arcsecond diameter, high brigthness H II regions clustered around larger H II complexes, and the existence of compact star clusters which would appear as individual stars at typical ground-base optical angular resolution. A full report of this data is in preparation.

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