Summary notes/paraphrases on "STAR FORMATION IN GALAXIES ALONG THE HUBBLE SEQUENCE" by Robert C. Kennicutt, Jr.

1. INTRODUCTION

paragraph 1: Declares that the review deals with the global star formation properties of galaxies, the systematics of those properties along the Hubble sequence, and their implications for galactic evolution.

paragraph 2: An important review of systematic investigations of the young stellar content of galaxies was done by Roberts (1963) by compiling the earlier studies on resolved young stellar populations of galaxies and analyses of galaxy colours and spectra.

paragraph 3: Later, more precise diagnostics of global SFRs in galaxies were developed.

- quantitative SFRs from evolutionary synthesis models of galaxy colours.
- modelling of blue galaxies revealed the importance of star formation bursts in the evolution of low-mass galaxies and interacting systems.
- SFR from integrated emission-line fluxes, near-ultraviolet continuum fluxes, and infrared (IR) continuum fluxes.

paragraph 4: Discovery of large populations of ultraluminous IR starburst galaxies and detection of star-forming galaxies at high redshift stimulated the growth in the field.

paragraph 5: Galaxies exhibit a huge dynamic range in SFRs, over six orders of magnitude even when normalized per unit area and galaxy mass.

paragraph 6: Mentions others reviews of interest.

2. DIAGNOSTIC METHODS

paragraph 1: Star formation properties of galaxies comes from integrated light measurements in the ultraviolet (UV), far-infrared (FIR), or nebular recombination lines. Earlier method of synthesis modeling of broadband colors are now largely applied to multicolor observations of faint galaxies.

2.1 Integrated Colors and Spectra, Synthesis Modeling

paragraph 1&2: The integrated spectra contain contributions from the full range of stellar spectral types and luminosities, the dominant contributors at visible wavelengths are intermediate-type main sequence stars (A to early F) and G-K giants. As a result, the integrated colors and spectra of normal galaxies fall on a relatively tight sequence, with the spectrum of any given object dictated by the ratio of young (<1 Gyr) to old (3–15 Gyr) stars.

paragraph 3: the scaling of the SFR to continuum luminosity is a smooth function of the color of the population, and this can be calibrated using an evolutionary synthesis model.

paragraph 4: Summary of the main steps in the construction of a synthesis model.

1. A grid of stellar evolution tracks is used to derive the effective temperatures and bolometric luminosities for various stellar masses as a function of time, and these are converted into broadband luminosities (or spectra) using stellar atmosphere models or spectral libraries.

2. The individual stellar templates are then summed together, weighted by an initial mass function (IMF), to synthesize the luminosities, colors, or spectra of single-age populations as functions of age.

3. These isochrones can then be added in linear combination to synthesize the spectrum or colors of a galaxy with an arbitrary star formation history, usually parametrized as an exponential function of time.

4. the colors of normal galaxies are well represented by a one-parameter sequence with fixed age, composition, and IMF, varying only in the time dependence of the SFR.

paragraph 5: lists available synthesis models (upto 1998).

paragraph 6: The synthesis models provide relations to make reasonable estimates of SFR per unit mass or luminosity from the integrated color of the population, especially for the bluer galaxies.

paragraph 7: This method should be avoided in applications where the dust content, abundances, or IMFs are likely to change systematically across a population.

2.2 Ultraviolet Continuum

paragraph 1: At wavelengths where the integrated spectrum is dominated by young stars (1250–2500 Å), the SFR scales linearly with luminosity.

paragraph 2: status of UV observations (upto 1998).

paragraph 3: The conversion between the UV flux over a given wavelength interval and the SFR can be derived using the synthesis models. For integrated measurements of galaxies, it is usually appropriate to assume that the SFR has remained constant over time scales that are long compared with the lifetimes of the dominant UV emitting population ($< 10^8$ $year$), in the "continuous star formation" approximation. Converting the calibration of Madau et al (1998) to Salpeter's (1955) IMF with mass limits 0.1 and 100 $M_\odot$ yields

$SFR(M_\odot year^{-1}) = 1.4 \times 10^{-28} L_\nu (ergs\ s^{-1}\ Hz^{-1})$

paragraph 4: It is important to apply an SFR calibration that is appropriate to the population of interest.

paragraph 5: The chief drawbacks of the method are its sensitivity to extinction and the form of the IMF. The spatial distribution of the extinction is very patchy, with the emergent UV emission dominated by regions of relatively low obscuration (Calzetti et al 1994), so calibrating the extinction correction is problematic.

paragraph 6: the 1500-2500 Å range is dominated by stars with masses above 5 $M_{\odot}$, so the SFR determination involves a large extrapolation to lower stellar masses.

2.3 Recombination Lines

paragraph 1: The nebular emission lines effectively re-emit the integrated stellar luminosity of galaxies shortward of the Lyman limit, so they provide a direct, sensitive probe of the young massive stellar population.

Paragraph 2: The conversion factor between ionizing flux and the SFR is usually computed using an evolutionary synthesis model. Only stars with masses of >10 $M_{\odot}$ and lifetimes of <20 Myr contribute significantly to the integrated ionizing flux, so the emission lines provide a nearly instantaneous measure of the SFR, independent of the previous star formation history.

paragraph 3: there is a significant variation among published calibrations ($\sim$ 30%), with most of the dispersion reflecting differences in the stellar evolution and atmosphere models.

paragraph 4: status of observations using this technique (upto 1998).

paragraph 5: The chief limitations of the method are its sensitivity to uncertainties in extinction and the IMF and the assumption that all of the massive star formation is traced by the ionized gas. The escape fraction of ionizing radiation from individual HII regions is around 15–50% in studies. But the escape fraction from a galaxy as a whole should be much lower ($\sim$ 3% in studies).

paragraph 6&7: The extinction, most important source of systematic error in H_{α} derived SFRs, can be measured by comparing H_{α} fluxes with those of IR recombination lines or the thermal radio continuum.

paragraph 8: The ionizing flux is produced almost exclusively by stars with >10 $M_{\odot}$, so SFRs derived from this method are especially sensitive to the form of the IMF. Fortunately, the H_{α} equivalent widths and broadband colors of galaxies are very sensitive to the slope of the IMF over the mass range 1–30 $M_{\odot}$, and these can be used to constrain the IMF slope.

2.4 Forbidden Lines

paragraph 1: The H_{α} emission line is redshifted out of the visible window beyond z $\sim$ 0.5, so there is considerable interest in calibrating bluer emission lines as quantitative SFR tracers. Unfortunately, the integrated strengths of H_β and the higher order Balmer emission lines are poor SFR diagnostics because the lines are weak and stellar absorption more strongly influences the emission-line fluxes.

paragraph 2: The strongest emission feature in the blue is the [OII] $\lambda 3727$ forbidden-line doublet. The luminosities of forbidden lines are not directly coupled to the ionizing luminosity, and their excitation is sensitive to abundance and the ionization state of the gas. However, the excitation of [OII] is sufficiently well behaved that it can be calibrated empirically (through H_α) as a quantitative SFR tracer.

paragraph 3&4: Calibrations of SFRs in terms of [OII] luminosity have been published by Gallagher et al (1989) and Kennicutt (1992). The observed [OII] luminosities must be corrected for extinction when SFR is estimated, in this case the extinction at H_α, because of the manner in which the [OII] fluxes were calibrated.

paragraph 5: The SFRs derived from [OII] are less precise than those from H_α because the mean [OII]/H_α ratios in individual galaxies vary considerably. The [OII]-derived SFRs may also be prone to systematic errors from extinction and variations in the diffuse gas fraction. Metal abundance has a relatively small effect on the [OII] calibration.

2.5 Far-Infrared Continuum

paragraph 1: A significant fraction of the bolometric luminosity of a galaxy is absorbed by interstellar dust and re-emitted in the thermal IR, at wavelengths of roughly 10–300 μm. The absorption cross section of the dust is strongly peaked in the ultraviolet, so in principle the FIR emission can be a sensitive tracer of the young stellar population and SFR.

paragraph 2: The simplest physical situation is one in which young stars dominate the radiation field throughout the UV–visible and the dust opacity is high everywhere, in which case the FIR luminosity measures the bolometric luminosity of the starburst.

paragraph 3: The FIR spectra of galaxies contain both a "warm" component associated with dust around young star-forming regions ($\sim 60 \mu m$) and a cooler "infrared cirrus" component (> 100 μm), which is associated with smore extended dust heated by the interstellar radiation field.

paragraph 4: In late-type star-forming galaxies, where dust heating from young stars is expected to dominate the 40- to 120-μm emission, the FIR luminosity correlates with other SFR tracers such as the UV continuum and H_α luminosities. However, early-type galaxies often exhibit high FIR luminosities but much cooler, cirrus-dominated emission. many early-type galaxies show no independent evidence of high SFRs, suggesting that the older stars or active galactic nuclei (AGNs) are responsible for much of the FIR emission.

paragraph 5: the FIR emission should provide an excellent measure of the SFR in dusty circumnuclear starbursts.

paragraph 6: In more quiescent, normal star-forming galaxies, the relation will be more complicated. The FIR luminosities share the same IMF sensitivity as the other direct star formation tracers, and it is important to be consistent when comparing results from different sources.

3. DISK STAR FORMATION

paragraph 1: large-scale star formation takes place in two very distinct physical environments: - one in the extended disks of spiral and irregular galaxies; - the other in compact, dense gas disks in the centers of galaxies.

3.1 Global Star Formation Rates Along the Hubble Sequence

paragraph 1: The absolute SFRs in galaxies, expressed in terms of the total mass of stars formed per year, show an enormous range. The highest SFRs are associated almost uniquely with strong tidal interactions and mergers.

paragraph 2: Part of the large dynamic range in absolute SFRs simply reflects the enormous range in galaxy masses, so it is more illuminating to examine the range in relative SFRs, normalized per unit mass or luminosity. This is illustrated in Figure 3 (see the original article), which shows the distribution of H_α + [NII] equivalent widths (EWs) in a sample of 227 nearby bright galaxies ($B_T < 13$) subdivided by Hubble type. The EW is defined as the emission-line luminosity normalized to the adjacent continuum flux, and hence it is a measure of the SFR per unit (red) luminosity.

paragraph 3: Figure 3 shows a range of more than two orders of magnitude in the SFR per unit luminosity. The EWs show a strong dependence on Hubble type, increasing from zero in E/S0 galaxies (within the observational errors) to 20-150 Å in late-type spiral and irregular galaxies. SFRs derived from the UV continuum and broadband visible colors show comparable behavior.

paragraph 4: High-resolution imaging of individual galaxies reveals that the changes in the disk SFR along the Hubble sequence are produced in roughly equal parts by an increase in the total number of star-forming regions per unit mass or area and by an increase in the characteristic masses of individual regions.

paragraph 5: Although there is a strong trend in the average SFRs with Hubble type, a dispersion of a factor of 10 is present in SFRs among galaxies of the same type. The scatter is much larger than would be expected from observational errors or extinction effects, so most of it must reflect real variations in the SFR.

paragraph 6: The relative SFRs can also be parametrized in terms of the mean SFR per unit disk area. This has the advantage of avoiding any effect of bulge contamination on total luminosities (which biases the EW distributions). Generally speaking, a parameter that scales with the SFR per unit mass (e.g. the H_α equivalent width) is most relevant to interpreting the evolutionary properties of disks, whereas the SFR per unit area is more relevant to parametrizing the dependence of the SFR on gas density in disks.

paragraph 7: Similar comparisons can be made for the FIR properties of disk galaxies, and these show considerably weaker trends with Hubble type.

paragraph 8&9: In at least some early-type spirals, the strong FIR emission is produced by luminous, dusty star forming regions, usually concentrated in the central regions of barred spiral galaxies. This exposes an important bias in the visible- and UV-based studies of SFRs in galaxies, in that they often do not take into account the substantial star formation in the dusty nuclear regions, which can dominate the global SFR in an early-type galaxy. However, it is also likely that much of the excess FIR emission in early-type spirals is unrelated to star formation, reflecting instead the effects of dust heating from evolved stellar populations.

3.2 Dependence of Star Formation Rates on Gas Content

paragraph 1-3: there is an underlying correlation between SFR and gas density that is largely independent of galaxy type. This shows that much of the scatter in SFRs among galaxies of the same type can be attributed to an underlying dispersion in gas contents. The scatter in SFRs at a given gas density is large, and most of this dispersion is probably introduced by averaging the SFRs and gas densities over a large dynamic range of local densities within the individual disks.

paragraph 4: [*talking about the sample in figure 5 here*] the stellar mass of a disk grows by about 1% per 10^8 years, i.e. the time scale for building the disk (at the present rate) is comparable to the Hubble time. Recycling of interstellar gas from stars extends the actual time scale for gas depletion by factors of 2–3.

3.3 Other Global Influences on Star Formation Rate

3.3.1 LUMINOSITY AND MASS

paragraph 1: Gavazzi & Scodeggio (1996) and Gavazzi et al (1996) have compiled UV, visible, and near-IR photometry for over 900 nearby galaxies, and they found an anti-correlation between the SFR per unit mass and the galaxy luminosity, as indicated by broadband colors and H_α EWs. The considerable overlap between the color-luminosity relations of different spiral types suggests that part of the trends that are attributed to morphological type may be more fundamentally related to total mass.

3.3.2 BARS

paragraph 1: Stellar bars can strongly perturb the gas flows in disks and trigger nuclear star formation, but they do not appear to significantly affect the total disk SFRs (based on H_α observations).

paragraph 2: Study using FIR emission also concluded that there is no significant correlation with bar structure.

paragraph 3: Another analysis of H_α and FIR-based SFRs for a sample of 32 late-type barred galaxies found a correlation between SFR and the strength and length of the bar. This suggests that large samples are needed to study the effects of bars on the large-scale SFR and that the structural properties of the bars themselves need to be incorporated in the analysis.

3.3.3 SPIRAL ARM STRUCTURE

paragraph 1: Grand-design spiral galaxies show strong local enhancements of star formation in their spiral arms, so the absence of a corresponding excess in their total SFRs suggests that the primary effect of the spiral density wave is to concentrate star formation in the arms, but not to increase the global efficiency of star formation.

3.3.4 GALAXY-GALAXY INTERACTIONS

paragraph 1: Numerous studies of the global H_α and FIR emission of interacting and merging galaxies have shown strong excess star formation. The average enhancement in SFR over large samples is a factor of 2–3.

3.3.5 CLUSTER ENVIRONMENT

paragraph 1: Many spiral galaxies located in rich clusters exhibit significant atomic gas deficiencies, which presumably are the result of ram pressure stripping from the intercluster medium, combined with tidal stripping from interactions with other galaxies and the cluster potential.

paragraph 2: They found a 37–46% lower H_α detection rate among Sb, Sc, and irregular galaxies in the clusters, but a 50% higher detection rate among Sa–Sab galaxies. They argued that these results arise from a combination of competing effects, including reduced star formation from gas stripping as well as enhanced star formation triggered by tidal interactions. Ram-pressure induced star formation may also be taking place in a few objects.

4. CIRCUMNUCLEAR STAR FORMATION AND STARBURSTS

paragraph 1: the circumnuclear regions of many spiral galaxies harbor luminous star-forming regions, with properties that are largely decoupled from those of the more extended star-forming disks.

4.1 Star Formation Rates and Physical Properties

paragraph 1: The nuclear SFRs implied by the H_α and IR fluxes span a large range, from a lower detection limit of $\sim 10^{-4}$ $M_\odot$ $year^{-1}$ to well over 100 $M_\odot$ $year^{-1}$ in the most luminous IR galaxies.

paragraph 2: the nuclear star formation at the low end of the SFR spectrum typically occurs in moderately obscured regions ($A_{H_\alpha} \sim$ 0–3 mag) that are not physically dissimilar from normal disk HII regions.

paragraph 3: high SFRs are not seen in optically selected samples, mainly because the luminous starbursts are uniquely associated with dense molecular gas disks, and for normal gas-to-dust ratios, one expects visible extinctions of several magnitudes or higher. These luminous nuclear starbursts represent a star formation regime that is distinct from the more extended star formation in disks and because these bursts often dominate the total SFRs in their parent galaxies.

paragraph 4&5: the luminous IR galaxies are associated with unusually high molecular gas masses, which partly accounts for the high SFRs. the typical SFR per unit gas mass is much higher than in normal disks.

paragraph 6: High-resolution IR photometry and imaging of the luminous IR galaxies reveals that the bulk of the luminosity originates in compact circumnuclear regions. Likewise, CO interferometric observations show that a large fraction of the molecular gas is concentrated in central disks.

paragraph 7: The circumnuclear star formation is especially distinctive (from the more extended star-forming disks of spiral galaxies) in terms of the absolute range in SFRs, the much higher spatial concentrations of gas and stars, its burst-like nature (in luminous systems), and its systematic variation with galaxy type.

paragraph 8&9: Figure 7 (see the original article) shows that the surface densities of gas and star formation in the nuclear starbursts are 1–4 orders of magnitude higher than in spiral disks overall. Densities of this order can be found in large molecular cloud complexes within spiral disks, but the physical conditions in many of the nuclear starbursts are extraordinary even by those standards.

paragraph 10: The starbursts follow a relatively well-defined Schmidt law, with index N $\sim$ 1.4. The mean conversion efficiency is six times larger than in the spiral disks.

paragraph 11: the luminous IR galaxies lie close to the limiting luminosity allowed by stellar energy generation, for a system that converts all of its gas to stars over a dynamical time scale.

paragraph 12&13: many of the most extreme circumnuclear starbursts lie near the physical limit for maximum SFRs in galaxies.

paragraph 14: the most luminous IR starburst galaxies represent systems in which a mass of gas comparable to the entire ISM of a galaxy has been driven into a region on the order of 1 kpc in size, and this entire ISM is being formed into stars, with almost 100% efficiency, over a time scale on the order of 10ˆ8 years. Such a catastrophic transfer of mass can only take place in a violent interaction or merger, or perhaps during the initial collapse phase of protogalaxies.

4.2 Dependence on Type and Environment

4.2.1 HUBBLE TYPE

paragraph 1: In contrast to the extended star formation in disks, which varies dramatically along the Hubble sequence, circumnuclear star formation is largely decoupled with Hubble type.

paragraph 2: Thus while luminous nuclear starbursts may occur across the entire range of spiral host types, the relative effect is much stronger for the early-type galaxies; most of the star formation in these galaxies occurs in the circumnuclear regions.

4.2.2 BAR STRUCTURE

paragraph 1: nuclear star formation is strongly correlated with the presence of strong stellar bars in the parent galaxy.

paragraph 2: The barred galaxies shows an extended tail of bright nuclei that is absent in samples of nonbarred galaxies.

paragraph 3: Bars appear to play an especially strong role in triggering the strong IR-luminous starbursts that are found in early-type spiral galaxies.

paragraph 4: the evolution of the circumnuclear region is largely decoupled from that of the disk at larger radii. Bars in bulge-dominated, early-type spirals tend to be very strong and efficient at transporting gas from the disk into the central regions, while bars in late-type galaxies are much weaker and are predicted to be much less efficient in transporting gas.

4.2.3 GALAXY INTERACTIONS AND MERGERS

paragraph 1: Numerous observations have established a clear causal link between strong nuclear starbursts and tidal interactions and mergers of galaxies.

paragraph 2: The evidence for interaction-induced nuclear star formation comes from two types of studies, statistical comparisons of the SFRs in complete samples of interacting and noninteracting galaxies, and studies of the frequency of interactions and mergers among samples of luminous starburst galaxies.

paragraph 3: while the interactions tend to increase the SFR throughout galaxies, the effects in the nuclear regions are stronger.

paragraph 4: The most luminous starbursts are associated almost exclusively with strong tidal interactions and mergers.

5. INTERPRETATION AND IMPLICATIONS FOR GALAXY EVOLUTION

5.1 Disk Evolution Along the Hubble Sequence

paragraph 1: A useful parameter for characterizing the star formation histories is the ratio of the current SFR to the past SFR averaged over the age of the disk, denoted b by Scalo (1986). The typical late-type spiral has formed stars at a roughly constant rate (b $\sim$ 1), which is consistent with direct measurements of the stellar age distribution in the Galactic disk. By contrast, early-type spiral galaxies are characterized by rapidly declining SFRs, with b $\sim$ 0.01–0.1, whereas elliptical and S0 galaxies have essentially ceased forming stars (b = 0).

paragraph 2: most of the variation in the integrated photometric properties of spiral galaxies is produced by changes in the star formation histories of the disks, not in the bulge-to-disk ratio.

paragraph 3: Many early-type barred spirals harbor luminous circumnuclear starbursts, with integrated SFRs that can be as high as the disk SFRs in late-type galaxies. it is important to delineate between the the nuclear regions and more extended disks when characterizing the evolutionary properties of galaxies.

paragraph 4: Although Figure 3 shows a strong change in the average star formation history with galaxy type, it also shows a large dispersion in b among galaxies of the same type.

paragraph 5&6: Most star formation at the present epoch resides in late-type gas-rich galaxies, but by z $\sim$ 1, all spiral types are predicted to have comparable SFRs, and (present-day) early-type systems become increasingly dominant at higher redshifts. the redshift dependence of the volume averaged SFR shows quite a different character, with a broad maximum between z $\sim$ 1–2 and a decline at higher redshifts. This difference probably reflects the importance of hierarchical processes such as mergers in the evolution of galaxies, mechanisms that are not included in the simple phenomenological description in Figure 8 (see the original article).

5.2 Evolution of Circumnuclear Star Formation

paragraph 1: the nuclear SFRs are closely associated with dynamical influences such as gas transport by bars or external gravitational perturbations, which stimulate the flow of gas into the circumnuclear regions.

paragraph 2: most spiral nuclei show SFRs consistent with steady-state or declining star formation, though it is likely that some of these nuclei are observed in a quiescent stage between major outbursts.

paragraph 3: Starbursts are clearly the dominant mode of star formation in IR-selected samples of nuclei. The most luminous nuclear starbursts ($L_{bol} > 10^{12} L_{\odot}$) are singular events. Maintaining such luminosities for even 10^8 years requires a total gas mass on the order of 10^{10}˘$10^{11} M_{\odot}$, equivalent to the total gas supply in most galaxies. Violent interactions and mergers are the only events capable of triggering such a catastrophic mass transfer.

5.3 Physical Regulation of Star Formation Rate

paragraph 1&2: The tight relation in Figure 9 (see the original article) shows that a simple Schmidt (1959) power law provides an excellent empirical parametrization of the SFR, across an enormous range of SFRs, and it suggests that the gas density is the primary determinant of the SFR on these scales.

paragraph 3: The uncertainty in the slope of the best-fitting Schmidt law is dominated by systematic errors in the SFRs, with the largest being the FIR-derived SFRs and CO-derived gas densities in the starburst galaxies.

paragraph 4: As discussed by Larson (1992) and Elmegreen (1994), a large-scale Schmidt law with index N $\sim$ 1.5 would be expected for self-gravitating disks if the SFR scales as the ratio of the gas density (ρ) to the free-fall time scale ($\propto \rho^{-0.5}$) and the average gas scale height is roughly constant across the sample ($\Sigma \propto \rho$). In a variant on this picture, Elmegreen (1997) and Silk (1997) have suggested that the SFR might scale with the ratio of the gas density to the average orbital time scale; this is equivalent to postulating that disks process a fixed fraction of their gas into stars in each orbit around the galactic center.

paragraph 5: These parametrizations offer two distinct interpretations of the high SFRs in the centers of luminous starburst galaxies. The central starbursts have densities that are on the order of 100–10,000 times higher than in the extended star-forming disks of spirals, so the global star formation efficiencies should be 6–40 times higher. Alternatively, in the kinematic picture, the higher efficiencies in the circumnuclear starbursts are simply a consequence of the shorter orbital time scales in the galaxy centers, independent of the gas density.

paragraph 6: the relatively shallow N $\sim$ 1.4 Schmidt law cannot account for the strong changes in disk SFRs observed across the Hubble sequence if the disks evolved as nearly closed systems. Likewise, the modest changes in galaxy rotation curves with Hubble type are too small to account for the large differences in star formation histories with a kinematical model. it is possible that other mechanisms, such as infall of gas, merger history, or bulge-disk interactions are responsible for the strong changes in star formation histories across the spiral sequence.

6. FUTURE PROSPECTS

paragraph 1: the picture remains primitive in many respects, as it is based in large part on integrated, one-zone averages over entire galaxies and extrapolations from present-day SFRs to crude characterizations of past star formation histories. Uncertainties in fundamental parameters such as the IMF and massive stellar evolution undermine the accuracy of the entire SFR scale and weaken the interpretations that are based on these measurements.

paragraph 2&3: observations of nearby galaxies will remain crucial for understanding many critical aspects of galaxy formation and evolution. Perhaps the greatest potential is for understanding the physical processes that determine the local and global SFRs in galaxies and understanding the feedback processes between the star formation and the parent galaxies.