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Optical Studies of Star Formation in Normal Spiral Galaxies: Radial Characteristics*

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Abstract

First results of a new, homogeneous CCD imaging survey of nearby southern spiral galaxies in V, I and Hα are presented. Elliptical aperture photometry has been used to determine the deprojected surface brightnesses as a function of galactocentric radius, and thus to trace the past and present star formation behaviour. From a sub-sample of nine mainly barred spirals, we find a couple of notable trends. Firstly, nearly all of the barred spirals show evidence of significant levels of ongoing star formation in the bulge, probably fed by gas inflow along the bar. Secondly, the disk Hα profiles are quite shallow compared with the broadband exponential disks, implying a relative insensitivity of the current star formation rate to the surface density of stars already formed. In both the bulge and the disk, the gas consumption timescales are such as to require gas replenishment, e.g. by radial inflow.

1. Introduction

A prescription for star formation is one of the major ingredients in any galaxy evolution model. Ideally, it will be able to account for the observed distribution of stars within a galaxy, as well as predict the rate and distribution of star formation in the current epoch. Despite recent advances in optical detectors such as CCDs, there is still a lack of consistent surveys which spatially resolve the various stellar populations in spiral galaxies, and thus of data with which to constrain the competing models of galaxy evolution. We have embarked on such a survey of nearby ($D \lesssim 20$ Mpc) spiral galaxies in the southern hemisphere.

On account of the apparent axisymmetry of spiral galaxies, radial plots of stellar surface brightness are quite fundamental diagnostics of star formation activity. For nearby galaxies, surface photometry in the V band is dominated by intermediate-age stars of a few solar masses, while the I band is more sensitive to the older low-mass population as well as being less affected by dust. Kennicutt (1983, 1989) has demonstrated how flux-calibrated Hα imaging can be used to trace the recent formation of massive ($M \gtrsim 10 M_{\odot}$) stars, as well as furnishing a quantitative estimate of the rate.

In the following sections, we outline the observational, data reduction and surface photometry procedures. Then we present results for a sub-sample of

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mainly barred-type spirals for which complete photometry is available, and discuss the implications of these results for the evolution of spiral galaxies.

2. Data Analysis

(a) Observations and Data Reduction

The observations have been carried out using the MSSSO 40″ reflector together with a $f/18 \rightarrow f/3{\cdot}45$ focal reducer (Dopita and Hart 1976) which yields an $8' \times 11'$ field of view at $1{\cdot}3$ arcsec pix^{-1} with a GEC CCD. Two 500 s exposures of each galaxy were taken through each of the V, I and red continuum (55 Å bandpass centred on 6676 Å) filters. Three 1000 s exposures were taken through one of three 16 Å bandpass Hα filters, chosen to suit the galaxy's heliocentric velocity. Images of E-region standards (Graham 1982) were used to calibrate the broadband images, while planetary nebulae in the Large Magellanic Cloud (Meatheringham and Dopita 1991) were used to flux-calibrate the Hα images.

The images were debiased then flatfielded using images of the twilight sky. Using appropriate tasks in the IRAF* package, the individual images for each filter were registered, scaled to a common mode then averaged together. The Hα images were sigma clipped prior to averaging to help eliminate cosmic rays that may be confused for H II regions. After background subtraction, the red continuum images were scaled and subtracted from the Hα images to leave a pure emission line image.

(b) Surface Photometry

The GASP (GAlaxy Surface Photometry) package originally written by M. Cawson has recently been modified at MSSSO by S. Meatheringham to handle images up to 1352×1352 and to run on SUN workstations. The GASP procedure has been described elsewhere, e.g. Davis *et al.* (1985) and Jedrzejewski (1987). Briefly, GASP iteratively attempts to fit ellipses of a specified semi-major axis to the galaxy image, varying the eccentricity and position angle so as to minimise residuals about the mode of the pixel values around the ellipse perimeter. When a satisfactory fit is achieved, it repeats the process for progressively larger ellipses until either the sky background is reached or less than 60% of an ellipse will fit onto the image.

By comparing the ellipse parameters at the $22{\cdot}5$, $23{\cdot}0$ and $23{\cdot}5$ mag arcsec^{-2} levels in both the V and I images, the most likely inclination and position angle of the disk are determined. In order to simulate aperture photometry of the galaxy as if we were viewing it face-on, we could either deproject the galaxy image, or project circular apertures as ellipses on to the observed image. We force GASP into doing the latter by having it determine the mean and modal intensities around ellipses held fixed at the disk inclination and position angle. The same set of elliptical apertures is used on the V, I and pure Hα images with field stars being used to register the images. To measure the unresolved smooth stellar disk, we use the modal surface brightness as a function of radius in the V and I images; owing to the patchy distribution of the resolved H II regions however, we

* IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

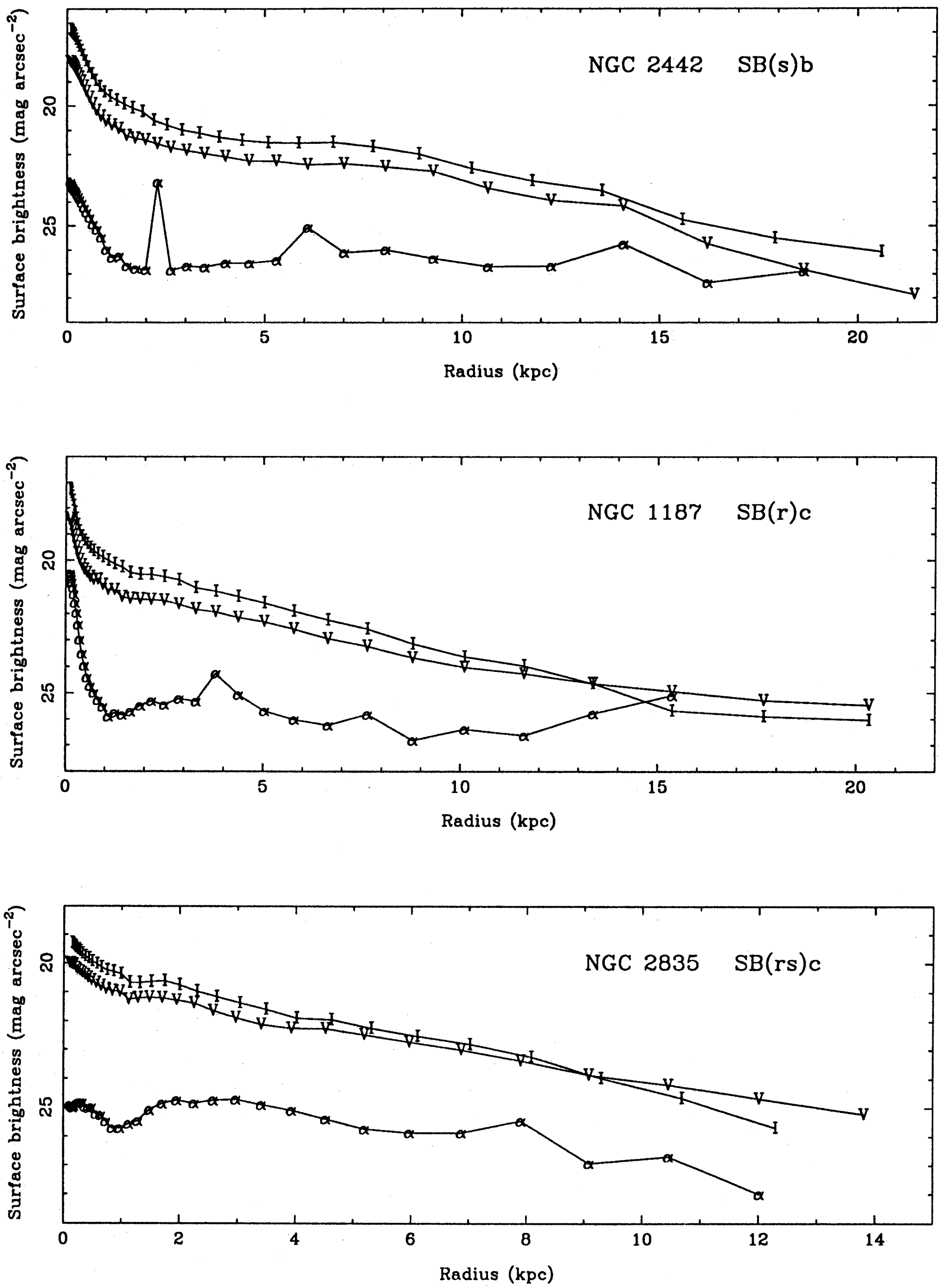

Fig. 1*a*. Plots of deprojected surface brightness versus deprojected galactocentric radius for three SB galaxies. The V and I surface brightnesses are identified by the appropriate letter, while the Hα is marked with the α symbol. The zero-point for the Hα surface brightness scale is the same for all plots, and has been chosen for convenience in the plotting.

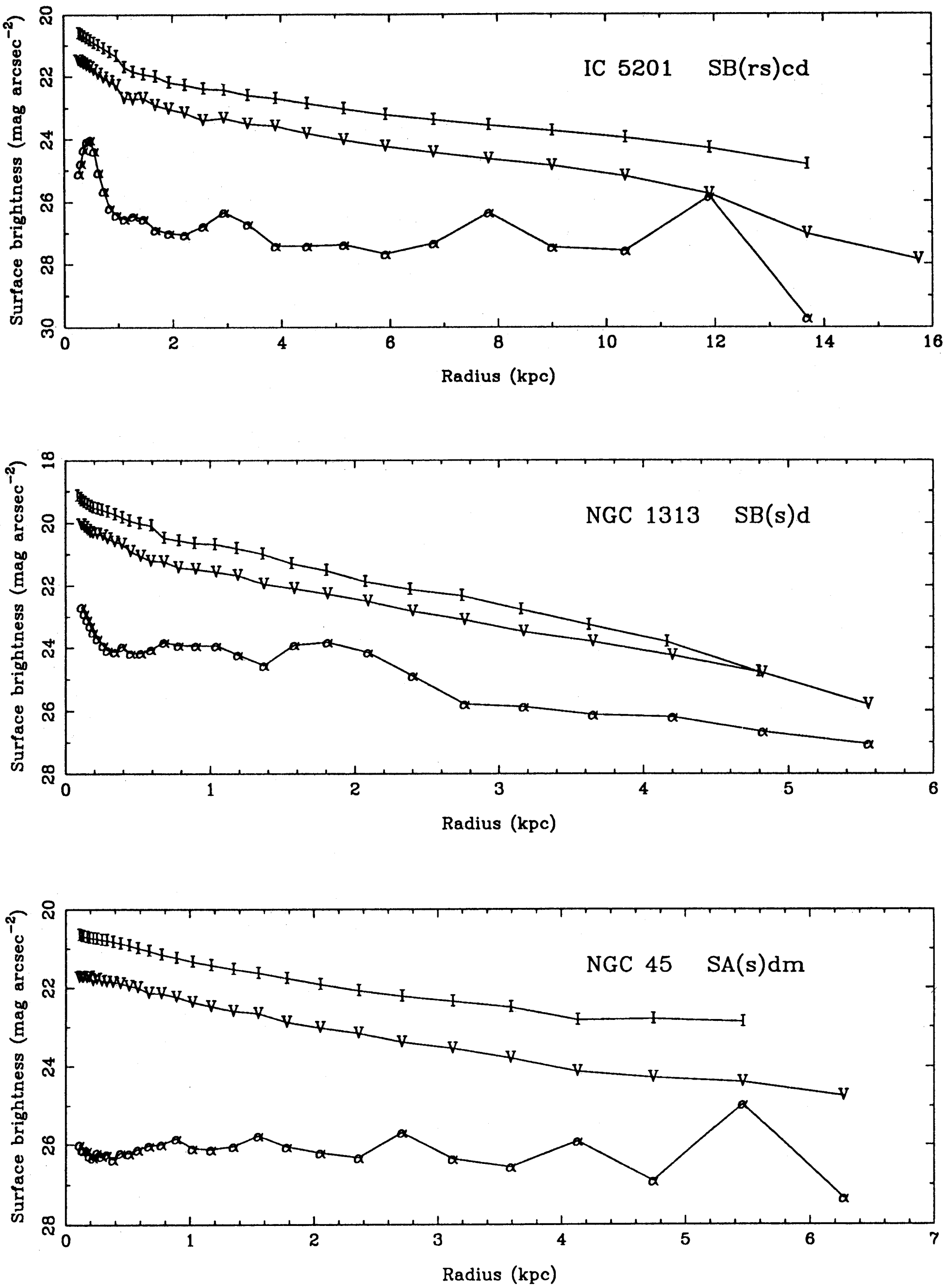

Fig. 1*b*. As for Fig. 1*a*, but for three other galaxies including NGC 45, the only galaxy definitely lacking a bar.

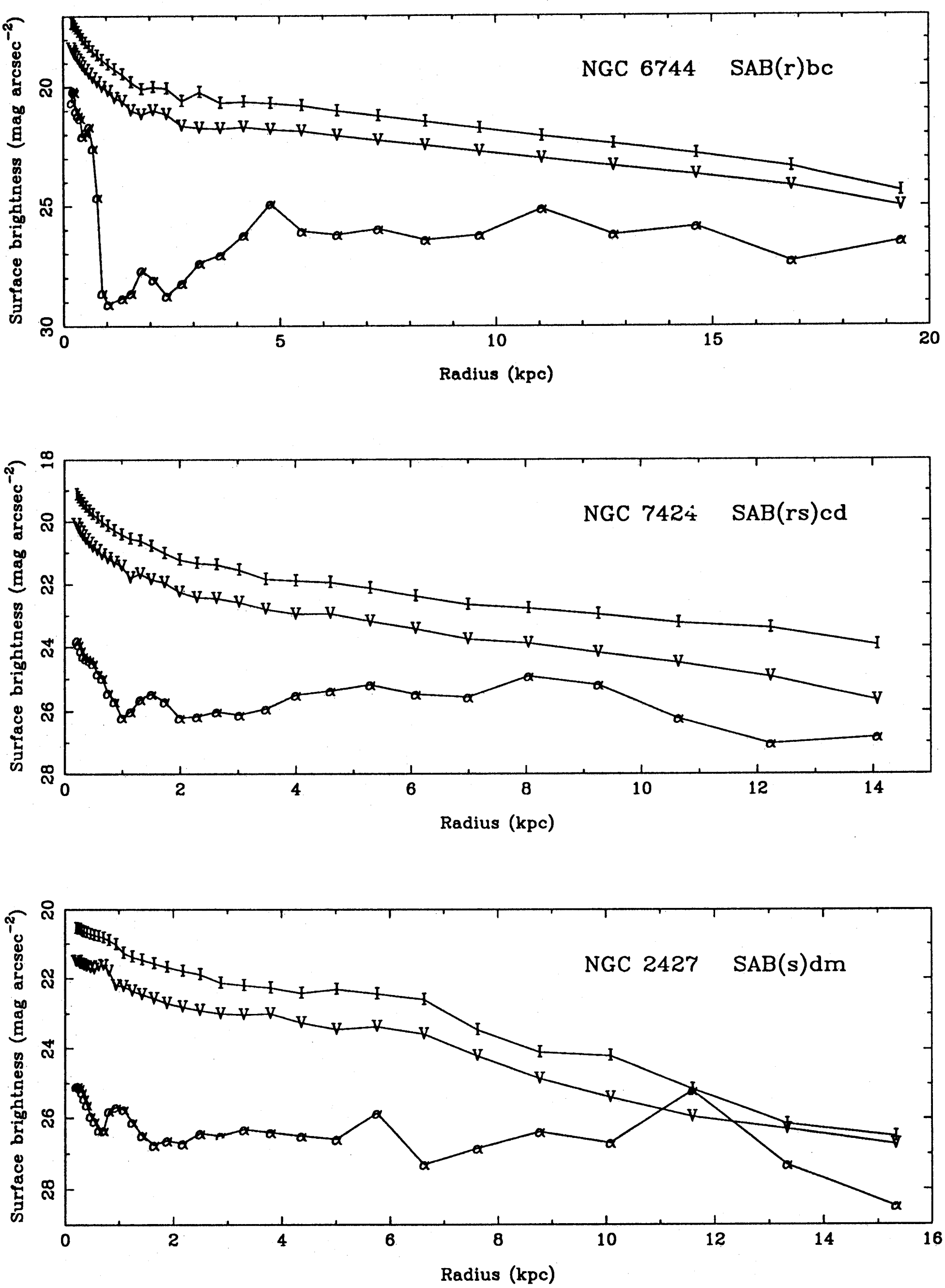

Fig. 1*c*. As for Fig. 1*a*, but for the three partly-barred galaxies in our sample.

must use the mean surface brightness as a function of radius in the Hα image to trace the present day massive star formation.

The surface brightnesses were deprojected to face-on values (assuming the disk to be optically thin—but see Disney *et al.* 1989), then corrected for extinction within our own Galaxy using the A_B values tabulated by Burstein and Heiles (1984) together with the interstellar extinction curve of Savage and Mathis (1979). No corrections have been applied to the surface brightness values for extinction within the galaxies themselves owing to the still uncertain nature of the distribution of dust in spiral galaxies. Standard atmospheric extinction corrections for Siding Spring have also been made to the data, while the effects of ambient temperature and galaxy redshift on the effective Hα filter transmission have also been taken into account.

3. Results

The sample processed so far consists of five spirals with well-defined bars (denoted SB in the Revised Morphological Type nomenclature of de Vaucouleurs *et al.* 1976), one without a bar (SA) and three intermediate cases (SAB); as such, most of our comments will be directed towards star formation in barred or partly-barred galaxies. The galaxy sub-types cover the range from those with a moderately strong bulge (Sb) to those bearing almost none, the late-type Magellanic-like spirals (Sdm). Radial plots of V, I and Hα surface brightness for each of the nine galaxies are shown in Fig. 1. The zero-point of the Hα magnitude scale has been chosen arbitrarily for convenience in the plotting, but is the same for all the galaxies.

While the V and I radial profiles show the expected bulge and exponential disk components (Freeman 1970), the majority of the Hα profiles behave somewhat differently. Two aspects are particularly worth noting, and are discussed further in the next section: firstly, the steep increase in Hα surface brightness in the nuclear regions, and secondly its relative flatness in the disk. All three SAB galaxies show a secondary Hα peak just outside the nucleus with an associated bump in the broadband profiles, which looks to be the result of an incomplete ring of H II regions. The central dip in the Hα profile of IC 5201 is due to the fact that the central H II regions are slightly offset from the broadband nucleus.

4. Discussion

(a) Nuclear Star Formation

Our imaging survey has revealed a clear excess of Hα emission in the nuclei of nearly all of the spirals with some hint of barred morphology. A similar narrow-band imaging program carried out by us with the Anglo-Australian Telescope, which provides an order of magnitude greater sensitivity has confirmed the existence of this excess in at least one of these galaxies, NGC 1313. But how can we be sure that these Hα photons represent bona fide massive star formation, and are not the result of some other process? Nuclear spectrophotometry by Keel (1983) and others suggests that nuclear Hα emission is present in *all* spirals at some level. Furthermore, the emission line ratios in the majority of the early-type (S0 to Sbc) spirals are inconsistent with a pure stellar photoionisation source; rather, they arise from low ionisation nuclear emission-line regions. These

LINERs are believed to represent the low luminosity end of the Seyfert 2 class of active galactic nuclei.

We have obtained nuclear spectrophotometry for two of the galaxies in our sample. The Hα/[N II]λ6584 ratio in NGC 6744 suggests it may well be a LINER, whereas that for NGC 2835 is consistent with that for an H II region. Given the scarcity of LINERs amongst galaxies of type Sc and later (i.e. the majority of our sample), we are probably fairly safe in assuming that the bulk of the nuclear Hα emission comes from H II regions. Even within LINER galaxies, some of the Hα emission could still be the result of star formation, and since we have not accounted fully for the absorption of Hα photons by both the underlying stellar continuum and by dust, we may not in fact be overstating the importance of any nuclear star formation.

Bearing all this in mind, let us proceed with the analysis. The central Hα spikes in these galaxies are most likely the result of 'funneling' of gas inwards by a rotating axisymmetric potential (namely the bar), followed by vigorous star formation in the nuclear region. Such a mechanism has been invoked previously (Hawarden *et al.* 1988) to explain the apparent requirement for barred morphology in galaxies with nuclear starbursts, as indicated by their IRAS colours. While we are not aware of any galaxies in our sample that are currently starbursting, or are abnormal in any obvious way (e.g. interacting), it could simply be a matter of the scale and efficiency of gas inflow by non-circular motions. Gas streaming motions along bars have been inferred from spectroscopic observations (de Vaucouleurs and Freeman 1972), although the ultimate fate of this gas is still uncertain.

Table 1. Galaxy parameters

The inclinations and star formation rates are deduced from this study, while the Revised Morphological Types are taken from the 'Second Reference Catalogue of Bright Galaxies' (de Vaucouleurs *et al.* 1976). Both the distances R and the absolute blue magnitudes M_B come from the 'Nearby Galaxies Catalog' (Tully 1988)

Galaxy	Type	Inc. (°)	R (Mpc)	M_B	Nuclear SFR $M_\odot$ yr^{-1}	Nuclear SFR $M_\odot$ pc^{-2} Gyr^{-1}	Disk SFR Hα SB	Disk SFR $M_\odot$ pc^{-2} Gyr^{-1}
NGC 6744	SAB(r)bc	47	10·4	−21·39	1·10	289	25·7	19
NGC 2442	SB(s)b	62	17·1	−20·66	0·18	14	26·0	21
NGC 1187	SB(r)c	42	16·3	−19·76	0·37	98	25·4	23
NGC 2835	SB(rs)c	51	10·8	−19·66	0·06	19	24·8	48
NGC 7424	SAB(rs)cd	28	11·5	−19·55	0·09	28	25·2	24
IC 5201	SB(rs)cd	62	11·1	−19·18	0·09	19	26·8	10
NGC 2427	SAB(s)dm	72	10·9	−19·01	0·02	15	26·3	24
NGC 1313	SB(s)d	41	4·5	−18·60	0·06	80	24·0	83
NGC 45	SA(s)dm	43	5·9	−17·82	0·002	9	25·8	16

An estimate of the rate of gas infall is possible by multiplying the observed rate of star formation in the nuclear region by an efficiency factor for the conversion of gas into stars. For each galaxy, the total Hα flux within the bulge region has been converted to a rate of star formation integrated over the entire interstellar mass function (IMF) as per Kennicutt (1983). Like Kennicutt, we have applied a correction for extinction of 1·1 magnitudes, although the extinction by dust within the galaxy nuclei is almost certainly greater than this. The derived star formation rates (SFR) are tabulated in Table 1 as well as the specific SFR, expressed as per unit area.

Clearly the total nuclear SFR follows only roughly an absolute magnitude sequence. When expressed as a specific SFR, however, the results span only one order of magnitude (with the exception of NGC 6744 in which the Hα may have a non-thermal origin). Lord and Young (1990) deduced a star formation efficiency (SFR divided by total gas surface density) within M51 of $0 \cdot 4 \pm 0 \cdot 1$ Gyr^{-1}. Since we have caught so many of our barred galaxies in the act of nuclear star formation, this is unlikely to be a transient phenomenon. Therefore, integrating these nuclear SFRs over half a Hubble time yields total amounts of gas inflow and consumption ranging from $4 \times 10^7 M_\odot$ to $3 \times 10^9 M_\odot$ (excluding NGC 6744). While these amounts may not seem significant, making up only a few per cent of a galaxy's total gas mass, they are probably just lower limits owing to the expected high levels of extinction mentioned previously. Even allowing for the recycling of gas in the star formation cycle and supernovae-driven galactic winds expelling gas from the nuclear regions, it seems likely that a sizable proportion of the gas in barred spirals is consumed in ongoing nuclear star formation.

Although nuclear star formation has been inferred previously from emission line spectroscopy (Heckman 1980), very little imaging has been carried out, perhaps due to difficulty with the continuum subtraction, or in the expectation that high extinction would conceal it. Yet in spite of this, we still see a clear excess of Hα emission in the bulges of barred spirals. While the significance of the bar in all this must await similar data for an unbarred sample, the implications of ongoing nuclear star formation for what is generally considered an 'old' population are important. For instance, it may not be necessary to invoke early bursts of star formation in the bulge in order to explain the high metal abundances observed there, if star formation has been occurring over a longer period than in the disk.

(b) Disk Star Formation

The second remarkable result from our study is the relative flatness of the disk Hα profiles, implying a SFR which is fairly constant with radius. The only exceptions to this are NGC 2835 (which also lacks the high levels of nuclear star formation discussed earlier) and NGC 1313 (which as we shall see has an anomalously high disk SFR). Previous Hα photographic studies by Hodge and Kennicutt (1983) and Kennicutt (1989) claimed that the outer Hα profiles of spiral disks could be fitted exponentially, and that the scale lengths agreed well with those determined from 'white-light' photometry in the literature. They took this as evidence that the large-scale distribution of disk star formation has not changed significantly with time, and that since the Hα traces a different mass regime from the white light, then the initial mass function must be fairly constant with radius.

Our Hα profile 'scale lengths' are always longer than that of the underlying stellar disk, not to mention one or two cases where the profile starts to rise in the outer parts. Admittedly our Hα profiles do not always extend out as far as Kennicutt's (1989) threshold values, partly due to the still limited spatial coverage of the CCD + focal reducer combination. Nevertheless, aside from the enhancements due to spiral arms, they do exhibit fairly flat behaviour over an appreciable radial extent (at least three broadband scale lengths). Kennicutt counted H II regions in elliptical annuli then appealed to the constancy of the H II region luminosity function with radius (Kennicutt *et al.* 1989) to equate star formation *distribution* with star formation *rate*. Our technique integrates *all* the Hα flux in the elliptical annuli, including the diffuse component from unresolved H II regions which can be significant especially in the early-type galaxies and inter-arm regions. This may partly explain the difference in our findings.

In order to investigate the level of ongoing star formation in the disk, a smooth curve has been drawn through each disk Hα profile and a characteristic peak surface brightness determined for each. These numbers, together with their corresponding specific SFRs are also listed in Table 1. We see once again that NGC 1313 has a surprisingly high rate of star formation for its absolute magnitude and may in fact be undergoing a mild starburst. Its morphology, kinematics and behaviour are in fact quite similar to those of the Magellanic Irregulars.

Wevers (1984) showed peak H I surface densities in spiral disks of 1–10$M_\odot$ pc^{-2}, while Lord and Young (1990) deduced (H_2 + He) surface densities of 30–100$M_\odot$ pc^{-2} in the disk of the Sbc spiral M51. Thus even the large-scale underlying star formation in the disk is capable of consuming a large percentage of the available disk gas in only half a Hubble time, and the enhancements caused by the passage of a spiral density wave will only accelerate this process. We are led to the conclusion that the gas supply in the disk is somehow being maintained, perhaps by radial inflow, as this would also be needed to feed the ongoing nuclear star formation.

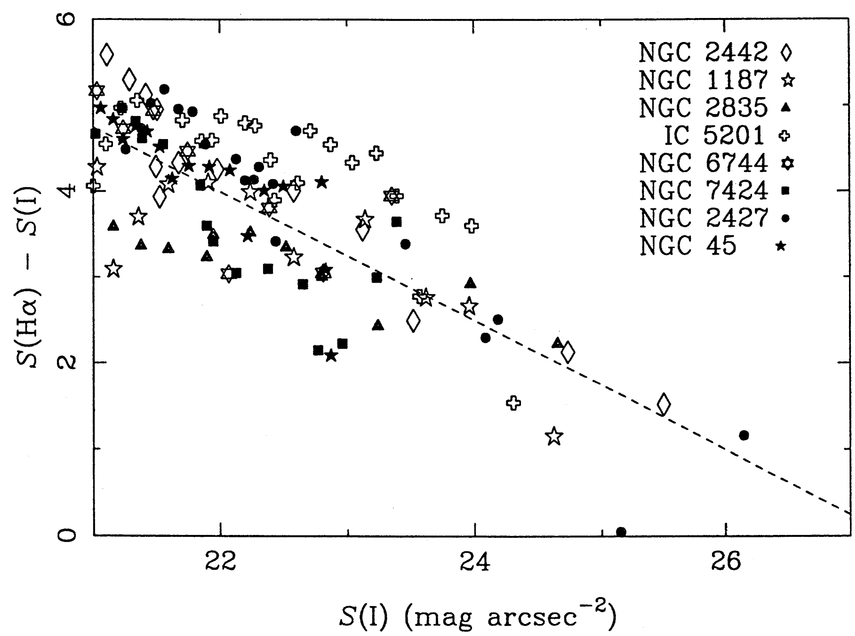

Fig. 2. Plot of S(Hα) − S(I) 'colour' versus I surface brightness S(I) in the disks of all sample galaxies with the exception of NGC 1313, which exhibits an anomalously high disk SFR. The dashed line is a least squares fit to the data points.

We can also investigate the relationship between the SFR and the surface density of stars already formed by comparing the Hα surface brightness profiles with the V and I profiles. Does there exist a common ratio of SFR/I as a function of I for all the galaxies in our sample? The surface brightness profiles indicate that the disk dominates for I fainter than about 21 mag arcsec^{-2}. In Fig. 2 we have plotted the $[S(\mathrm{H}\alpha) - S(\mathrm{I})]$ 'colour' against $S(\mathrm{I})$ [where $S(\mathrm{H}\alpha)$ and $S(\mathrm{I})$ denote the surface brightness in Hα and I respectively] for all the galaxy disks with the exception of the anomalous NGC 1313. A scatter of less than one magnitude rms in $[S(\mathrm{H}\alpha) - S(\mathrm{I})]$ over some five orders of magnitude in disk surface brightness is quite remarkable, and demonstrates that there is indeed a simple law relating the expected SFR to the observed I surface brightness. The dashed line is the best least squares fit, given by

$$S(\mathrm{H}\alpha) - S(\mathrm{I}) = -0{\cdot}75\, S(\mathrm{I}) + 20{\cdot}5\,.$$

We have, thus,

$$S(\mathrm{H}\alpha) = 0{\cdot}25\, S(\mathrm{I}) + c\,,$$

where c is a constant dependent on the zero-point of the Hα magnitude scale. Since

$$S(\mathrm{H}\alpha) \propto \log\frac{L(\mathrm{H}\alpha)}{\text{unit area}}\,,$$

then the Hα surface brightness can be related to a specific SFR (i.e. per unit area of the disk); similarly the I surface brightness can be related to a stellar mass surface density μ_* via a mass-to-light ratio. The above relation between $S(\mathrm{H}\alpha)$ and $S(\mathrm{I})$ can therefore be expressed as a power law:

$$\frac{\mathrm{SFR}}{\text{unit area}} \propto \mu_*^{1/4}\,.$$

Thus the specific SFR in spiral disks is fairly insensitive to, but distinctly related to the surface density of stars already formed in the disk.

The implications of such a shallow SFR distribution in spiral disks are again significant and could cast some doubt on the conclusions of Kennicutt (1989) listed earlier. Either the IMF is a function of galactocentric radius, or it is not, in which case the V and I exponential disks should themselves become shallower with time, as a fixed amount of new star formation makes less of a contribution in high surface brightness areas than in low ones. Such an effect might manifest itself in the colour gradients, except that they are themselves a complex function of the star formation and chemical evolution history of the individual galaxy. In an effort to resolve some of these issues, we are currently measuring abundance gradients for a few of these galaxies from spectrophotometry of their H II regions.

5. Summary

We have carried out a consistent CCD imaging survey in the V, I and Hα line emission bands of several nearby spiral galaxies in the southern hemisphere. Ellipse fitting has been used to determine the disk inclinations and position angles, from which appropriate elliptical apertures have been used to measure deprojected surface brightnesses as a function of galactocentric radius. Analysis of a sub-sample of nine mainly barred spirals has revealed the following characteristics:

(1) In spite of the expected high extinction and possible non-thermal contributions, clear excesses of Hα emission have been found in the nuclei of nearly all the barred spirals, suggesting ongoing massive star formation there. This fits in with the inferred gas infall and streaming along the bar and would by now have consumed much of the gas available in the bulge region.

(2) Disk Hα profiles are usually much shallower than the broadband exponential disk. The rate of star formation in the disk is only weakly affected by the density of stars already formed, and would also rapidly deplete the available gas supply unless it could be replenished, say by radial inflow or continual infall of gas onto the disk.

Clearly, if these results are borne out by the rest of the galaxies in our sample then we may have to seriously rethink many of our ideas about the rates, mechanisms and distribution of star formation in spiral galaxies.

Acknowledgments

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