A test of arm–induced star formation in spiral galaxies from near–IR and $\text{H}\alpha$ imaging

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ABSTRACT

We have imaged a sample of 20 spiral galaxies in $\text{H}\alpha$ and in the near–infrared $K$ band (2.2 $\mu$m), in order to determine the location and strength of star formation in these objects with respect to perturbations in the old stellar population. We have found that star formation rates are significantly enhanced in the vicinity of $K$ band arms. We have also found that this enhancement in star formation rate in arm regions correlates well with a quantity that measures the relative strengths of shocks in arms. Assuming that the $K$ band light is dominated by emission from the old stellar population, this shows that density waves trigger star formation in the vicinity of spiral arms.

Key words: galaxies: fundamental parameters – galaxies: ISM – galaxies: spiral – galaxies: stellar content – infrared: galaxies

1 INTRODUCTION

Two of the leading theories of star formation in spiral galaxies use the concept of a density wave, either as the actual triggering mechanism, or as a means of organisation of star–forming material. The first of these theories has been termed the large scale galactic shock scenario (Roberts 1969; see also Shu et al. 1972; Tosa 1973; Woodward 1975; Nelson & Matsuda 1977). This model hypothesises that the gas settles into a quasi–stationary state, with a velocity and density distribution that is driven by the gravitational field of the galaxy. The gas response can be non–linear to an imposed azimuthal sinusoidal potential, if relative motion between the density wave and the cold interstellar medium (ISM) is supersonic (Binney & Tremaine 1987). This leads to the formation of a shock near the trailing edge of spiral arms, assuming that the region is inside the corotation radius, which compresses the gas to densities at which stars can form. Observations of spiral galaxies the shock is thought to be characterised by dust–lanes seen on the trailing edges of arms. The time delay needed for the onset of star formation after the compression of the gas implies that star–forming regions should be seen towards the leading edges of arms.

Many of the recent advances in this area have arisen from studies of the atomic and molecular gas in nearby spiral galaxies, through HI and CO line emission (e.g Nakai et al. 1994; Rand 1993, 1995). These studies reveal streaming velocities of gas through the spiral arms and find offsets between the peaks of the gas density and the old stellar population, in agreement with the predictions of the large scale shock scenario.

The alternative picture to this form of triggered star formation is stochastic star formation. Ópik (1953) first hypothesised that a supernova explosion could trigger star formation. A model proposed and developed by several authors (e.g. Gerola & Seiden 1978; Seiden & Gerola 1982; Seiden 1983; Jungwiert & Palous 1994; Sleath & Alexander 1995, 1996) suggests that the dominant process for forming stars is stochastic self–propagating star formation, and not density wave triggering. In this model, density waves are only responsible for the organisation of the ISM and stars, and for concentrating new HII regions along spiral arms (Elmegreen & Elmegreen 1986; Elmegreen 1993). Thus, star formation rate efficiency (i.e. normalised to unit mass of disc material) should be unaffected by location in arm or interarm regions, in this model. This is in clear distinction to the predictions of the large–scale shock model.

Previous $\text{H}\alpha$ studies of spiral galaxies (Kennicutt 1989, 1998a; Kennicutt, Tamblyn & Congdon 1994; and the review by Kennicutt 1998b) have mainly looked at global star–formation, particularly the form of the Schmidt law (Schmidt 1959, 1963). In this paper we are looking at localised star formation in disc galaxies as well as global properties of star formation, and comparing the distribution of star formation with the underlying old stellar population. The main aim of this paper is the analysis of star formation efficiencies in arm and interarm regions in spiral galaxies.
Other studies of star formation efficiencies include Lord & Young (1990) and Tacconi & Young (1986). Lord & Young (1990) looked at the molecular, neutral, and ionized hydrogen distributions in M51. They compared a ratio of massive star formation rates (MSFR) to gas surface density between arm regions and interarm regions and found a higher ratio in the arm regions. Tacconi & Young (1986) performed a similar analysis for NGC 6946 and also found that star formation is more efficient in arm regions than in interarm regions. Cepa & Beckman (1990) and Knapen et al. (1992) again looked at star formation efficiencies in arm and interarm regions, but with high spatial resolution. Cepa & Beckman (1990) compare the $\text{H}\alpha/\sigma_{\text{HI}}$ ratio (where $\sigma_{\text{HI}}$ is the HI surface brightness) in the arm and interarm regions of NGC 3992 and NGC 628. Knapen et al. (1992) compare the $\text{H}\alpha/\sigma(H_2+\text{HI})$ ratio in arm and interarm regions. Both Knapen et al. (1992) and Cepa & Beckman (1990) explicitly find evidence for spiral arm triggering of star formation, via a non-linear dependence of SFR on gas density. Wyder, Dolphin & Hodge (1998) obtained HST WFPC2 $V$ band (F555W) and $I$ band (F702W) data of the spiral galaxy NGC 4321. From the $I$–$V$ colour of the arm and interarm regions, they concluded that the SFR over the last 5 Myr has been approximately 4 times larger in the arm regions than in the surrounding interarm regions. Also, Knapen (1998) performed a study of HI regions in M100, using a new H$\alpha$ image. He found that the arms collect HI regions in a similar way to that described by Elmegreen & Elmegreen (1986). He concluded that spiral arms may trigger some star formation, but do not affect the HI region luminosity function or mass distribution. Finally, Alonso-Herrero & Knapen (2001) used the specific SFR or SFR per stellar mass (i.e. a comparison of Pa$\alpha$ flux with $H$ band continuum emission), and found that while the specific SFR in the central region does not vary statistically with galaxy type, it is higher in barred than in non-barred galaxies.

The remainder of this paper is arranged as follows. Section 2 describes the observations and data analysis; section 3 describes local star–formation rates with respect to properties of spiral structure; and section 4 contains our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

In this sample, 14 of the galaxies were selected as part of a program designed to understand the underlying structure of galaxies. The selection of these galaxies, and near–IR observations and data reduction, is described in Seigar & James (1998a). Briefly, the full galaxy sample is comprised of 45 spirals of types Sa–Sdm, with inclinations $\leq 45^\circ$ and diameters $\leq 15'.5$, the latter enabling them to be imaged in the field of the UKIRT near–IR camera IRCAM3. A further 5 galaxies have been observed with the UKIRT Fast Track Imager (UFTI), with the same selection criteria. The final galaxy was observed with INGRID on the William Herschel Telescope (WHT), again with the same selection criteria, except its diameter was chosen to be $\leq 4'.5$.

The optical data presented here are broad–band (R) and narrow–band (redshifted H$\alpha$) images of the 20 galaxies described above. The observations were made using the 1.0m Jacobus Kapteyn Telescope (JKT) on La Palma. Some of the galaxies were observed on the nights 1998 May 14–20, with some additional observations being taken during a later run, 1999 February 4–11, using the 1024×1024 Tek4 CCD camera which has 0.331 pixels and a field of 5'65×5'65. The rest of the objects were observed between February 2000 and January 2002, using the 2048×2048 SSTe2 CCD camera, which has 0.33 pixels and a field of 11'3×11'3. The filters used were standard Harris R filter, and narrow–band filters with the following central wavelengths in Angstroms (full–width at half maximum in brackets): 6504(44), 6626(44), 6656(44), 6686(44), 6695(53), 6712(42), 6727(48), 6785(58). Measured transmission curves are available for all these filters, and were used in selecting the optimum filter for each galaxy redshift, and in flux calibrating the images, as described below.

All 20 galaxies were observed in redshifted H$\alpha$ filters, with between one and four 1200 second integrations for each galaxy. All were also observed at R with integration times of 300–900 seconds. In addition, the following standard stars, selected from Landolt (1992), were observed: PG1047+003 A, B & C; PG1323–086 A, B & C; PG1633+099 B, C & D; SA111–773; and SA111–775. Two spectrophotometric standards from Oke (1990), Feige 34 and G191B2B, were also observed.

Data reduction made use of standard STARLINK image reduction packages. All images were bias subtracted, and then flat fielded using twilight sky flats. There was no evidence for any fringing effects in broad– or narrow–band images. The H$\alpha$ images were continuum–subtracted using scaled R band images. The scaling factor applied to the R band images was calculated photometrically, using the ratio of fluxes of red standard stars from the Landolt (1992) list. These values were checked using the spectrophotometric standards from Oke (1990), to ensure that the red standards did not have strong spectral features in the passband of the H$\alpha$ filter, and by numerically integrating under the filter profiles. All methods gave very similar results, but the red standards were adopted as best representing the colour of the galaxy continuum light. The throughputs of the narrow band filters to continuum light were measured in this way to be between 36 and 64 times lower than that of the R band filter. The narrow–band images were continuum subtracted by normalising broad– and narrow–band images to the same integration time, dividing the former by the ratio of the throughputs, and subtracting this scaled broad–band image.

Calibration of the H$\alpha$ photometry required calculation of the effective throughput of the narrow–band filter to H$\alpha$ light. This was done by calculating the throughputs of both narrow– and broad–band filters at the wavelength corresponding to redshifted H$\alpha$, for each galaxy, from the measured transmission curves. The narrow–band transmission was then corrected by subtracting the broad–band transmission, scaled by the ratio of continuum throughputs (36–64, as given above). Given the large size of this factor, the continuum subtraction works well, even though the R band filter contains the H$\alpha$ line, and the only effect of this is to reduce the effective throughput for H$\alpha$ emission by a few percent. Effective throughputs calculated in this way were in the range 28–50%, typically ~45%.

This continuum subtraction procedure worked extremely well, with the only problems being flat–fielding
residuals which were apparent in some of the continuum (R band) images taken in bright moonlight, and a slight change in plate–scale between the broad– and narrow–band images, which was not significant over the size of the galaxies in this study. The accuracy of the continuum subtraction was confirmed by the almost complete removal of old–stellar light in the resulting line images.

The photometry was obtained using the STARLINK software package GAIA. This extracted Hα fluxes as raw counts, which were then corrected for airmass, using a correction based on the R band observations of the standard stars listed above. A correction was then applied for the effective throughput of the narrow–band filter to the redshifted Hα radiation as described above.

Photometry was then obtained using the STARLINK software package GAIA. This extracted Hα fluxes as raw counts, which were then corrected for airmass, using a correction based on the R band observations of the standard stars listed above. A correction was then applied for the effective throughput of the narrow–band filter to the redshifted Hα radiation as described above.

Table 1 contains the following entries: Galaxy name (column 1), galaxy classification (column 2), heliocentric redshift in km s$^{-1}$ (column 3) and the telescope and instrument with which they were observed (column 4).

| Galaxy name | Galaxy Classn. | $V_{rec}$ (km s$^{-1}$) | Telescope/instrument |
|-------------|----------------|-------------------------|---------------------|
| IC 742      | SBab           | 6425                    | UKIRT/IRCAM3        |
| NGC 2628    | SAbc           | 3622                    | UKIRT/IRCAM3        |
| NGC 5737    | SBb            | 9517                    | UKIRT/IRCAM3        |
| NGC 6347    | Scd            | 6144                    | UKIRT/IRCAM3        |
| NGC 6379    | Sb             | 5973                    | UKIRT/IRCAM3        |
| NGC 6574    | SAbc           | 2282                    | UKIRT/IRCAM3        |
| UGC 3053    | Scd            | 2407                    | UKIRT/IRCAM3        |
| UGC 3171    | SBcd           | 4553                    | UKIRT/IRCAM3        |
| UGC 3296    | Sab            | 4266                    | UKIRT/IRCAM3        |
| UGC 3578    | Sab            | 4531                    | UKIRT/IRCAM3        |
| UGC 3936    | SBBc           | 4725                    | UKIRT/IRCAM3        |
| UGC 4270    | SABBc          | 2479                    | UKIRT/UFTI          |
| UGC 4705    | SBB            | 2526                    | UKIRT/UFTI          |
| UGC 4779    | SAc            | 1289                    | WHT/INGRID          |
| UGC 5433    | SABB           | 5580                    | UKIRT/IRCAM3        |
| UGC 5786    | SABBc          | 993                     | UKIRT/UFTI          |
| UGC 6132    | SBb            | 979                     | UKIRT/UFTI          |
| UGC 6332    | SBA            | 6245                    | UKIRT/IRCAM3        |
| UGC 7985    | SABd           | 652                     | UKIRT/UFTI          |
| UGC 11524   | Sc             | 5257                    | UKIRT/IRCAM3        |

3 RESULTS

In this section we look at how density waves affect the local star formation rates within the discs of individual galaxies, even though other factors such as cold gas mass or galaxy environment may dominate the differences in star formation rate between galaxies. To test the local effect of arms, we compared the degree of concentration of Hα and K band light in the arms of the present galaxy sample. We use the Hα data as an indicator of star formation rate and the K band data as a tracer of where the density waves are (the K band largely reflects old stars, which is a good tracer of the overall stellar mass density, and hence of density waves within discs). If the simple model of Elmegreen (1993) is true, the density waves should simply gather up all types of disc material to the same extent, and the same arm–to–interarm contrast should be seen in all disc tracers. Then, arms would be just as prominent in the near–IR emission from old stars as in the Hα emission from star–formation regions. If, however, spiral density waves trigger star formation to a significant extent, then the arm–to–interarm contrast could be substantially enhanced in the star–formation tracer relative to the old stellar population. Note that this rather naive argument neglects the effects of extinction, but since the optical light is likely to be more affected than the near–IR, any relative enhancement in Hα arm contrasts compared to say the K band should be a strong indication of arm–induced star formation.

3.1 A comparison of Hα/K ratios for arm and interarm regions

In order to measure any enhancement in Hα arm contrasts compared to K band arm contrasts, we came up with the following conservative test, which is based on the technique used to measure star–formation efficiency by Knapen et al. (1996), to identify arm–induced star formation in the present sample of galaxies. For those galaxies which showed well–defined spiral arms in their K band images, we rebinned the K images to the same pixel scale as the Hα images, and shifted them to overlay the Hα images, using stellar centroids as references. This procedure should be accurate to a fraction of a pixel, or better than 0′.1. We then used the ‘ARD region’ option within the STARLINK GAIA package to define a polygon lying around each K band arm, without reference to any of the optical images. Elliptical regions were also fitted by eye to define the disc of the galaxy, excluding the central bulge, and extending to the outer ends of the spiral arms. The images were sky subtracted, and then the number of detected counts within each of the arm polygons, and the overall disc, were calculated. GAIA then permits the apertures to be imported into the Hα images, which had been aligned exactly, such that the apertures lie over the same physical regions of the galaxies at both K and Hα. Photometry was then obtained for all regions (arms, total disc and nucleus) in the Hα images in exactly the same way as for the K images. Finally, ratios were calculated of Hα flux divided by K band flux for all of the regions. The test is then to see whether this ratio is larger for the arm regions than for the disc generally, where the latter ratio is taken from the total disc minus the central region. Any obvious foreground stars are removed from from the arm and disc regions before this comparison is done.

If arms represent regions where all disc material is concentrated by an equal factor, then the Hα/K ratio would be the same in arms as in the disc overall. If there were no connection between star formation and K band structure, then this ratio would be lower in the selected arm regions, since these were chosen to have higher than average K surface brightnesses. However, in the majority of cases, we found Hα/K ratios to be significantly higher in the K band arms than in the discs generally. We measured a total of 49 arm regions in 20 galaxies (see Table 2); 38 (76%) of these arms had Hα/K ratios greater than that of the
the same analysis for the original H\(\alpha\) in the sky background from the H\(\alpha\) calculated by both adding and subtracting the uncertainty ratio within their arm regions. The errors in table 2 were changed had we used checked that the location of the arms would not have been

ing of triggering of star formation within spiral arms. We

nature of the test, this represents a highly significant find-

which may be affected by starbursts. Given the conservative

the median ratio in order to give less weight to galaxies

in the arms than in the corresponding discs. We have taken

for all 49 arms, the median ratio was 1.47

atic variations in the sky structure. Combining the results

in the sky background was calculated using both the formal

image added by the sky background uncertainty. The error

\(\alpha\) subtracted by the sky background uncertainty, and the H\(\alpha\) band image, but there is little or no H\(\alpha\) K

UGC 3053 exhibits 3 well–defined arm segments in its

HII regions associated with these arms. This is reflected in

contribute to galaxy light at

K

J

rather than

K

images, and thus our

images, and performing

K

ratios.

offset between the dust lane and the peak of the induced star formation.

Two of the galaxies warrant further comment. UGC 3053 exhibits 3 well–defined arm segments in its K band image, but there is little or no H\(\alpha\) luminosity from HIII regions associated with these arms. This is reflected in the low H\(\alpha\)/K ratios for all three arm regions in this galaxy, which thus appears to have no arm–induced star formation according to this test. UGC 6332 has two tightly wound arms, which could be classified as a single ring, and which appear highly symmetrical in the K image. However, this symmetry breaks down completely in H\(\alpha\) light, since one arm is clearly associated with a string of HIII regions, and the other with no detectable HIII regions at all. As a result, these two arms give rise respectively to the second–highest, and to easily the lowest, of the 49 measured H\(\alpha\)/K ratios. This asymmetry could be an extinction effect, due to the

Table 2. Normalised H\(\alpha\)/K ratios for 49 arm regions in 20 galaxies.

| Galaxy name | Arm 1 | Arm 2 | Arm 3 | Arm 4 | Average |
|-------------|-------|-------|-------|-------|---------|
| IC 742      | 1.19±0.12 | 1.48±0.13 | –     | –     | 1.33±0.18 |
| NGC 2628    | 0.95±0.04 | 1.48±0.06 | 1.73±0.10 | 1.32±0.08 | 1.37±0.10 |
| NGC 5737    | 1.45±0.07 | 1.12±0.12 | –     | –     | 1.29±0.12 |
| NGC 6347    | 1.89±0.08 | 1.19±0.06 | –     | –     | 1.54±0.10 |
| NGC 6379    | 3.35±0.18 | 1.81±0.13 | 0.77±0.13 | –     | 1.98±0.13 |
| NGC 6574    | 1.17±0.09 | 1.39±0.09 | 0.87±0.09 | 1.67±0.09 | 1.28±0.09 |
| UGC 3053    | 0.78±0.06 | 0.93±0.09 | 0.58±0.06 | –     | 0.76±0.06 |
| UGC 3171    | 1.21±0.15 | 2.59±0.21 | 1.21±0.08 | 1.56±0.12 | 1.64±0.12 |
| UGC 3286    | 1.03±0.12 | 1.68±0.08 | –     | –     | 1.36±0.12 |
| UGC 3578    | 1.95±0.22 | 2.14±0.16 | –     | –     | 2.05±0.19 |
| UGC 3936    | 1.23±0.11 | 1.01±0.09 | 0.90±0.08 | –     | 1.05±0.09 |
| UGC 4270    | 1.02±0.10 | 1.20±0.05 | –     | –     | 1.10±0.08 |
| UGC 4705    | 2.49±0.41 | 0.94±0.19 | –     | –     | 1.72±0.32 |
| UGC 4779    | 1.71±0.19 | 2.29±0.27 | –     | –     | 2.00±0.23 |
| UGC 5434    | 1.79±0.13 | 0.86±0.05 | –     | –     | 1.32±0.12 |
| UGC 5786    | 2.17±0.29 | 0.97±0.01 | –     | –     | 6.02±0.54 |
| UGC 6132    | 1.53±0.23 | 2.20±0.32 | –     | –     | 1.87±0.25 |
| UGC 6332    | 2.95±0.09 | 0.32±0.08 | –     | –     | 1.63±0.29 |
| UGC 7985    | 2.34±0.27 | 1.90±0.20 | –     | –     | 2.12±0.17 |
| UGC 11524   | 0.87±0.30 | 1.91±0.46 | –     | –     | 1.39±0.30 |

Figure 1. H\(\alpha\)/K ratio versus Arm EA/Arm FWHM ratio.

3.2 The effect of arm strength on star formation rate

A further test of arm induced star formation is to see if the enhancement in H\(\alpha\) flux in the arm regions relates to the strength of shocks in the arms. Seigar & James (1998b) used the ratio between arm equivalent angle (EA) and arm full
width half maximum (FWHM) as measured from K band images, as a measure of the relative strength of shocks in spiral arms. From here on, we refer to this ratio as the ‘central arm contrast’. Arm EA is defined as that angle subtended by the disc that contains an amount of light equivalent to that in the spiral arm (see Seigar & James 1998a for a detailed discussion) and is therefore a measure of the amount of light contained in a spiral arm. However, it contains no information about how concentrated the light from the arm is, and this is the justification in dividing this quantity by arm FWHM (measured from the cross-sectional light profiles of K band arms) to estimate the ‘central arm concentration’. If shocks are necessary to drive star formation, it seems reasonable that an arm with a high central arm concentration will be more efficient at forming stars than an arm with a low central arm concentration. We have investigated the relationship between this quantity and the Hα/K ratios measured in Table 2. The result is shown in Figure 1. One galaxy is left out of this plot, UGC 5786, which is an HII galaxy, and may have processes other than arm induced star formation, contributing to its extraordinarily high star formation rate. Figure 1 shows a non-linear relationship between these two quantities, which is significant at the 99.93% confidence level. It therefore seems that the star formation in spiral galaxies is triggered by shocks in arms, up to a certain limiting threshold, where Hα/K~2.

3.3 The star formation rate in UGC 5786

Finally, UGC 5786 (NGC 3310) has a strong ring of star formation at an average radius of 0.42±0.06 kpc from its centre. The ring of star formation observed in this galaxy has been the subject of many previous studies (e.g. Elmegreen et al. 2002). Rings of nuclear star formation are typically associated with the Inner Lindblad Resonance (ILR) and have been found in other galaxies, e.g. M 74 (Wakker & Adler 1995; James & Seigar 1999). It should also be noted that UGC 5786 is classified as an HII galaxy. Bell & Kennicutt (2001) report an Hα luminosity, \( L_{H\alpha} = 3 \times 10^{41} \) ergs s\(^{-1}\). Using the following equation,

\[
SFR(M_\odot/yr) = 7.9 \times 10^{-42} L_{H\alpha}(\text{ergs s}^{-1})
\]

they calculated a SFR of 2.37 M_\odot/yr. We have measured an \( L_{H\alpha} = (1.336\pm0.084)\times10^{42} \) ergs s\(^{-1}\). Also using Equation 1, we have calculated a SFR of 10.55\pm0.66 M_\odot/yr. This is clearly in disagreement with the SFR reported in Bell & Kennicutt (2001). It should be noted that we calculated a distance of 18.2 Mpc from a Virgo-centric inflow model (and using Hα=75 kms\(^{-1}\)Mpc\(^{-1}\)) for UGC 5786, whereas Bell & Kennicutt (2001) use the distance calculated by Waller et al. (1997), which is 13.9 Mpc. However, even taking into account this difference in measured distances to UGC 5786, our SFR is still a factor of \( \sim 2.6 \) larger than that reported by Bell & Kennicutt (2001).

4 CONCLUSIONS

We have found an increase in Hα flux in the vicinity of K band arms in this sample. If the K band arms are dominated by light from the old stellar population, then this can be interpreted as star formation triggered by a density wave. This result is in agreement with Lord & Young (1990), who found a higher star formation efficiency in arm regions. It also agrees with Cepa & Beckman (1990) and Knapen et al. (1992) who found evidence for spiral arm triggering of star formation via a non-linear dependence of SFR on gas density. This result therefore agrees with the large scale shock scenario (Roberts 1969; Shu et al. 1972; Tosa 1973; Woodward 1975; Nelson & Matsuda 1977), which predicts a higher star formation efficiency in arm regions. It does not support the ideas of stochastic self-propagation star formation (e.g. Gerola & Seiden 1978; Seiden & Gerola 1982; Seiden 1983; Jungwiert & Palous 1994; Sleath & Alexander 1995, 1996) which predict no change in the star formation efficiency from interarm to arm regions.

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