Star formation rates, efficiencies and initial mass functions in spiral galaxies

I. Method

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Abstract. A new method of evaluating relative (arm with respect to the interarm disk) star formation rates and relative star formation efficiencies, together with spiral arm-amplitudes, as a function of the galactocentric radius, using broad-band photometry is derived. The classical method for obtaining star formation rates from H\textalpha photometry is discussed, and a new method is derived for diagnosing the possible presence of biased star formation due to different initial mass functions in the arms and in the interarm disk. As an example, these methods are applied to the spiral galaxies NGC 4321 and NGC 4254, obtaining their arm amplitudes, relative arm/interarm star formation efficiencies, and relative arm/interarm initial mass functions for each arm, as a function of the galactocentric radius. Both objects present evidence of massive star formation triggering in the spiral arms consistent with the spiral density-wave theory, and a different initial mass function in the arms from that in the rest of the disk, in the sense of favoring a larger fraction of massive stars in the arms. This biased star formation is present in the zones of the arms where there is triggering of massive star formation, and is then related to, and probably caused, by the density-wave system. However, due to this biased star formation, the spiral arms of the galaxies studied do not trigger the formation of a larger total mass of stars (of all spectral types) with respect to the interarm disk.

Key words: galaxies: NGC 4321, NGC 4254 – galaxies: spiral – galaxies: stellar content – galaxies: structure – stars: formation

1. Introduction

Since the first steps by Lindblad (1959) in the search for a theory to explain spiral structure in galaxies harmonizing permanent structures in the disk with its differential rotation—thus avoiding the “winding dilemma”—and the

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formulation of Lin (1968) in what would become the spiral density-wave theory, our conceptions about the origin of spiral structure and its relation with star formation have evolved, although not so dramatically as might be expected. Some points seem reasonably established, such as the presence of density waves in the disk (Elmegreen & Elmegreen 1984), while others remain controversial. Can the arms propagate through corotation (Patsis et al. 1994, and references therein)? Do density waves enhance star formation in the arms? Regarding this point, Elmegreen & Elmegreen (1984) found that grand-design spirals (those with continuous, well-defined arms) have stronger density waves than flocculents (those with patchy and less well-defined arms), but that the arms of grand-design galaxies were nearly purely density wave enhancements. Moreover, from the analysis of several star formation tracers, Elmegreen & Elmegreen (1986) found that the star formation rate per unit area is virtually the same in flocculent that in grand-design galaxies, concluding that density waves do not significantly enhance star formation in the arms with respect to that in the interarm disk. From this and similar studies, such as that of McCall & Schmidt (1986), it seemed that the mechanism accounting for star formation in the arms would probably be self-propagating star formation as that proposed by Gerola & Seiden (1978), instead of a shock triggered when the material of the disk in its differential rotation encounters the density wave at supersonic speeds. This line of thought was reinforced by the findings of Lubow, Balbus & Cowie (1986), who showed that when taking into account the viscosity of the gas and/or gas gravity the gas does not shock. However, Cepa & Beckman (1990a), studied the efficiency of the massive star formation (say the massive star formation rate per unit mass of gas) in the arms with respect to that in the interarm disk (the so-called relative massive star formation efficiency) as a function of the galactocentric radius for some grand-design spirals and an intermediate-arm type one (M 33), finding that the spiral arms of the grand-design galaxies studied were more efficient at forming stars than the interarm disk by a factor ranging from 2 up to 15 or more, showing a pattern of peaks and troughs coinciding with the position of the resonances and corotation radius predicted by the density-wave theory, when a pattern speed is fitted to the curves \( \Omega_p = \Omega \pm \kappa/m \), where \( \Omega_p \) is the pattern speed, \( \Omega \) is the rotation curve, \( \kappa \) is the epicyclic frequency and \( m \) is the number of arms. This, and similar results that followed (Cepa & Beckman 1990c), led to the conclusion that some mechanism is bound to be forming stars in the spiral arms in a different way than in the interarm disk and consistently with the spiral density-wave predictions. Moreover, this behavior was not observed in the case of the intermediate-arm type galaxy studied (M 33), indicating that perhaps in at least some intermediate-arm type spirals the mechanism forming stars in the arms could be a self-propagating one, operating in the arms and in the interarm disk. But, even in this case, some spiral density wave has to be present in the disk to allow a self-stochastic star formation mechanism to form stable spiral arms, since three-dimensional simulations of this mechanism do not form stable spiral arms by themselves (Statler, Comins & Smith 1983).

Some of these results are consistent with those observed by other authors using different techniques (Tacconi & Young 1990 in NGC 6946; Wilson & Scoville 1991 in M 33). Although this could seem to be in contradiction with the studies of Elmegreen & Elmegreen (1986) and Lubow, et al. (1986), it was pointed out by Cepa & Beckman (1990b), on the basis of Elmegreen & Elmegreen’s (1986) results, that if the star formation rate is not averaged over the entire
disk and only those parts of the disk where the star formation is taking place are taken into account, the star formation rate per unit area of star forming zones could be as much as 6 times larger in grand-design than in flocculent spirals. Also, star formation could be enhanced in the arms by mechanisms other than a large-scale shock (Elmegreen 1992, 1994), and hence the expression “star formation front” would, in general, be more accurate than “shock front”.

However, the studies of relative arm/interarm star formation efficiencies mentioned above require spatially resolved measures of the HI and CO over the whole disk of a galaxy, which limits the rate of data acquisition, thereby hampering statistically significant results unless large amounts of radio observing time are employed. There are also additional observational difficulties: the resolution required for this kind of work is critical and should be of the order of a star forming region, i.e., ~0.5 kpc (Cepa & Beckman 1990a), otherwise the arm/interarm CO contrast is underestimated. This resolution is difficult to achieve and slow to map in CO unless interferometric techniques are employed, in which case, and given the size of nearby galaxies, a mosaic of observations is needed (again slow to map). It could also be difficult to detect interarm CO using interferometers. Other critical points are that the conversion factor from CO to H$_2$ (Garcia-Burillo & Guélin 1990), the initial mass function (see, for example, Shu, Adams & Lizano 1987, and references therein), and the physical properties of HII regions, could be different in the arms from those in the interarm disk, and that the optical measures (to get the star formation rate) could be significantly affected by extinction. All these effects may cause severe alterations, either increasing or lowering the measures of arm/interarm efficiency ratios by a factor difficult to estimate, depending on the galaxy and the galactocentric radius within a given galaxy.

The methods proposed in the present work allow the measurement of relative arm/interarm (or in general from one zone of the disk with respect to another) star formation rates and star formation efficiencies as a function of the galactocentric radius using optical broad- and narrow-band (H$_\alpha$ and H$_\beta$) imaging observations only. It is possible then not only to study these parameters for a larger sample of galaxies in a more efficient way, since no radio measurements are needed, but also, from the narrow-band data, to correct for extinction and to diagnose possible differences between the initial mass function in the arms and the interarm zone, thus avoiding most of the uncertainties mentioned in the previous paragraph.

The method is described in § 2. Section 3 describes the observations, data reduction, flux calibration and the procedure followed to apply the method to the observed spirals, while the results are discussed in § 4. Finally, a summary is given in § 5. In this paper we present the method and an example of the application to two grand-design spirals. In Paper II we will present the results obtained for a larger sample of objects of different arm types.

2. Method
2.1. Relative star formation rates

We consider the total luminosity of a massive star forming zone (i.e., an HII region) in the disk of a galaxy as consisting of the luminosity due to the massive star formation plus the luminosity of the underlying older disk population. The total luminosity at a given $\lambda$ of a massive star forming zone in the interarm disk can then be written as

\[ L_{\lambda}^{\text{IARM}} = L_{\lambda}^{\text{DISK}} + L_{\lambda}^{\text{DSF}} \] (1)

where $L_{\lambda}^{\text{DISK}}$ is the luminosity, at a given $\lambda$, of the underlying older disk, and $L_{\lambda}^{\text{DSF}}$, the luminosity due to the massive star formation in the interarm disk. Also, the total luminosity of a massive star forming zone in the arm is,

\[ L_{\lambda}^{\text{ARM}} = A_* (L_{\lambda}^{\text{DISK}} + L_{\lambda}^{\text{ASF}}) \] (2)

where $L_{\lambda}^{\text{ASF}}$ is the luminosity due to the massive star formation, and $A_*$ is the stellar density contrast (in the arm with respect to the interarm disk). All these quantities depend on the galactocentric radius although the dependence is not explicit to simplify the equations.

The luminosity due to recent star formation can be expressed as a function of the star formation rate ($\psi$), the initial mass function (IMF), $\phi$ and the luminosity, at a given $\lambda$, of the stars of masses between $m$ and $m + dm$,

\[ L_\lambda = \psi \int_{m}^{m+dm} \phi(m) L_\lambda(m) \, dm = \psi \Phi_\lambda \] (3)

Then $\Phi_\lambda$ represent the luminosity per unit mass emitted at $\lambda$ of the stars formed, and (1) and (2) can be written,

\[ L_{\lambda}^{\text{IARM}} = L_{\lambda}^{\text{DISK}} + \psi_{\text{DSF}} \Phi_{\lambda}^{\text{DSF}} \] (4)

and

\[ L_{\lambda}^{\text{ARM}} = A_* (L_{\lambda}^{\text{DISK}} + \psi_{\text{ASF}} \Phi_{\lambda}^{\text{ASF}}) \] (5)

$\psi_{\text{ASF}}$ and $\psi_{\text{DSF}}$ are the SFRs in the arm and in the interarm disk. $\Phi_\lambda$ depends on the IMF and the luminosity of the stars in every range of masses at the given passband $\lambda$, and we will consider that the only possible differences between $\Phi_\lambda$ in the arm and the interarm region will be caused by differences between the IMFs in the arm and the interarm region due to a biased initial mass function.

Using these equations, the relative arm over interarm star formation rate (RSFR) may be expressed,

\[ \text{RSFR} = \frac{A_* \psi_{\text{ASF}}}{\psi_{\text{DSF}}} = \frac{L_{\lambda}^{\text{ARM}} - A_* L_{\lambda}^{\text{DISK}}}{L_{\lambda}^{\text{ARM}} - L_{\lambda}^{\text{DISK}}} \frac{\Phi_{\lambda}^{\text{DSF}}}{\Phi_{\lambda}^{\text{ASF}}} \] (6)

$L_{\lambda}^{\text{ARM}}$, $L_{\lambda}^{\text{IARM}}$ and $L_{\lambda}^{\text{DISK}}$ are observable quantities that can be obtained performing aperture photometry on a spiral arm, a massive star forming zone in the interarm disk, and a zone of the interarm disk with little or no star formation, respectively. The passband $\lambda$ has to be sensitive to star formation, i.e., it has to allow the clear distinction between star forming zones and non-star forming zones. In this work we will use the Johnson $B$ band, which fulfils this requirement.
and is, at the same time, easy to observe (for example, the Johnson $U$ band requires much longer integration times to achieve the same signal-to-noise ratio). Also, is reasonably free of emission lines: only H$\beta$ lies on the red edge of the filter spectral response curve (Allen 1976) at $\sim$50% of the peak response, or even less, given a redshifted systemic velocity.

The stellar density contrast can be estimated from the ratio of arm to interarm disk luminosities of non-star forming zones in a passband less sensitive to star formation, i.e., that approximately traces stellar density variations. We have used the $I$ band, because it is less affected by extinction and is reasonably free of strong emission lines: [O II] at $\lambda\lambda$ 7325 Å lies on the blue edge of the filter at $\sim$65% of the peak response (Benn & Cooper 1987), and [S III] at $\lambda\lambda$ 9069 Å falls on the red edge at $\sim$25% of the peak response (Benn & Cooper 1987), or even less given a redshifted systemic velocity. Then,

$$A = \frac{I_{\text{ARM}}}{I_{\text{DISK}}} K_I$$ (7)

where $K_I$ is a factor to correct for the contribution to $I$ band from newly formed stars in the arm. From Schweizer (1976) it results that $K_I \sim 0.85$, in agreement with the observational result of Elmegreen & Elmegreen (1984).

Finally, using (7) and applying (6) to Johnson $B$ band, (6) can be written,

$$RSFR = \frac{B_{\text{ARM}} I_{\text{DISK}} - K_I I_{\text{ARM}} B_{\text{DISK}}}{I_{\text{DISK}} (B_{\text{ARM}} - B_{\text{DISK}})} \frac{1}{\chi_B}$$ (8)

In general, $\chi_B = \Phi^{\text{ASF}}_B / \Phi^{\text{DSF}}_B \geq 1$. If the IMF is the same over all the disk, $\chi_B = 1$. If the star formation is biased towards a larger fraction of massive stars in the arm with respect to the interarm disk, $\chi_B > 1$. Moreover, in this case the value of $\chi_\lambda$ depends on the passband used: the effect of biased star formation (BSF) would be more noticeable at shorter wavelengths.

All the quantities on the right hand side of (8) are luminosities which can be measured directly, except $\chi_B$, which is not an observable in the present work. Then,

$$RSFR_{\text{meas}} = RSFR \chi_B$$ (9)

and $RSFR_{\text{meas}}$ is the RSFR if no BSF is present, otherwise the factor $\chi_B$ has to be taken into account. Also, $RSFR_{\text{meas}}$ gives an estimate of the relative star formation rate for stars of intermediate masses, i.e., the ones that contribute more to the $B$-band luminosity.

2.2. Relative star formation efficiency

We define the relative (arm with respect to the interarm disk) star formation efficiency (RSFE) caused by density waves as

$$RSFE = \frac{RSFR}{A}$$ (10)
which represents the efficiency of density waves inducing star formation in the arms. From (1):\[\text{RSFE} = \frac{\psi_{\text{ARM}}}{\psi_{\text{DISK}}}\].

As in the case of RSFR,\[\text{RSFE}^{\text{meas}} = \text{RSFE} \chi_B\] (11)

Henceforward, the RSFR$^{\text{meas}}$ and RSFE$^{\text{meas}}$ will be termed intermediate-mass star formation rate and efficiency, respectively.

2.3. Relative massive star formation rates

The H$\alpha$ luminosity ($L_{\text{H}\alpha}$) of a star forming zone can be related with the number of ionizing photons ($N_{\text{UV}}$), assuming case B conditions and spherical HII regions via (Osterbrock 1989):

\[L_{\text{H}\alpha} = h\nu_{\text{H}\alpha} N_{\text{UV}} \epsilon_{\text{eff}} \frac{\alpha_{\text{H}\alpha}}{\alpha_B} \] (12)

where $\nu_{\text{H}\alpha}$ is the frequency of the Balmer $\alpha$ line, $\epsilon$ measures the efficiency of the gas absorbing photons, and $\alpha_{\text{H}\alpha}$ and $\alpha_B$ depend on the temperature (and hence on the position of the HII region), and their values are tabulated for case B recombination (Osterbrock 1989).

By assuming a certain IMF it is possible to relate the H$\alpha$ luminosity with the star formation rate:

\[L_{\text{H}\alpha} = h\nu_{\text{H}\alpha} \epsilon \frac{\alpha_{\text{H}\alpha}}{\alpha_B} \int_{m_B}^{m_U} \phi(m) N_{\text{UV}}(m) \, dm\] (13)

where $m_B$ is the lower mass limit for a star to emit photons with a frequency above the Lyman limit, and $N_{\text{UV}}(m)$ is the number of ionizing photons emitted by a star of mass $m$. This relation will, in general, depend on the position in the disk (due, for example, to different metallicities). Also,

\[N_{\text{UV}}(m) = \int_{\nu_o}^{\infty} \frac{L(m, \nu)}{h\nu} \, d\nu\] (14)

where $L(m, \nu)$ is the luminosity of a star of mass $m$ at frequency $\nu$, and $\nu_o$ is the frequency of the Lyman limit.

Then, if\[Q = \frac{\epsilon_{\text{ARM}} \alpha_{\text{ARM}} \alpha_{\text{ARM eff}}}{\epsilon_{\text{ARM}} \alpha_{\text{ARM}} \alpha_{\text{ARM eff}} \alpha_B} \] (15)

and

\[\chi_{\text{H}\alpha} = \int_{m_B}^{m_U} \frac{\phi_{\text{ASF}} N_{\text{UV}} \, dm}{\int_{m_B}^{m_U} \phi_{\text{DISF}} N_{\text{UV}} \, dm}\] (16)

the relative arm/interarm star formation rate inferred from massive stars can be written, using the same notation as in the previous subsection,

\[\text{RSFR}_{\text{OB}} = \frac{A_{\text{ASF}}}{\psi_{\text{DSF}}} = Q \frac{H_{\alpha}^\text{ARM}}{H_{\alpha}^\text{H II}} \frac{1}{\chi_{\text{H}\alpha}}\] (17)
where $H\alpha^{\text{ARM}}$ and $H\alpha^{\text{IARM}}$ are, respectively, the $H\alpha$ luminosities of a star forming region in an arm and in the interarm disk, respectively, at a similar galactocentric distance $R$ (because quantities in (17) and (15) depend on the position in the disk).

It is difficult to estimate the ratio $Q$ of (17). Let us consider first the ratio between interarm and arm zone of the term $\alpha_{\text{eff}}^{\text{ARM}}/\alpha_B$. This ratio depends on the temperature. The densest HII regions could be situated in the arms, and densest HII regions are likely to be hotter (McCall, Rybski & Shields 1985). If we assume that in the most extreme case HII regions would have a temperature of 15000 K in the arms and 5000 K in the interarm regions, from Osterbrock (1989) it turns out that this ratio takes a value of 1.1. However, the metallicity of HII regions in the arms might be higher, and this effect would tend to lower the temperature (Shields 1990, and references therein). Also, the mean temperature of HII regions in the arms may well be similar to that in the interarm zone, and then the ratio would be of order unity. We can then consider that

$$1.0 \leq \frac{\alpha_{\text{eff}}^{\text{IARM}}}{\alpha_B} \frac{\alpha^{\text{ARM}}}{\alpha^{\text{IARM}}} \leq 1.1 \quad (18)$$

Concerning the ratio between the gas efficiencies in absorbing photons in arm and interarm zones, McCall et al. (1985) pointed out that the HII regions of their sample were ionization bounded, so that in this case $\epsilon$ would be 1.0. Moreover, there is prima facie evidence that the HII regions in the arms and in the interarm zone do not differ in their boundary conditions (Cepa & Beckman 1989; Cepa & Beckman 1990d), thus leading to the conclusion that it is likely that $\epsilon^{\text{IARM}}/\epsilon^{\text{ARM}} = 1.0$. However, the regions of the sample of McCall et al. were mainly located in the arms, and it may be argued that, at least in some cases, HII regions in the interarm zone are density bounded while HII regions in the arms are ionization bounded. In this case the ratio $\epsilon^{\text{IARM}}/\epsilon^{\text{ARM}}$ would be less than unity. We can do a first-order estimate of this ratio, taking $\epsilon$ as proportional to the number of atoms divided by the number of ionizing photons in the HII region. The column density of atoms that can be ionized in a cloud is proportional to its diameter and density, and the number of ionizing photons is proportional to the SFR and IMF. The SFR is itself proportional to the product of the gas density and the star formation efficiency (SFE). If the SFE is larger in the arms and/or the IMF is different in arms and interarm regions, in the sense of favoring the formation of more massive stars in the arms, then $\epsilon^{\text{IARM}}/\epsilon^{\text{ARM}} \geq \phi^{\text{IARM}}/\phi^{\text{ARM}}$, where $\phi$ represents the diameter of the HII region. For example, from Cepa & Beckman (1990d), this ratio is 0.75 for NGC 4321, and from Knapen et al. (1993) this ratio is 0.72 for NGC 6814. Then, in general,

$$0.7 \leq \frac{\epsilon^{\text{IARM}}}{\epsilon^{\text{ARM}}} \leq 1.0 \quad (19)$$

and finally,

$$0.7 \leq Q \leq 1.1 \quad (20)$$
This factor has to be taken into account when evaluating relative arm/interarm star formation efficiencies using H$\alpha$ luminosities. In the present work, 

$$\text{RSFR}_{\text{meas}}^{\text{OB}} = \text{RSFR}_{\text{OB}} \chi_{\text{H}\alpha} \frac{\chi_{\text{H}\alpha}}{Q}$$  \hspace{1cm} (21)$$

and 

$$\text{RSFE}_{\text{meas}}^{\text{OB}} = \frac{\text{RSFR}_{\text{meas}}^{\text{OB}}}{A_{\star}}$$  \hspace{1cm} (22)$$

Note that, except for the factor $Q$, RSFR$_{\text{meas}}^{\text{OB}}$ and RSFE$_{\text{meas}}^{\text{OB}}$ are an estimate of the relative (arm over interarm disk) star formation rate and efficiency, respectively, of massive stars, and so will be termed henceforward when referring to the measured quantities.

2.4. Biased star formation

The ratio between RSFR and RSFR$_{\text{OB}}$ has to be unity. However, this does not apply to the ratio of the measured RSFRs, 

$$\frac{\text{RSFR}_{\text{meas}}}{\text{RSFR}_{\text{meas}}^{\text{OB}}} = Q \chi$$  \hspace{1cm} (23)$$

where $\chi = \chi_{\text{B}}/\chi_{\text{H}\alpha}$.

If there is no biased star formation, $\chi = 1$. Otherwise, $\chi$ would be less than 1.0, because H$\alpha$ samples higher stellar masses than B. Then the ratio $\chi$ could provide an observational test for the presence of biased star formation. From (21), 

$$0.7 \chi \leq \frac{\text{RSFR}_{\text{meas}}}{\text{RSFR}_{\text{meas}}^{\text{OB}}} \leq 1.1 \chi$$  \hspace{1cm} (24)$$

so it is possible to affirm that there is evidence for biased star formation in the arms with respect to the interarm disk if $\text{RSFR}_{\text{meas}}/\text{RSFR}_{\text{meas}}^{\text{OB}} \leq 0.7$.

3. Observations, data reduction and flux calibration

3.1. Observations

In this paper we present some results derived from the application of the method previously presented to two grand-design spiral galaxies, NGC 4321 and NGC 4254 (Table 1).

Images were taken for both galaxies in broad ($B$ and $I$) and narrow bands ($H\alpha$ and $H\beta$). For narrow-band images we used interference filters, including the corresponding continuum filters to the lines $H\alpha$ and $H\beta$. To derive the filter transmission in the $H\alpha$ and $H\beta$ lines, both the redshift of the galaxy as well as the shifts in wavelength in the filter due to temperature changes (Peletier 1994) were taken into account and, when applicable (as in the case of the prime focus of the Isaac Newton Telescope), the shift in central wavelength due to the non-converging beam (Peletier 1994, see Tables 2 and 3).
The images of NGC 4321 in the $B$, $I$, $H\alpha$ and $H\beta$ continuum filters were taken in 1994 March with a $1024\times1024$ pixel Thompson CCD camera attached to the cassegrain focus of the 0.8-m IAC-80 telescope at the Teide Observatory (Tenerife, Spain), the scale obtained with this configuration being 0.43 arcsec pix$^{-1}$. The $H\beta$ and $H\beta$ continuum images were obtained in 1995 June at the Cassegrain focus of the 1.5-m Danish Telescope at ESO (La Silla, Chile), using a $1024\times1024$ pixel Tektronics CCD, giving 0.38 arcsec pix$^{-1}$. The images of NGC 4254 were taken in 1995 April with a $1024\times1024$ pixel Tektronics CCD camera attached to the prime focus of the 2.5-m Isaac Newton Telescope (INT) at the Roque de los Muchachos Observatory (La Palma, Spain). In this case the scale obtained was 0.59 arcsec pix$^{-1}$.

Landolt catalogue stars (Landolt 1973) were used for the broad-band calibration. For the narrow band we used the spectrophotometric standard stars of Oke & Gunn (1983) and Stone (1977). Atmospheric extinction was evaluated in the broad-band filters via the observation of Landolt (1973) standards at different airmasses each night or for the INT data using the $V$ extinction given by the Carlsberg Automatic Meridian Circle. These extinctions allow the evaluation of extinctions in other filters assuming a grey atmosphere and a theoretical extinction curve versus wavelength (King 1985). In Table 4 we present the total integration times, and in Table 5 the limiting fluxes and magnitudes attained in the observations. To facilitate the continuum substraction and to correct for underlying absorption lines (described in § 3.3 and § 3.4), both the on-line and the continuum images were flux calibrated.

3.2. Data reduction

Data reduction was performed using the IRAF package. The bias was subtracted using the overscanned part of the chip. Several flatfields were taken for each filter each night and were later averaged to obtain a master flatfield for each filter and each night. The sky background was determined for each image by averaging and substracting regions free of objects. Afterwards, in the case of the observations taken with the IAC-80 or the ESO Danish Telescope, where several 1800 s exposures were taken for each filter (except for the continuum $H\beta$ at the ESO Danish Telescope where the exposure time was 1200 s per image), the off-sets among the different images were determined by fitting Gaussians to several field stars in each frame, the images were aligned to a fraction of a pixel and then averaged using a sigma clipping algorithm to get rid of cosmic ray events. The single exposures obtained with the INT were interactively cleaned of cosmic rays.

3.3. Flux calibration and continuum substraction

Both on-line and continuum images were flux calibrated using a procedure similar to that described in Barth et al. (1994). The flux calibrated continuum image was then shifted to a fraction of a pixel to match the on-line image, scaled by different factors around 1.00, in steps of 0.05, and substracted from the on-line image. From the different resulting images, the one that showed values closer to zero in regions of the interarm disk free from HII regions, and no conspicuous negative values in the bulge zone was selected. The scaling factors found in this way were 1.00 for $H\alpha$ images and 0.90 for $H\beta$ images. This procedure for the continuum substraction might eliminate diffuse emission.
coming from the interarm disk, but this contribution is irrelevant for the present work (see di Serego Alighieri 1987 for an overview of on-line imaging and its pitfalls). Figures 1 and 2 show the resulting Hα images.

3.4. Application of the method

To apply the method outlined here to the data, it is necessary to evaluate luminosities through three different sets of apertures for each galaxy:

1. The apertures to measure arm luminosities have been taken as contiguous, except when there are abundant arm 
   HII regions, where the apertures overlap slightly, and when very few or no arm HII regions are apparent, where the 
apertures undersample the arm. These arm apertures are located in the most intense part of the Hα image of each arm. 
When the Hα image presented a gap in the arms, the B-band image was used as a guide to follow the arm in the Hα image.

2. The apertures to measure luminosities of star forming (HII) regions on the disk have been defined using the Hα 
   image. Zones of doubtful assignation (to an arm or to the disk), too near to dust lanes or to the tips of a bar, have been avoided.

3. Finally, aperture positions for zones of the disk without star formation have been selected avoiding: (i) disk star 
   forming zones (the Hα image has been used for this selection), (ii) emission coming from the spiral arms (using the 
   B and I images), and (iii) dust lanes (using the B and I images). The latter is necessary since it is not possible to 
correct these points for internal extinction, only for Galactic extinction. Except for the previous stated exceptions, 
zones equidistant from the spiral arms and avoiding bars have been used.

The size of the apertures employed is fixed for each galaxy and is large enough to get isolated Hα emission patches 
of the disk fully inside them. This implies diameters of 8′′ for NGC 4321 and NGC 4254 (∼0.8 kpc assuming a distance 
of 20 Mpc).

Afterwards, aperture photometry for the whole set of apertures and all the images (except Hα and Hβ and their 
corresponding continua in the case of disk regions without star formation) was performed. The coordinates of the 
apertures with respect to the center of the galaxy, defined as the peak of maximum emission in the I band, were then 
de-projected using the position angles and inclinations given in Table 1.

The luminosities thus obtained were corrected for extinction and underlying absorption (in the case of Hβ) following 
the procedures described below.

3.4.1. Extinction correction

Since extinction in the disk can be quite large, especially in the spiral arms, the relative star formation rates must 
necessarily be corrected for internal extinction to be able to apply the method described in §2 with a certain confidence. 
For instance, extinction can either increase or decrease the RSFR, the RSFE and the RSFE_{OB}, depending on the zones 
considered in the arms and in the interarm disk, while usually RSFR_{OB}, and A∗ will be lowered by extinction (assuming
that the extinction is larger in the arms than in the interarm disk). In the present work, we have used the ratio of the Balmer emission lines \( \text{H}_\alpha \) and \( \text{H}_\beta \) to do a first-order correction for galactic and extragalactic extinction, using the reddening law of Whittet (1992), assuming case B with an electron density of 100 cm\(^{-3}\) and a temperature of 10\(^4\) K, from which we obtain

\[
A_V = 2.6 \ln \left( \frac{F_{\text{H}_\alpha}}{F_{\text{H}_\beta}} \right)_{\text{obs}}
\]

which allows us to derive extinctions for our photometry.

This reddening law is not substantially different from that of Schild (1977). Moreover, recent results (see Davies & Burstein 1995) show that it can be applied reliably to external galaxies, at least in the visible and NIR bands.

However, this method can be applied only to \( \text{H}_\text{II} \) regions. So, with this method, the luminosities with a superscript DISK (§ 2) cannot be corrected for internal extinction, only for extinction due to our Galaxy and internal extinction for correction to face-on, using \( A_B \) from de Vaucouleurs, de Vaucouleurs & Corwin (1976). In these circumstances, \( \text{RSFE}_{\text{OB}}^{\text{meas}} \) is lower, the measured \( A_* \) is larger and if \( \text{RSFE}_{\text{meas}}^{\text{meas}} < 1 \) (see Appendix) \( \text{RSFR}_{\text{meas}}^{\text{meas}} \) and \( \text{RSFE}_{\text{meas}}^{\text{meas}} \) are larger than the same fully extinction-corrected quantities. Also, if \( \text{RSFE}_{\text{meas}}^{\text{meas}} < 1 \), the ratio given by equation (23) is larger than if it were fully extinction corrected, and then it is still true that if \( (23) \) is lower than 0.7, there is evidence for biased star formation.

3.4.2. Line-absorption correction

Apart from extinction, there are several effects that may influence the observed fluxes, namely the absorption lines in the calibration stars and the underlying stellar absorption of the studied region. The first effect is negligible because the equivalent widths of the absorption lines are \( \approx 2 \) Å (McCall et al. 1985) i.e., small in comparison to the filter widths. Hence, the absorbed flux is always lower than 4% of the continuum flux for a filter of 50 Å FWHM or more, such as those used in this work. The second effect may be more significant reaching reductions in the \( \text{H}_\beta \) Balmer line equivalent widths of 50% (McCall et al. 1985). This effect leads to an overestimate of the absorption. For this correction we used the method given by McCall et al. (1985), which allows us to correct for the underlying absorption effect using the equivalent widths of the \( \text{H}_\alpha \) and \( \text{H}_\beta \) lines. First, a mask was derived with pixel values equal to unity when the pixels of the same coordinates in the \( \text{H}_\alpha \) line image had values greater than or equal to three times the r.m.s. of the background, and pixel values otherwise equal to zero. This mask was multiplied by the continuum images in order to obtain continuum the contribution of emission-line regions only, not of regions which are pure continuum. This allows to evaluate equivalent widths. Since the internal (non-atmospheric) extinction is different in the line and in the continuum due to the different central wavelengths of the filters used, it is necessary to apply an iterative process to correct for underlying absorption and to derive extinctions: initially the \( \text{H}_\alpha \) and \( \text{H}_\beta \) equivalent widths uncorrected for extinction are calculated, from those we evaluate the absorption-corrected \( \text{H}_\beta \) fluxes, before deriving the internal extinction. This internal extinction is used to correct the \( \text{H}_\alpha \) and \( \text{H}_\beta \) line and continuum fluxes. Using these first-order
extinction-corrected fluxes, we calculate the equivalent widths again, and the Hβ flux is later corrected for underlying absorption, which allows the determination of the extinction, etc. This procedure is repeated until a convergent value is obtained, which takes only few iterations.

Another effect that might lead to errors in line intensities is contamination produced by the [N II] λ 6584 Å line. However this effect will not affect the arm/interarm ratios, except in the case that the variation of the metallicity between the arm and interarm is significant, since arm/interarm ratios are evaluated at similar galactocentric distances, thus avoiding the effect of possible metallicity gradients in the disk.

Finally, the deprojected, extinction-corrected luminosities, for each arm, and interarm disk, with and without star formation, at similar deprojected galactocentric distances, were used to apply the formulae of § 2, to determine arm amplitudes, intermediate-mass star formation rates, massive star formation rates, the corresponding star formation efficiencies, and look for possible biased star formation in spiral arms with respect to the interarm disk as a function of radius.

4. Results

4.1. NGC 4321

NGC 4321 is one of the most conspicuous spiral galaxies in the Virgo cluster. It has two impressive, very well defined spiral arms (of arm class 12 according to Elmegreen & Elmegreen 1987). The northern arm extends in the east-north-west direction and the southern arm in the west-south-east direction.

4.1.1. Triggered star formation

Figures 3 and 4 represent the relative (arm/interarm) intermediate-mass star formation rate, and the relative massive star formation rate versus radius for the southern and northern arm, respectively. In both arms the qualitative behavior of both quantities as a function of radius is noticeably similar for each arm. In the southern arm there is a descent below unity of both RSFRs from 105″ to 140″. In the northern arm there is a dip at 110″ and a descent below unity at 140″. In these zones, the stellar arm density contrasts are also lower (Fig. 5). In the zones where the RSFRs are less than unity, the interarm disk is forming more stars per unit time than the arm, and can be identified with parts of the arms with almost no HII regions, as can be seen in the Hα image (Fig. 1). These dips and descents can be due to the presence of corotation or to resonances. In the modal theory due to Lin and collaborators, oscillations in the amplitude of the wave are related to the oscillations of the radial eigenfunctions (see for example Lin & Lau 1979). In the stellar theory for non-linear spirals (Contopoulos & Grosbøl 1986, 1988) there is evidence for stellar orbit crowding between resonances, and it is possible to find some minima in the arm amplitudes placed at different resonances. We assume that corotation is located at ~110–120″, where dips in the RSFRs, and stellar density contrasts can be seen in both arms. In this case, the dip at 140″ corresponds to the 4:1 Outer Lindblad Resonance (O4:1), while the dip
at 60″ coincides with the 4:1 Inner Lindblad Resonance, using the rotation curve published by Sempere et al. (1995). The corotation radius determined in this way is consistent with that of Sempere et al. (1995), who found that it is located from 85″ to 115″, using a test based on the HI residual velocity field, and that of Elmegreen, Elmegreen & Seiden (1989), at ∼120″, using morphological arguments.

Figure 6 shows the relative intermediate-mass star formation efficiency versus radius for both arms of NGC 4321. The arms are less efficient, or as efficient at forming intermediate-mass stars than the interarm (then the reasoning of Appendix A is valid, implying that the RSFE of massive stars is lower, and \( A_\star \), RSFR and RSFE of intermediate-mass stars are larger than the same quantities using extinction-corrected disk non-star forming zone luminosities), except beyond 150 arcsec, where measurement uncertainties are quite large. In contrast, Fig. 7 shows the relative massive star formation efficiency versus radius for both arms of NGC 4321. In some zones, the southern arm is more efficient at forming massive stars than the interarm disk by a factor up to ∼2.5–3.5, indicating that density waves are triggering massive star formation, a result which was already pointed out by Cepa & Beckman (1990c) using gas density contrasts. However, in the northern arm, the RS\(F_{\text{meas}}^{\text{OB}}\) is, in general, less than one. Del Río (1995) and del Río & Cepa (1997), using azimuthal photometric profiles in Johnson B and I bands, found that the density wave is quite inefficient at forming stars in the northern arm, except in a localized region outside corotation, which can be identified with the region of high RS\(F_{\text{meas}}^{\text{OB}}\) at ∼150″ in Fig. 7. Nevertheless, arm density contrasts are in general larger in the northern arm than in the southern arm (Fig. 5), the reason probably being due to the physical conditions of the molecular gas. Also, if there is no triggering of massive star formation, a linear relation between the RS\(F_{\text{meas}}^{\text{OB}}\), and the arm density contrasts should be expected, and vice versa: triggering should show up as a non-linear relation between arm density contrast amplitude and relative massive star formation. From Fig. 8 it appears that there is no evidence for correlation between the RS\(F_{\text{meas}}^{\text{OB}}\) and the southern arm amplitude, again leading to the presence of some sort of triggering mechanism. However, there is a remarkable linear relation between the points where no triggering of massive stars is present (with a RS\(F_{\text{meas}}^{\text{OB}}\) less than one), which are situated around the corotation radius (Pearson correlation coefficient \( r_P = 0.993 \) for \( n = 5 \), giving a confidence level of 99.9 % for this correlation). In the northern arm, avoiding the points being beyond 140″ (where there is some triggering of the star formation), we observe a linear relation between RS\(F_{\text{meas}}^{\text{OB}}\) and the north arm density constrast (Fig. 9), with a Pearson correlation coefficient \( r_P = 0.891 \) for \( n = 9 \), at a 99.8 % confidence level for this particular correlation. This linear correlation points to the absence of massive star formation triggering in the northern arm, since larger arm density contrast corresponds to proportionally larger RS\(F_{\text{meas}}^{\text{OB}}\). However, there is evidence for triggering of the massive star formation beyond 140″.

This difference in behavior between both arms might be due to the interaction of NGC 4321 with NGC 4322.

4.1.2. Biased star formation

From the previous section, it turns out that the density wave system in NGC 4321 is triggering the formation of massive stars, while intermediate-mass stars are formed in larger fractions in the interarm disk. This result suggests
that there might be biased star formation in the spiral arms with respect to the rest of the disk. As pointed out in § 2.4, values of $\frac{\text{RSFR}^{\text{meas}}}{\text{RSFR}_{\text{OB}}^{\text{meas}}}$ lower than 0.7 constitute strong evidence for a different IMF in the arms with respect to the interarm disk, or, in other words, biased star formation (BSF). In Fig. 10 we have plotted this ratio as a function of the galactocentric radius for the northern and the southern arms. In the northern arm, the ratio of relative measured star formation rates is only systematically lower than 0.7 from 130$''$ to 150$''$, and in 60$''$ and 90$''$. It would then seem that there is BSF, and that it is mainly situated in the zone where there is triggered massive star formation. In the southern arm the ratio is less than 0.7 except in a zone from 100$''$ to 130$''$. Again, there is BSF, mainly in the zone where massive star formation is triggered, and not near corotation (where no triggering is expected). This is a strong suggestion that density waves cause a change in the IMF in the arms. This is in some agreement with Shu, Lizano & Adams (1986) who proposed that regions of higher (lower) star formation efficiency corresponds to regions of high (low)-mass star formation. A possible reason might be (Zinnecker 1987) that the giant molecular clouds—located in the spiral arms—form massive stars earlier than the standard molecular clouds, the less massive stars not having a chance to form. Also this result is in agreement with that of Scoville, Sanders & Clemens (1986) who proposed that OB stars form as a result of cloud-cloud collisions, which happen more frequently in the arms. There is some other evidence for the presence of BSF in spiral galaxies: Miller & Scalo (1978) conclude that in OB associations in our own Galaxy, which are tracers of the spiral arms, only stars with $M \geq 2 - 5 M_\odot$ are formed. Beyond our Galaxy Rieke et al. (1980) found a burst in the center of M82 where they estimate a value of $m_\ell \sim 3.5 M_\odot$ for the lower mass limit (see the review by Shu et al. 1987 for more examples).

4.2. NGC 4254

Iye et al. (1982) found a strong $m=1$ component in the Fourier transforms, superimposed on the $m=2$ component, giving the observed $m=3$ spiral structure in NGC 4254. Recent studies made by Phookun, Vogel & Mundy (1993) ascribe the cause of the strong $m=1$ component to the presence of an extragalactic cloud which merges with the galaxy.

The optical images clearly show three arms, one of them appearing weaker in H$\alpha$ than the others. We have studied the star formation in the strongest arms: the northern arm, which extends in the west-north-east direction, and the southern arm, which extends in the east-south-west direction (Fig. 2).

4.2.1. Triggered star formation

In Figs. 11 and 12 we have plotted $\text{RSFR}^{\text{meas}}$ and $\text{RSFR}_{\text{OB}}^{\text{meas}}$ versus radius for the south and the north arms, respectively. In both arms there is a common minimum of both quantities between 85$''$ and 95$''$, which also appears in the arm amplitudes and in $\text{RSFE}^{\text{meas}}_{\text{OB}}$, as can be seen in Figs. 13 and 14, respectively. From this behavior we should expect that the corotation will be between 85$''$ and 95$''$, a result consistent with findings reported by Elmegreen, Elmegreen & Montenegro (1992), who placed the corotation at $\sim 87''$. Using this corotation radius, from Fig. 14 it turns out
that $RSF_{OB}^{meas}$ in the northern arm is greater than unity before and after corotation, and less than unity near or at corotation, as in the southern arm of NGC 4321. This arm of NGC 4254 contains a region of strong star formation at 115" (Fig. 2), which has not been included since it is quite possible that it was not triggered by the density wave. In fact, the massive star formation efficiency in that zone is an order of magnitude greater than in any other zone of star formation in this galaxy, and it coincides approximately with the area where the extragalactic cloud observed by Phookun et al. (1993) merges with the galaxy, this merger being perhaps the cause of the strong star formation in the zone. In the southern arm (Fig. 14) there is also some triggering of massive star formation mainly after corotation.

In general, there is no evident correlation between $RSF_{OB}^{meas}$ and the stellar density contrast in any arm (Figs. 15 and 16). This fact supports the hypothesis that there is triggering of massive star formation in the spiral arms with respect to the interarm disk. However, there is a good linear relation for the points in the southern arm having a $RSF_{OB}^{meas}$ clearly less than one (Fig. 15), i.e., zones where there is no triggering of massive stars (Pearson correlation coefficient $r_P = 0.994$ for $n = 5$, giving a confidence level of 99.9% for this correlation).

As in the case of NGC 4321, the measured RSFEs (Fig. 17) are less than or of the order of unity except in some points of the southern arm at $\sim 30$, 40, and 60 arcsec. The density wave system, then, is triggering massive star formation in the arms, but intermediate-mass stars are formed preferentially outside the arms, suggesting again the possible presence of biased star formation in the arms.

4.2.2. Biased star formation

Figure 18 represents the ratio $RSF_{OB}^{meas}/RSF_{OB}^{meas}$ as a function of the galactocentric radius for the south and the north arm. This value is lower than 0.7 in both arms beyond corotation, implying strong evidence for BSF after corotation, although a BSF before corotation for the southern arm (depending on the values of $Q$) cannot be ruled out. The lowest value corresponds to 120" in the southern arm, correlated with the peak in $RSF_{OB}^{meas}$ at this distance (Fig. 14). Although there seems to be no correspondence between the peak in $RSF_{OB}^{meas}$ at $\sim 80"$ observed in the northern arm and a dip in $RSF_{OB}^{meas}/RSF_{OB}^{meas}$, the observed change of behavior in this ratio before and after corotation, mainly in the southern arm, suggests that the density wave is responsible for the observed BSF.

5. Summary

We have developed a procedure for deriving relative (arm/interarm) star formation rates, arm density contrasts, and relative star formation efficiencies as a function of the galactocentric radius in spiral galaxies, using broad-band (blue and near infrared) and continuum-subtracted H$\alpha$ and H$\beta$ imaging. We have also developed a procedure for assessing whether there is biased star formation in the arms with respect the rest of the disk, i.e., whether the spiral arms have a different initial mass function from that of the interarm disk, as a function of radius.

We have applied the previous procedures to the spiral galaxies NGC 4321 and NGC 4254, finding that density waves greatly influence the star formation and initial mass function in the spiral arms.
From the relative star formation rates and arm amplitudes as a function of the radius, it results that the corotation radius is located at 110–120″ in NGC 4321 and at 85–95″ in NGC 4254.

From the relative intermediate-mass star formation efficiencies and massive star formation efficiencies as a function of radius, it is found that density waves trigger massive star formation in both galaxies, although not with the same strength in the different arms of the same galaxy. However, they do not trigger intermediate-mass star formation. Also, triggering is not present near the corotation radius where, in the case of NGC 4321, a linear relation between relative massive star formation rate and arm amplitude can be observed. This linear relation is also apparent in the zones outside corotation where the relative massive star formation efficiency is less than unity, i.e., where no triggering of massive star formation by the density wave is taking place.

Near corotation (and, in the case of NGC 4321, near the Inner and Outer Lindblad 4:1 Resonances), the interarm disk presents larger star formation rates and star formation efficiencies than the spiral arms, as if the star formation were inhibited in the spiral arms near corotation. In fact, a break in the arms or a clearly lower number of H\textasciimacron{i} regions in this zone can be seen in the H\textalpha images.

Intermediate-mass stars form more efficiently in the interarm disk, and the IMF is different in the arms from that in the disk, favoring the formation of a larger fraction of massive stars in the arms. This biased star formation seems closely related and probably caused by the density-wave system, since it is not present where there is no triggering of massive star formation (relative massive star formation efficiencies less than unity), in the case of NGC 4321, or it is present after the corotation radius and not before, as in NGC 4254.

The observed correlation between biased star formation and higher massive star formation efficiency is consistent with the theoretical work of Shu et al. (1986).

Finally, we can conclude that, for the grand-design galaxies studied, density waves trigger massive star formation, but do not trigger star formation of stars of all masses, on the contrary, the interarm disk is more efficient at forming intermediate-mass stars than the arms, and this is due to different IMFs in the arms from those in the rest of the disk.

To be able to draw more general conclusions, it is necessary to apply the method described in this paper to a larger sample of objects, including intermediate-arm type spirals, where no triggering and consequently no biased star formation should be expected.

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The Isaac Newton Telescope is operated on the island of La Palma by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.
A. Appendix

Differentiating (8) considering as variables $I_{\text{DISK}}$ and $B_{\text{DISK}}$, and dividing the result by (8), we obtain

$$\frac{\Delta RSFR}{RSFR} = \frac{-\Delta A_{*}B_{\text{DISK}}}{B_{\text{ARM}} - A_{*}B_{\text{DISK}}} - \frac{A_{*}\Delta B_{\text{DISK}}}{B_{\text{ARM}} - A_{*}B_{\text{DISK}}} + \frac{\Delta B_{\text{DISK}}}{B_{\text{ARM}} - B_{\text{DISK}}}$$  \hspace{1cm} (A1)

where

$$\frac{\Delta A_{*}}{A_{*}} = -\frac{\Delta I_{\text{DISK}}}{I_{\text{DISK}}}$$  \hspace{1cm} (A2)

$\Delta B_{\text{DISK}}$ and $\Delta I_{\text{DISK}}$ are negative quantities that represent the correction to apply to the extinction corrected $B_{\text{DISK}}$ and $I_{\text{DISK}}$, respectively, to obtain the measured corresponding quantities. Then, $\Delta A_{*} > 0$.

However, since extinction is larger at shorter wavelengths, and the colors of disk non star forming regions are red, $|\Delta I_{\text{DISK}}|/I_{\text{DISK}} < |\Delta B_{\text{DISK}}|/B_{\text{DISK}}$, and the second term of (A1) is larger than the first.

If RSFE < 1, then RSFR < $A_{*}$, and, neglecting the first term of (A1), it results that $\Delta RSFR > 0$.

Using a similar procedure, it can be demonstrated that if RSFE < 1, then $\Delta RSFE > 0$.

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Figure captions

Fig. 1. Hα continuum-subtracted image of NGC 4321. North is top and east left. Axes represent offsets in arcseconds from the nucleus.

Fig. 2. Hα continuum-subtracted image of NGC 4254. North is top and east left. Axes represent offsets in arcseconds from the nucleus. The star formation region marked with an “X” sign has not been included in the present study.

Fig. 3. Relative massive star formation rate and relative intermediate-mass star formation rate as a function of the galactocentric radius for the southern arm of NGC 4321.

Fig. 4. Relative massive star formation rate and relative intermediate-mass star formation rate as a function of the galactocentric radius for the northern arm of NGC 4321.

Fig. 5. Arm amplitudes of NGC 4321 as a function of the galactocentric radius.

Fig. 6. Relative intermediate-mass star formation efficiency for the spiral arms of NGC 4321 as a function of the galactocentric radius.

Fig. 7. Relative massive star formation efficiency for the spiral arms of NGC 4321 as a function of the galactocentric radius.

Fig. 8. Relative massive star formation rate as a function of the arm amplitude for the southern arm of NGC 4321.

Fig. 9. Relative massive star formation rate as a function of the arm amplitude for the northern arm of NGC 4321.

Fig. 10. Ratio of the relative (arm/interarm) intermediate-mass star formation rate over that of massive stars as a function of the galactocentric radius for the northern (upper diagram) and southern (lower diagram) arms of NGC 4321. Points below the continuous line (which indicates the 0.7 value) indicate the presence of biased star formation.

Fig. 11. Relative massive star formation rate and relative intermediate-mass star formation rate as a function of the galactocentric radius for the southern arm of NGC 4254.
Fig. 12. Relative massive star formation rate and relative intermediate-mass star formation rate as a function of the galactocentric radius for the northern arm of NGC 4254

Fig. 13. Arm amplitudes of NGC 4254 as a function of the galactocentric radius

Fig. 14. Relative massive star formation efficiency for the spiral arms of NGC 4254 as a function of the galactocentric radius

Fig. 15. Relative massive star formation rate as a function of the arm amplitude for the southern arm of NGC 4254

Fig. 16. Relative massive star formation rate as a function of the arm amplitude for the northern arm of NGC 4254

Fig. 17. Relative intermediate-mass star formation efficiency for the spiral arms of NGC 4254 as a function of the galactocentric radius

Fig. 18. Ratio of the relative (arm/interarm) intermediate mass star formation rate over that of massive stars as a function of the galactocentric radius for the southern (upper diagram) and northern (lower diagram) arms of NGC 4254. Points below the continuous line (which indicates the 0.7 value) indicate the presence of biased star formation.
Table 1. Observational parameters of the galaxies observed

| Galaxy   | Hubble type | Arm class | P.A. (deg) | i (deg) | $D_{B25}$ (arcsec) |
|----------|-------------|-----------|------------|---------|-------------------|
| NGC4321  | SAB(s)bc(1) | 12(2)     | 151(3)     | 31(3)   | 6.9(1)            |
| NGC4254  | SA(s)c(1)   | 9(2)      | 58(1)      | 27(1)   | 5.4(1)            |

(1) de Vaucouleurs, de Vaucouleurs & Corwin (1976)

(2) Elmegreen & Elmegreen (1984)

(3) Cepa et al. (1992)
Table 2. Characteristics of the narrow band filters for NGC 4321

| Filter | $\lambda_c$ (Å) | FWHM (Å) | Peak response |
|--------|----------------|-----------|---------------|
| H$\alpha$ | 6570 | 95 | 0.63 |
| H$\beta$ | 4897 | 50 | 0.78 |
| H$\alpha$C | 6260 | 133 | 0.53 |
| H$\beta$C | 4926 | 53 | 0.67 |
Table 3. Characteristics of the narrow band filters for NGC 4254

| Filter | $\lambda_c$ (Å) | FWHM (Å) | Peak response |
|--------|----------------|----------|---------------|
| H\(\alpha\) | 6607 | 53 | 0.54 |
| H\(\beta\) | 4863 | 97 | 0.68 |
| H\(\alpha\)C | 6565 | 45 | 0.56 |
| H\(\beta\)C | 4540 | 114 | 0.53 |
Table 4. Total exposure times in seconds per filter for NGC 4321 and NGC 4254. The aperture of the telescope used is given in brackets.

| Filter | NGC 4321 | NGC 4254 |
|--------|----------|----------|
| Hα     | 7200 (0.8 m) | 1800 (2.5 m) |
| HαC    | 5400 (0.8 m) | 1800 (2.5 m) |
| Hβ     | 5400 (1.5 m) | 1800 (2.5 m) |
| HβC    | 3600 (1.5 m) | 1800 (2.5 m) |
| B      | 7200 (0.8 m) | 1200 (2.5 m) |
| I      | 7200 (0.8 m) | 600 (2.5 m)  |
Table 5. Limiting fluxes and magnitudes for NGC 4321 and NGC 4254, at three times the r.m.s. of the sky background.

| Filter | NGC 4321       | NGC 4254       |
|--------|----------------|----------------|
| Hα     | $1.1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ | $3.4 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ |
| Hβ     | $5.1 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ | $6.0 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ |
| B      | 23.34 mag arcsec$^{-2}$ | 25.40 mag arcsec$^{-2}$ |
| I      | 22.18 mag arcsec$^{-2}$ | 23.10 mag arcsec$^{-2}$ |
This figure "fig1.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/9707270v1
This figure "fig2.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/9707270v1
Points beyond the 04:1 resonance (140°)
Points where there is no triggering
