The impact of gas inflows on star formation rates and metallicities in barred galaxies

Sara L. Ellison,1⋆ Preethi Nair,2 David R. Patton,3 Jillian M. Scudder,1 J. Trevor Mendel1 and Luc Simard4

1Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 1A1, Canada
2INAF-Astronomical Observatory of Bologna, Via Ranzani 1, 40127 Bologna, Italy
3Department of Physics & Astronomy, Trent University, 1600 West Bank Drive, Peterborough, Ontario K9J 7B8, Canada
4National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, British Columbia V9E 2E7, Canada

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ABSTRACT
The star formation rates (SFRs) and metallicities of a sample of 294 galaxies with visually classified, strong, large-scale bars are compared to a control sample of unbarred disc galaxies selected from the Sloan Digital Sky Survey Data Release 4. The fibre (inner few kpc) metallicities of barred galaxies are uniformly higher (at a given mass) than the unbarred sample by ∼0.06 dex. However, the fibre SFRs of the visually classified barred galaxies are higher by about 60 per cent only in the galaxies with total stellar mass $M_\star > 10^{10} \, M_\odot$. The metal enhancement at $M_\star < 10^{10} \, M_\odot$ without an accompanying increase in the SFR may be due to a short-lived phase of early bar-triggered star formation in the past, compared to on-going SFR enhancements in higher mass barred galaxies. There is no correlation between bar length or bar axial ratio with the enhancement of the SFR. In order to assess the relative importance of star formation triggered by bars and galaxy–galaxy interactions, SFRs are also determined for a sample of close galaxy pairs. Both mechanisms appear to be similarly effective at triggering central star formation for galaxies with $M_\star > 10^{10} \, M_\odot$. However, due to the much lower fraction of pairs than bars, bars account for ∼3.5 times more triggered central star formation than interactions.

Key words: galaxies: abundances – galaxies: interactions – galaxies: structure.

1 INTRODUCTION
Radial gas flows can alter the characteristic properties of galaxies on relatively short time-scales. Subsequent changes in the star formation rates (SFRs), gas-phase metallicities, stellar populations and morphologies contribute to the overall progression of galaxy evolution. The mechanisms responsible for gas flows and the changes that they ultimately trigger within galaxies are at the heart of understanding galaxy transformations. In particular, the relative contributions of secular galaxy evolution, whereby galaxies develop a prominent bulge in the absence of exterior influence, and galaxy–galaxy interactions is an ongoing debate (e.g. Kormendy & Kennicutt 2004; Weinzierl et al. 2009).

In the case of galaxy mergers, the theory and observations are largely in agreement. When two gas-rich galaxies interact, the loss of angular momentum of gas in the outer discs results in radial inflows, which are expected to lead to triggered star formation as the gas surface density increases in the inner regions (Barnes & Hernquist 1996; Di Matteo et al. 2007; Cox et al. 2008). These predictions are supported by observations of SFRs that are increased by a factor of a few in close pairs of galaxies (Kennicutt et al. 1987; Barton, Geller & Kenyon 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic, Cullen & Alexander 2004; Ellison et al. 2008a), with a clear tendency for the triggered star formation to be located in the galactic centres (Barton et al. 2000; Kewley, Geller & Barton 2006; Ellison et al. 2010; Patton et al. 2011). The level of the SFR enhancement in close pairs is similar out to $z \sim 1$, despite the global increase of the volume averaged SFRs at these earlier epochs (Jogee et al. 2009; Robaina et al. 2009). Simulations have also predicted that the triggered star formation should be more effective in interactions between approximately equal mass galaxies (Cox et al. 2008). Again, this is borne out by observations (Woods, Geller & Barton 2006; Ellison et al. 2008a). Including chemical enrichment into the models leads to predictions that, in addition to triggering star formation, the transport of metal-poor gas from the outer parts of the galaxy results in an initial dilution of the central gas-phase metallicity (Montuori et al. 2010; Rupke, Kewley & Barnes 2010). Studies of the luminosity– or mass–metallicity relations in close pairs of galaxies indeed find that the metallicities are ∼0.05 dex lower in the centres than in the outskirts.

⋆E-mail: sarae@uvic.ca
lower than in galaxies with no close companion (Kewley et al. 2006; Ellison et al. 2008a; Michel-Dansac et al. 2008), and that abundance gradients are flatter (Kewley et al. 2010; Rupke, Kewley & Chien 2010).

In the absence of an interaction, the most effective mechanism for radial motions of gas (important for bulge growth) is likely to be the presence of a galaxy bar. Simulations predict that bars facilitate not only inflow, but also outflow, so that mixing and triggered star formation can result in a more complex picture of chemical enrichment within the galaxy (Friedli, Benz & Kennicutt 1994). Studies of the SFRs and metallicities of barred galaxies have yielded complex results. For example, whilst many studies have found an increased SFR in barred galaxies (Hummel et al. 1990; Martin 1995; Hayward, Huang & Gu 1996; Huang et al. 1996), bars are apparently neither required nor guaranteed to yield high SFRs (Pompea & Rieke 1990; Martinet & Friedli 1997; Chapelon, Contini & Davoust 1999).

Enhanced SFRs may depend on the morphology of galaxies, being apparently prevalent in early type barred galaxies, but largely absent in late types (Huang et al. 1996; Ho, Filippenko & Sargent 1997; James, Bretherton & Knapen 2009). It has been suggested that the dependence of SFR enhancement on morphological type may be due to the generally longer, stronger (more elongated) bars in the former (Elmegreen & Elmegreen 1985, 1989; Erwin 2005; Menendez-Delmestre et al. 2007). Simulations indicate that only strong bars are effective at funnelling gas to the inner kpc (e.g. Regan & Teuben 2004). Indeed, Martin (1995) found that ~70 per cent of starbursts in their sample had a strong bar. Martinet & Friedli (1997) also found that only galaxies with strong and long bars show star formation enhancement, but even strong bars may be in a pre- or post-starburst phase with ‘normal’ SFRs. Studies of enhanced molecular gas concentrations in the inner kpc of barred galaxies (e.g. Sakamoto et al. 1999; Sheth et al. 2005) paint a similar picture of an early versus late-type galaxy separation, plus considerable variation in SFRs for a given morphological type. Indeed, Jogee, Scoville & Kenney (2005) find that the SFRs of barred galaxies can vary by an order of magnitude for a given central molecular gas mass. Sheth et al. (2005) find that early-type bars have higher molecular gas masses in their centres than late types, yet find a notable population of early types with no central concentration of molecular gas. Sheth et al. (2005) suggest that these are galaxies which have used up their molecular gas in past starbursts, indicating that the bar lifetime is long compared to the gas inflow/triggered star formation time-scales (see also Sakamoto et al. 1999). Other indirect evidence that bars are not promptly destroyed by the build-up of central mass concentrations comes from the relatively high bar fractions out to z ~ 1 (Sheth et al. 2003; Jogee et al. 2004), old stellar populations (Perez, Sanchez-Blazquez & Zurita 2009; Sanchez-Blazquez et al. 2011), multiple extended episodes of star formation in the bar (Cantin et al. 2010) and the lack of unbarred galaxies whose molecular concentrations resemble those in bars (Sakamoto et al. 1999).

The chemical enrichment of barred galaxies is similarly complex. Abundance gradients are often found to be flatter in barred galaxies than their unbarred counterparts (e.g. Vila-Costas & Edmunds 1992; Martin & Roy 1994). However, a range of abundance gradients exists amongst the barred population, including some that are considerably steeper than unbarred spirals (Edmunds & Roy 1993; Oey & Kennicutt 1993; Zaritsky et al. 1994; Considere et al. 2000). Whilst most previous studies have focused on gas-phase abundances, there have also been a handful of studies of the stellar populations. Perez et al. (2009) find that stellar metallicity gradients within bars can be either positive or negative. In a detailed study of two early-type barred galaxies, Sanchez-Blazquez et al. (2011) find stellar abundance gradients that are flatter in the bar than the disc. The diversity of gradients may be due, at least in part, to a dependence on bar length and galaxy type, whereby long, strong bars and later types tend to exhibit flatter gradients (Oey & Kennicutt 1993; Zaritsky et al. 1994; Martin & Roy 1994; Dutil & Roy 1999).

An added complication is the presence of breaks in the gradient, often leading to steeper inner slopes and flatter values outside of the bar (Martin & Roy 1995; Roy & Walsh 1997; Considere et al. 2000). Simulations predict such dependences, due to the efficiency and quantity of gas transport and whether or not star formation accompanies these motions (Friedli, Benz & Kennicutt 1994; Friedli & Benz 1995).

Characteristic (at a given galactocentric radius) and central abundances in barred galaxies yield perhaps the most puzzling results. Henry & Worthey (1999) found no difference at a given $M_B$ between barred and unbarred metallicities. Dutil & Roy (1999) found that (both early and late type) barred systems were more metal poor (by 0.5 dex) at a given $M_B$ than unbarred and weakly barred galaxies. Considere et al. (2000) also found lower central abundances for a given $M_B$ in their starbursting barred sample. However, whilst bar strength may influence the nuclear star formation (Martin 1995) it is apparently uncorrelated with central metallicity (Chapelon et al. 1999). In contrast to the observations, simulations predict that star formation should lead to higher central abundances (Friedli et al. 1994; Friedli & Benz 1995). High stellar metallicities in the bulges of barred galaxies have recently been reported by Perez & Sanchez-Blazquez (2011), but similar enhancements in the gas-phase abundances have not been convincingly demonstrated.

In this paper we aim to use a large sample of visually classified barred galaxies to quantify differences in the SFRs and metallicities relative to an unbarred control set. In addition to sample size, the main advantage of our study is internal consistency in parameter determination and calibration, as well as a control sample that is fully representative of the barred galaxies’ properties. We are also, for the first time, able to quantify the SFR and metallicity enhancements on a galaxy-by-galaxy basis and can hence search for dependences on structural parameters. Finally, the enhanced SFRs of barred galaxies are compared to those in close pairs of galaxies. The results yield an insight into the relative efficiency of star formation triggered by bar-driven gas flows and galaxy–galaxy interactions. We adopt a cosmology with values of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2 SAMPLE

Our sample of barred galaxies is taken from the catalogue of Nair & Abraham (2010a). In brief, Nair & Abraham (2010a) performed visual classifications of 14 034 $z < 0.1$ galaxies from the spectroscopic galaxy sample in the Data Release 4 (DR4) of the Sloan Digital Sky Survey (SDSS). In addition to the redshift cut, a magnitude cut was also imposed such that the extinction corrected SDSS g-band modelMag is brighter than 16.0. A total of 9917 galaxies are classified as discs (T Type $> -2$), of which 2218 are classified as barred galaxies (barflag = 2.4.8 for strong, intermediate and weak bars, respectively) and 7316 are classified as unbarred (barflag = 0). The remaining 383 galaxies are either classified as ‘bar unsure’, or as other nuclear structure, such as anae or peanut morphologies. Nair & Abraham (2010a) note that even their ‘weak’ bars (barflag = 8) would correspond to a strong bar classification in the RC3. The classification of strong, intermediate and weak corresponds to the
relative light contribution of the bar, but in all cases the presence of a bar is considered sure. See Nair & Abraham (2010a) for extensive discussion of their classification process and comparison with other catalogues.

Although the bar selection was done with a purely visual classification, ellipses are fitted post-identification to the bars to determine their parameters. The ellipse fitting, which is described in Section 5, yields typical bar lengths of 3–10 kpc with bar axial ratios mostly in the range 0.2–0.6, with a median value of 0.37. Therefore, although bars can exhibit a range of sizes, including nuclear and small-scale bars with lengths \( \ll 1 \) kpc, our sample is dominated by strong, large-scale bars due to the resolution of the SDSS images. To remain concise, we will refer to our visually classified sample as a ‘barred’ sample, with the caveat that the sample is not complete for small and/or weak bars.

Even for large-scale bars, the effectiveness of visual classifications diminishes with galaxy inclination, so we further restricted our sample to have galaxies with axial ratio \( b/a \geq 0.4 \). Bars also become more difficult to identify at higher redshifts. Nair & Abraham (2010a) find a constant bar fraction in their sample out to at least \( z \sim 0.06 \). However, in order to maintain sufficient statistics in our sample of close pairs (which we use in Section 6.3 to compare the relative importance of gas inflows from bars and interactions) we do not impose an a priori redshift cut. Instead, we have checked that none of the results from the barred sample are affected by a redshift dependence by repeating the analysis described in Sections 3–5 with an upper redshift cut of 0.06. Hence we can confirm that there is no effect from redshift selection in our analysis.

From the list of clearly classified barred and unbarred disc galaxies, we then select those galaxies with strong emission lines for which both SFRs and metallicities can be determined. SFRs are based on techniques described in Brinchmann et al. (2004). Values deduced directly from the spectra (fibre SFRs) are corrected to total galactic rates using global galaxy colours (e.g. Brinchmann et al. 2004; Salim et al. 2007). Brinchmann et al. (2004) show that their colour-based corrections essentially remove all aperture effects. Stellar masses must also be available. The DR4 catalogue of stellar masses (Kauffmann et al. 2003) has now been extended to the DR7.1 Whereas the DR4 galaxy masses were derived from the spectra, the DR7 masses used here are derived from fits to the five-band SDSS photometry. There is generally excellent agreement between the two methods.

Metallicities are derived from the SDSS line fluxes available at http://www.mpa-garching.mpg.de/SDSS/DR7/. We require high-quality detections of \([\text{O} \, \text{ii}] \lambda 3727, \ H\beta \lambda 4863, \ [\text{O} \, \text{iii}] \lambda 5007, \ H\alpha \lambda 6563\) and \([\text{N} \, \text{ii}] \lambda 6584\), which necessitates a lower redshift cut of 0.02. Extensive quality control tests (see Scudder et al., in preparation) were run in order to ensure reliable line fluxes and our final selection criteria require a \( S/N > 5 \) in all of the lines above. The measured line fluxes (which are already corrected for Galactic extinction and underlying absorption in the stellar continuum) are further corrected for internal extinction using the ratio of \( \text{H} \beta / \text{H} \alpha \) and a Small Magellanic Cloud (SMC) extinction curve (Pei 1992). Galaxies whose emission line ratios indicate a significant photoionization contribution from an active galactic nucleus (AGN) are excluded (Kewley et al. 2001). Metallicities are calculated based on the recalibration of the Kewley & Dopita (2002) recommended method as presented by Kewley & Ellison (2008).

The above criteria result in a final sample of 294 bar galaxies and 806 unbarred galaxies with well-determined metallicities, SFRs and stellar masses. Fig. 1 shows the SDSS postage stamps for a selection of our barred sample. However, the barred sample is biased to more face-on galaxies, due to the difficulty of visually classifying bars in edge-on galaxies. We therefore construct an unbiased control sample by finding the unbarred galaxy which is the best simultaneous match in redshift, stellar mass and galaxy axial ratio (\( b/a \)) without replacement. The process is repeated for the second best match and a Kolmogorov–Smirnov test confirms that the distributions of redshift, mass and \( b/a \) of the bars and control samples are consistent (all probabilities \( > 25 \) per cent). Fig. 2 shows the distributions of stellar mass, redshift and galaxy axial ratios for the two samples. Our control sample size is therefore 588 unbarred galaxies.

### 3 Star Formation Rates

There is a strong correlation between SFR and stellar mass (Brinchmann & Ellis 2000; Brinchmann et al. 2004; Noeske et al. 2007; Lara-Lopez et al. 2010a). In order to search for differences in the SFRs of barred and unbarred galaxies we fit the SFR–mass relation of unbarred galaxies with a second-order polynomial. In the first instance, we consider total SFR and total stellar mass. For each barred galaxy we determine a \( \Delta \text{SFR} \) as the observed total SFR minus the total SFR predicted for its stellar mass (in log units) based on the fit to the unbarred population:

\[
\Delta \text{SFR} = \log \text{SFR} - \log \text{SFR}_{\text{predict}}. \tag{1}
\]

Positive values of \( \Delta \text{SFR} \) therefore indicate an enhancement in the SFR of a factor of \( 10^{\Delta \text{SFR}} \). The SFR residuals (in bins of stellar mass) of the unbarred control sample have median values around zero and scatter typically less than 0.05 dex.

In the top panel of Fig. 3 we plot the \( \Delta \text{SFR} \) values as a function of total stellar mass. Over the range of total stellar masses in Fig. 3, the number of galaxies per mass bin is \( \sim 20 \) (see Fig. 2). With the exception of two elevated points at the highest masses (of which only one has more than 1σ significance), there is no evidence for increased total SFRs in the barred galaxies. However, simulations of gas flows in bars (Friedli et al. 1994; Friedli & Benz 1995; Regan & Teuben 2004) indicate that gas build-up, and hence star formation is most likely to happen in the central kpc, rather than throughout the galactic disc. Similar predictions exist for the gas flows in galaxy–galaxy interactions and observations of close galaxy pairs support the prediction of null star formation (Barton et al. 2000; Ellison et al. 2010; Patton et al. 2011). We therefore repeat the above experiment with fibre SFRs, which sample the inner few kpc of the galaxy.2

The SFR–mass relation for unbarred galaxies is re-fit for the fibre values of both SFR and mass, where the latter are derived from fibre magnitudes. In the bottom panel of Fig. 3 we plot the \( \Delta \text{SFRs} \) calculated from the fibre values, although the total stellar mass is still plotted on the \( x \)-axis. Using the fibre SFRs allows us to focus on the central part of the galaxy and also alleviates any residual uncertainty in the aperture corrections. The figure shows that for the inner galactic regions sampled by the fibre, there is an enhancement of around 60 per cent (0.2 dex) in the SFRs in barred galaxies compared to the unbarred sample. However, this enhancement is only seen in barred galaxies with total stellar masses \( M > 10^{10} \) \( \text{M}_\odot \).

1 http://www.mpa-garching.mpg.de/SDSS/DR7/

2 For 0.02 < \( z < 0.1 \) the 3 arcsec fibre diameter corresponds to a physical size of 1.22–5.53 kpc.
Gas inflows in barred galaxies

The positive $\Delta$ SFR seen in the fibre, but not the global metric indicates that the enhanced star formation is both centrally located ($g$ band covering fractions for our galaxies are typically $\sim$15 per cent) and occurring at a sufficiently modest rate (on average) that it doesn’t drastically affect the overall galactic SFR. As noted in Section 2, we have checked that this is not the result of a redshift bias by checking that the result remains even with a redshift cut of $z < 0.06$ (the range up to which Nair & Abraham 2010a confirm a constant bar fraction). Moreover, the generally high fraction of bars in low-mass galaxies indicates that bars are not systematically missed below $10^{10} M_\odot$ due to other effects such as dust.

4 METALLICITIES

We apply the same offset technique to metallicities as a function of mass. The total stellar mass–metallicity relation of unbarred galaxies is fit with a second-order polynomial and $\Delta O/H$ is defined as the offset between the metallicity of a barred galaxy and the value predicted for its total stellar mass:

$$\Delta O/H = \log O/H - \log O/H_{\text{predict}}. \tag{2}$$

The O/H residuals (in bins of stellar mass) of the unbarred control sample have median values around zero and scatter typically less than 0.02 dex.

Note that, unlike the SFRs, no attempt is made to correct the abundance value to a total metallicity. The metallicity values used throughout this paper are fibre values. Kewley, Jansen & Geller (2005) found that covering fractions of $>20$ per cent should yield abundances that are representative of integrated light spectra over the entire galaxy. The majority of our galaxies have fibre covering fractions $<20$ per cent, so that imposing such a cut would leave a sample hampered by small number statistics. However, considering the fibre stellar mass–metallicity relation circumvents the issue of aperture bias, under the assumption that the unbarred galaxies have a similar distribution of radial coverage to the barred sample. The consistent distributions of mass and redshift between the barred and unbarred galaxies indicate that this is a reasonable assumption.

The upper panel of Fig. 4 shows $\Delta O/H$ as a function of total stellar mass. The metallicities of barred galaxies are higher than the unbarred sample by $\sim 0.06$ dex when the total mass of the galaxy $M_\star > 10^{10} M_\odot$. This is a similar transition mass to the enhanced SFRs in Fig. 3. The lower panel of the same figure shows the offset from the fibre mass–metallicity relation. The metallicities of barred galaxies are now higher by $\sim 0.06$ dex across the entire mass range. The appearance of enhanced metallicities at low masses when fibre quantities are considered can be understood by plotting the fraction of mass in the fibre as a function of total stellar mass (Fig. 5). Since barred galaxies with $M_\star < 10^{10} M_\odot$ are dominated by late types (Nair & Abraham 2010b) whose bulges and bars are small compared to their discs, the fibre contains a smaller fraction of the total galaxy mass (see also Fig. 1). Above $M_\star > 10^{10} M_\odot$, there is a rapid transition to a population dominated by early-type spirals,
whose bulge fraction is much higher. The low fraction of mass covered by the fibre for low-stellar mass galaxies results in a more pronounced difference in the fibre mass–metallicity offsets in the lower panel of Fig. 4.

5 BAR LENGTH AND AXIAL RATIO

The results in Section 3 indicate that gas flows in barred galaxies strongly depend on stellar mass. Barred galaxies with masses \( M > 10^{10} \, M_\odot \) show higher central SFRs and higher metallicities. Galaxies at lower stellar masses, when corrected for covering fraction, show similar increases in metallicity, but without the accompanying SFR enhancement. Clues to this mass dependence come from the work of Nair & Abraham (2010b) who have shown that the fraction of galaxies with bars shows a strong dependence on stellar mass, which in turn is linked to the predominance of late type barred galaxies at \( M < 10^{10} \, M_\odot \) and early types at higher masses.\(^3\)

The changes in metallicity and SFR may therefore also be linked to position in the Hubble sequence. Late-type barred galaxies tend to have shorter, weaker bars than early types (Elmegreen & Elmegreen 1985, 1989; Martin 1995; Chapelon et al. 1999). Simulations indicate that the amount of gas involved in radial inflows depends on bar length and strength, with the longer, stronger bars transporting more material at a faster rate than short, weak bars (Friedli & Benz 1993; Regan & Teuben 2004). Observations generally support these predictions. Martin (1995) found that the majority of starbursting barred galaxies have small axial ratios (i.e. the bars are strong). Martinet & Friedli (1997) also found that only the long, strong bars in their sample of barred late types showed signs of enhanced star formation, although they point out that even strong bars may be in a pre- or post-starburst phase with ‘normal’ SFRs. The same is apparently true of early-type bars: Chapelon et al. (1999) find both starbursting and normal galaxies in their strongly barred sample.

Complete details on the measurement of bar sizes and axial ratios will be provided in a future paper (Nair et al, in preparation). In summary, we use the frequently used procedure based on fitting ellipses to isophotes (Friedli et al. 1996; Jogee, Abraham et al. 1999; Kenney & Smith 1999; Abraham & Merrifield 2000; Sheth et al. 2003, 2008; Jogee et al. 2004; Marinova & Jogee 2007; Menendez-Delmestre et al. 2007). The original reduced SDSS frames are used to re-extract galaxies with SExtractor (Bertin & Arnouts 1996) and the segmentation of each image is checked to ensure ‘parent’ and ‘child’ objects are correctly separated. For those galaxies visually classified as barred and with galaxy axial ratios >0.4, we calculate an ellipse from the second-order moment of the light distribution in the g band, stepping from the outer ellipse towards the centre in sigma bins. For each galaxy we overplot the ellipses on the galaxy

\(^3\) The actual fraction of barred galaxies remains a contentious issue, and is likely due to a variety of visual and automated classification techniques, and whether classification is done in the optical or infrared, e.g. Masters et al. (2011).
Gas inflows in barred galaxies

Figure 4. The metallicity offset of barred spirals from the mass–metallicity relation of unbarred spirals. The top panel shows the metallicity offset between barred and unbarred galaxies at a given total galactic stellar mass (as a function of total galactic stellar mass). The lower panel shows the metallicity offset between barred and unbarred galaxies at a given fibre stellar mass (as a function of total galactic stellar mass). The increase in \( \Delta [\text{O/H}] \) at small stellar masses in the lower panel is due to the smaller fraction of stellar mass in the SDSS fibre below total stellar masses of \( \sim 10^{10} \, M_\odot \) (Fig. 5).

Figure 5. The fraction of stellar mass in the SDSS fibre for barred galaxies as a function of total stellar mass. Barred galaxies with \( M_* < 10^{10} \, M_\odot \) are dominated by late-type spirals with relatively small bulges and hence a lower fraction of the total galaxy mass is in the fibre. Barred galaxies with \( M_* > 10^{10} \, M_\odot \) are dominated by early-type spirals with relatively large bulges (see Fig. 1 for examples) so that the fibre contains a larger fraction of the total galaxy mass.

image and determine the best-fitting ellipse by eye, which normally corresponds to a maximum in the radial profile of ellipticity and a plateau in the radial profile of the position angle. The semimajor axis of the fitting ellipse is taken to be the bar length.

In Fig. 6 we show the distribution of bar lengths in our sample. We plot both the absolute value of bar length (in kpc) and the length relative to the half light radius (taken from Simard et al. 2011). Cases where the bar length could not be measured (usually because of its small scale) are allocated lengths of \(-1\) in the figure. The non-measurements are included in the calculation of binned medians shown in the lower two panels of Fig. 6. Most of the bar lengths are between 3 and 12 kpc in the \( g \) band, and the median value is 5.9 kpc. In all cases, the bars are larger than the size of the SDSS fibre (upper right panel of Fig. 6), so that the spectra always sample within the corotation radius.\(^4\) We note that there is little variation in the bar covering fraction in the mass range \( 10^{9.5} < M_* < 10^{10.5} \, M_\odot \), indicating that transition to enhanced fibre SFRs at \( M \sim 10^{10} \, M_\odot \) shown in Fig. 3 is not due to aperture bias.

In agreement with previous studies, we find that the more massive (early type) barred galaxies tend to have longer bars. This is true both in an absolute sense (lower left panel of Fig. 6) and relative to the half light radius (also measured in the \( g \) band) of the galaxy (lower right panel of Fig. 6). We now consider whether the SFR enhancement in our barred sample is linked to the length of the bar. Previous analyses have tackled this issue by comparing the structural parameters of starbursting and ‘normal’ barred galaxies. Our analysis technique differs from these earlier studies because we do not simply classify galaxies as starbursting or normal, but quantify the extent to which star formation is enhanced (\( \Delta \text{SFR} \)). This allows us to look for trends between SFRs and bar properties, rather than simply comparing the distributions of two samples.

When investigating whether there is a correlation between bar length and enhanced SFR, we consider only galaxies with \( M > 10^{10} \, M_\odot \), which is the regime in which the enhanced rates are detected. Fig. 7 shows \( \Delta \text{SFR} \) as a function of relative and absolute bar length. The lack of correlation indicates that either bar length is not the most important factor in determining gas inflow efficiency, or there is some lower limit to the bar length for inflows that all of our sample exceeds. Note also the significant scatter in \( \Delta \text{SFR} \) at a given bar length, supporting previous conclusions that the presence of a bar does not guarantee enhanced star formation. There is a broad correlation between bar axial ratio, \( b/a \), (which is often used as an indicator of bar ‘strength’) and bar length. However, the resolution of SDSS images makes it difficult to measure small axial ratios accurately. Nuclear structures such as inner rings can also complicate the fitting procedure. Visual inspection of the axial ratio fits yields a sample of 229 acceptable bar \( b/a \) measurements. Just as there is no dependence of \( \Delta \text{SFR} \) on bar length, we also find no correlation with axial ratio.

\(^4\) Bars form within the corotation radius and observations of bar pattern speeds indicate that most bars end just within corotation (e.g. Aguerri, Debattista & Corsini 2003).
6 DISCUSSION

6.1 Star formation rates

It is well established that star formation enhancements in barred galaxies are mostly seen amongst the early-type population (e.g. Huang et al. 1996; Ho et al. 1997). One of our principal results is that the enhancement in SFR in barred galaxies can be associated with the more fundamental parameter of galactic stellar mass. The increase in SFR in bars is only evident in our sample at $M_\ast > 10^{10} M_\odot$. Earlier conclusions of morphology-dependent SFR enhancements follow from this mass dependence, since barred galaxies with $M_\ast > 10^{10} M_\odot$ are dominated by early types. Our results highlight that the dependence of morphological type on mass can complicate the interpretation of trends in barred galaxies. For example, Aguerri (1999) found that bar strength correlates with SFR. However, as discussed above, bar strength is known to correlate with Hubble type: low-mass late types having generally weaker bars than high-mass early types. The correlation of SFR and bar length found by Aguerri (1999) may therefore simply be a reflection of the mass–SFR relation. Our results emphasize the importance of looking for trends at a given stellar mass, and we have tackled this by calculating SFR offsets from the unbarred SFR–mass relation. In contrast to Aguerri (1999), we do not find a correlation between SFR enhancement and bar length. Instead, there seems to be a mass threshold of $M_\ast \sim 10^{10} M_\odot$ above which fibre SFRs are higher, on average, by $\sim 60$ per cent than unbarred galaxies of the same stellar mass. This threshold corresponds to the mass at which the barred population transitions from late to early type barred galaxies. The nature of the bar itself changes at this morphological boundary, the late types being exponential and the early types being flat (Elmegreen & Elmegreen 1985). Clues to understanding the differences in bars can be gleaned from simulations. Combes & Elmegreen (1993) found that late-type bars stop growing soon after their formation, whereas bars in early types continue to gain in strength and length. The morphological distinction is driven (in the simulations) by the more concentrated mass profiles of early types, whose bulges are more prominent than in the late types. Galaxies with high bulge fractions have their corotation radius well within the galactic disc and can therefore effectively transfer angular momentum outwards and grow the bar. In turn, a growing bar has continued access to the disc’s gas supply, so that early-type bars may experience extended inner star formation, regardless of the current length of the bar. Observational support for these theoretical predictions comes from a correlation between bar length and bulge fraction (Gadotti 2011).

6.2 Metallicities

We have found the ostensibly surprising result that barred galaxies have higher central metallicities for their (fibre) mass by about...
It has been recently demonstrated that the mass–metallicity relation for the general star-forming galaxy population is itself modulated by SFR, such that galaxies with higher SFRs tend to have lower metallicities (Ellison et al. 2008b). Mannucci et al. (2010) and Lara-Lopez et al. (2010b) have even suggested a fundamental relation between SFR, mass and metallicity in star-forming galaxies that can be fitted with a plane. Interestingly, barred galaxies do not (qualitatively) follow this general trend, since they have both enhanced SFRs and higher metallicities for their mass, and would therefore presumably be outliers on the ‘fundamental relation’.

We now consider what physical reasons may lead to an apparent discrepancy between our metallicity results (enhancement in barred galaxies at a given mass) with past studies (low central abundances in barred galaxies at a given luminosity). We are guided in this endeavour by predictions from numerical simulations. For example, Friedli et al. (1994) study the evolution of abundance gradients after bar formation and distinguish between cases with and without star formation. They show that in the absence of star formation, radial mixing leads to a flattened gradient due to both a lower abundance within the bar corotation radius and a higher metallicity at larger radii due to the effect of outward mixing. If star formation is included, the outer region is again relatively metal rich with a flat gradient, just as in the no star formation case. However, inside the corotation radius, the extra star formation leads to chemical enrichment, steepening the gradient. In fact, the inner gradient is largely indistinguishable from the original (pre-bar) metal distribution, with the exception of strong metal enhancement (by $\sim 0.6$ dex in the models of Friedli et al. 1994) in the inner kpc. All of our fibre metallicities sample regions well within the bar itself, so for interpreting our results we need only consider the regime within corotation. Hence, gas flows with no accompanying star formation should lead to lower metallicities and with star formation we would expect a metallicity enhancement, assuming there has been sufficient time for the metals to be returned to the ISM.

Let us now consider the observational results which can be compared to these theoretical predictions. Most previous studies have focused on late-type (low mass) barred galaxies, in which we find no bar-induced star formation excess, so the simulations would predict relatively flat, unbroken gradients. This is indeed the case, with only a fraction of barred galaxies exhibiting abundance gradient breaks (Zaritsky et al. 1994; Martin & Roy 1995; Roy & Walsh 1997; Martin, Lelievre & Roy 2000). In these cases, extrapolating the gradient to zero galactocentric radius would indeed yield values lower than their unbarred counterparts. So, why do we find high abundances in the low-mass (late type) bars in the SDSS, even in the absence of higher SFRs? This can not be a covering fraction effect whereby we sample the metal-enriched gas beyond corotation, because the fibres always sample well within the bar length (Fig. 6). One possible explanation for the high metallicities at low masses builds on the scenario described above for the lack of bar growth in late types (Combes & Elmegreen 1993). The high metallicities, but normal SFRs in the low-mass (late type) bars in our sample may be due to an early episode of gas inflow and star formation soon after bar formation. However, the gas reservoir available for inflow is quickly depleted, but we now see the enrichment of that early burst.

At masses $M_* > 10^{10} \, M_\odot$, where our sample is dominated by early type barred spirals, we find enhanced SFRs. The model of Friedli et al. (1994) therefore predicts that the integrated metallicity within the bar exceeds the unbarred value. The models also predict that in this regime abundance gradient breaks (flatter beyond corotation and steeper towards the galactic centre) should be commonplace...
in galaxies with high stellar masses (preferentially early types). The majority of galaxies studied in past abundance work are late types where the gas fraction is relatively high and the number of H ii regions is large. Such samples may be dominated by galaxies without the higher central SFRs that lead to gradient breaks. Dutil & Roy (1999) measured relatively flat gradients in eight early-type barred galaxies, but did not report breaks. However, in most cases the inner kpc of the galaxies were not well-sampled and the abundance scatter at a given radius is typically 0.4 dex. In one detailed case study (of NGC 4900), Cantin et al. (2010) find bright emission line regions and gas phase abundances of twice solar only a few hundred pc from the galactic centre. Modern instrumentation and recalibrated strong line abundance diagnostics have significantly reduced measurement error and diagnostic uncertainty, yielding tighter gradients (e.g. Moustakas et al. 2010). It would be interesting to revisit abundance gradients for a large sample of barred galaxies, focussing on the inner regions.

The high SFRs and high metallicities in barred galaxies with $M_\star > 10^{10} M_\odot$ stand in contrast to close pairs of galaxies which trace interaction-induced gas flows. Although enhanced SFRs in pairs are ubiquitously reported in the literature, the metallicities are lower at a given mass (Ellison et al. 2008a; Michel-Dansac et al. 2008). This may be because galaxies that are still easily identifiable as pairs (as opposed to post-mergers) are relatively early on in the dynamical process. Simulations predict that the gas-phase metallicity does not increase as a result of the triggered star formation until hundreds of Myr after the starburst, by which time the merger may be almost complete (Montuori et al. 2010). This is because of the time delay of both the supernovae and also the cooling time of the gas to reach the $\sim 10^4$ degrees to which the nebular emission lines respond. Since the high-mass barred galaxies are metal enhanced, the process which triggered the star formation (which we still see to be on-going) must be long-lived ($\geq 10^8$ yr). This is consistent with the reconstruction of star formation histories in barred galaxies that indicate multiple episodes of central star formation (e.g. Cantin et al. 2010).

6.3 Comparison with galaxy–galaxy pairs

Since the two main mechanisms for torquing gas to the centres of galaxies are usually considered to be the presence of a bar and galaxy–galaxy interactions (e.g. Mihos & Hernquist 1996; Di Matteo et al. 2007), it is of interest to compare the relative impact of these two processes. Although bars can themselves be the result of an interaction, we note that none of the barred galaxies in our sample appear to be currently undergoing any interaction (or has a close companion within 30 kpc). Bars may therefore represent a much more extended phase in the galaxy’s history than a fly-by or merger (as supported by the observations cited in this paper), as well as having a contribution from secular formation mechanisms. Our comparison is therefore also one of time-scales, comparing the effect of a close encounter which is short lived but potentially dramatic, and the longer lived bar phase (which may be either interaction-induced or secular). We will explicitly address the formation of bars in close galaxy pairs in a future paper where we look at the fraction of close pairs in which a bar is detected (Nair et al., in preparation).

It has not previously been possible to compare the relative efficiencies of bars versus interactions, which requires a large sample of homogeneous data for both barred galaxies and galaxies with close companions. We can now tackle this comparison for the first time, by comparing the SDSS study of barred galaxies presented here with the SFRs that we have previously published for SDSS galaxy pairs (Ellison et al. 2008a, 2010). The galaxy pairs are selected from the sample presented by Patton et al. (2011), compiled from the DR7. The stellar masses of the galaxy and its companion are within a factor of 3 and the upper redshift cut is $z = 0.1$ (which matches the limit of the bars sample). We select the closest pairs in order to yield a sample most likely to yield enhanced SFRs. The redshifts must therefore agree to within $\Delta V < 300$ km s$^{-1}$ and the projected separation is within 30 kpc. The control sample is matched in stellar mass and redshift.

In Fig. 8 we show the change in fibre SFR as a function of mass for both galaxies with a close companion and barred galaxies (the latter are the same as the points from Fig. 3). The level of enhancement is consistent with the findings of Ellison et al. (2008a) who found aperture corrected enhancements of $\sim 60$ per cent in their 1:3 mass ratio sample. The maximum increase in the fibre SFRs of both barred galaxies and galaxies with a close companion is around 0.2–0.3 dex (60–100 per cent), indicating that these two processes can be equally efficient. However, the mass dependence on fibre SFR is very different between the pairs and the bars. In Section 3 we discussed how the increase in SFRs in barred galaxies is strongly mass dependent, showing a sharp transition at $M_\star \sim 10^{10} M_\odot$. This is not seen in the pairs (where the mass is that of the individual galaxy), with enhancements up to a factor of 2 in the fibre SFR down to total stellar masses $M_\star \sim 10^9 M_\odot$. One interpretation of Fig. 8 is that galaxy–galaxy interactions and bars can trigger star formation in different mass regimes. However, the enhanced metallicity in low-mass bars indicates that their past SFRs were enhanced, but the enhancement was short lived. Therefore, the detection of a SFR enhancement in pairs of all stellar masses is more likely due to them being observed in the brief window of triggered star formation which is usually strongest after the first pericentric passage and at coalescence (e.g. Montuori et al. 2010).

Although bars and galaxies with a close companion appear to have similar triggering efficiencies, the contribution of these processes depends on the frequency of bars and pairs. We can make a simple estimation of the relative contribution of bars and pairs to the fibre SFR enhancements ($\epsilon_{b/p}$) in galaxies from

$$
\epsilon_{b/p} = \frac{f_b}{f_p} \times \frac{f_{\star,b}}{f_{\star,p}} \times \frac{10^{\Delta SFR_b}}{10^{\Delta SFR_p}}.
$$

(3)

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The first ratio is the fraction of the galaxy population in bars and pairs \( f_b \) and \( f_p \), respectively. In order to calculate \( f_p \), we use the statistics of Patton & Atfield (2008), but scaled to our different pair criteria (mass ratio, projected separation and \( \Delta V \)). This fraction corrects for fibre incompleteness, but not interloper fraction, since the latter effect is also present in our estimate of the SFR enhancement. We determine \( f_p = 0.024 \). Nair & Abraham (2010b) quote the fraction of bars in their sample to be \( \sim 30 \) per cent. However, this is a fraction of the disc population with bars, whereas we require the fraction of the total population that has a bar. Imposing a redshift cut of \( z > 0.02 \) (which is part of the metallicity criterion) and galaxy b/a > 0.4 on the Nair & Abraham (2010a) sample yields 1657 bars out of a total of 9914 moderately inclined galaxies, leading to \( f_b = 0.167 \). We note that this is likely to be a conservative fraction as bar incidences tend to be fairly low in visual classifications of optical images. The second component in equation (3) is the ratio of the fraction of bar and pair galaxies that pass the emission line criterion (Section 2) to enter into our sample of star-forming galaxies \( (f_{b*,} \) and \( f_{p*,} \), respectively). The ratio of these fractions accounts for the different selection functions of bars and pairs, such as differences in covering fraction and mass distributions which can affect the typical strength of emission lines. The number of galaxies in close pairs \( (R_p < 30 \) kpc and \( \Delta V < 300 \) km s\(^{-1}\)) with \( 0.02 < z < 0.1 \) in the sample is 1770, of which 431 have emission lines strong enough to be included in our star-forming sample, leading to \( f_{b*,} = 0.24 \). Of the original \( 0.02 < z < 0.1 \) bar sample of 1657, 294 are in our star-forming sample. However, we make a further conservative decision to only count the bars that contribute to the \( \text{on-going} \) enhanced star formation, i.e. those with \( M > 10^{10} \) M\(_{\odot} \), of which there are 212. We have argued above that there may have been a past enhancement in the SFR of lower mass bars, which we can not constrain. We hence determine \( f_{b*,} = 0.128 \). The third ratio in equation (3) is the ratio of the SFR enhancements in bars and pairs. Although there is some mass dependence seen in Fig. 8, on average this ratio \( \frac{f_{b,p}}{f_{p}} \sim 1 \) (recall that we are only including the bars with \( M_\star > 10^{10} \) M\(_{\odot} \) in our calculation). Combined, these adopted values lead to \( \epsilon_{b/p} \sim 3.5 \), indicating that approximately 3.5 times more central star formation is triggered by the presence of a bar than by interactions. This value of \( \epsilon \) is quite sensitive to the selection criteria, e.g. the definition of a close pair and how the bar fraction is calculated. None the less, \( \epsilon_{b/p} \sim 3.5 \) is probably a conservative estimate for the reasons described above and indicates the important role of bars in the build-up of central stellar mass. We emphasize that our results can be used to calculate the relative contributions of bars and pairs to the central star formation, due to the low covering fractions in the bars sample. Neither bars nor pair interactions appear to induce additional star formation in the disc (e.g. Ellison et al. 2010; Patton et al. 2011).

7 SUMMARY

We have compiled a sample of 294 galaxies with a large-scale bar and a control sample of 588 unbarred galaxies visually classified from the SDSS DR4. All of the galaxies have measurements of stellar mass, SFR and gas phase metallicity. The sample is used to study differences in SFRs and chemical abundances between the visually classified barred and unbarred populations in order to investigate evidence of bar-induced radial gas flows. Our analysis fits the SFR–mass and mass–metallicity relations to the fibre values of mass, SFR and metallicity of unbarred galaxies and then measures deviations from these relations in barred galaxies. Using the fibre values compensates for differences in the fraction of mass in the fibre and reveals trends that are absent in global measurements. Our observations reveal the following.

(i) The central SFRs of visually classified barred galaxies with \( M_\star > 10^{10} \) M\(_{\odot} \) are higher than unbarred galaxies of the same mass by \( \sim 60 \) per cent. Lower mass barred galaxies show no increase in their central SFRs, above the values observed in unbarred spirals.

(ii) In contrast to theoretical expectations and inferences from past observational studies, we find no significant correlation between SFR enhancement and bar length or bar axial ratio in the galaxies where increased star formation is found (i.e. at \( M_\star > 10^{10} \) M\(_{\odot} \)).

(iii) A 60 per cent enhancement is also typical of the star formation triggered in galaxy–galaxy interactions at masses \( M_\star \sim 10^{10} \) M\(_{\odot} \). However, interactions also show SFR enhancements at masses \( M < 10^{10} \) M\(_{\odot} \), whereas visually classified barred galaxies do not.

(iv) Although the enhancement in the SFRs of visually classified barred and pair galaxies is similar, the higher fraction of barred galaxies than pairs means that bars dominate over interactions in their contribution to the central SFRs for galaxies with \( M_\star > 10^{10} \) M\(_{\odot} \). We estimate that \( \sim 3.5 \) times more central star formation comes from the presence of a bar than from interactions.

(v) In contrast with previous observations that have found low central gas phase abundances in visually classified barred galaxies, we find higher metallicities by \( \sim 0.06 \) dex relative to unbarred galaxies at the same mass. The high metallicities in barred galaxies also contrast with galaxy pairs where gas inflows lead to low metallicities.

(vi) The metal enrichment is seen even in low-mass barred galaxies where no enhancement in the SFR is observed.

Taken together, these results suggest a picture of mass dependent gas inflows in galaxies with strong stellar bars. The enhanced chemical abundances in barred galaxies of all masses indicate that most of them have undergone some past enhancement in their SFRs. Due to the time delay for enrichment following the star formation, this in turn indicates that the bars themselves are relatively long lived. However, our results are consistent with a distinction between the triggered star formation histories experienced by low-mass, late-type, barred galaxies and the higher mass, early types. Below a mass threshold of \( M_\star \sim 10^{10} \) M\(_{\odot} \), the star formation that has led to higher chemical abundances has now ceased, indicating that any SFR enhancement was relatively short lived. For barred galaxies with stellar masses \( M_\star > 10^{10} \) M\(_{\odot} \), the enhanced star formation is ongoing.

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