Star formation in bars: where and why?

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Abstract We present first results in a project devoted to understanding the conditions which inhibit/favour star formation in bars and their spatial relation with the main bar dynamical features. We have carried out a detailed analysis of the strong bar of NGC 1530, our pilot target. The analysis comprises N–body/SPH modelling and *BVRKs* and Hα photometry. The simulations reproduce remarkably well the observed general morphology and kinematics, but fail to predict the loci of massive star formation. We find differences in the Hα equivalent width of the H II regions of the bar, which are related to their position with respect to the bar dust–lanes: the Hα equivalent width of the H II regions located downstream the bar dust–lane are lower than the rest. The possible factors producing this difference have been carefully analysed and age has been confirmed to be the most plausible explanation. This result implies that the H II regions located further away from the bar dust–lane, in its leading side (downstream), are older than the rest. The possible scenarios explaining this result are discussed.

1 Introduction

Bars in galaxies have been intensively studied during the last decades, however mainly with the motivation of investigating their role in the transport of material towards the central regions of galaxies, where it can participate in star formation

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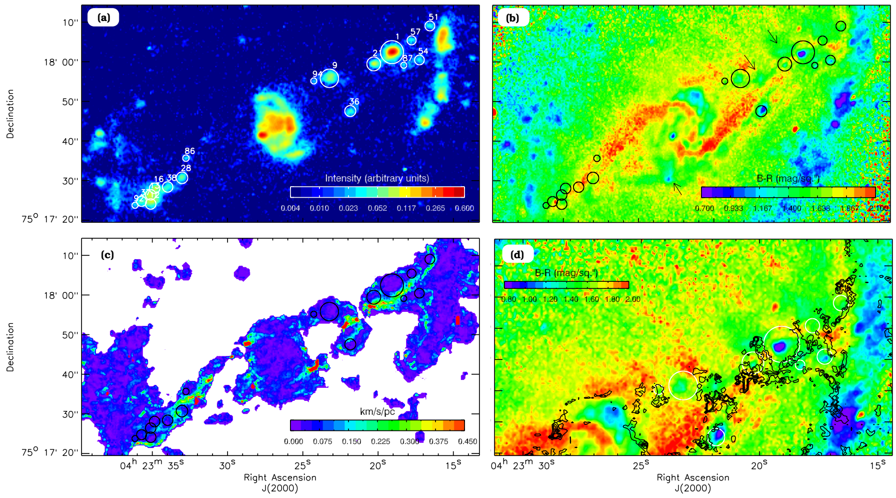

Fig. 1 Snapshots of the bar region of NGC 1530. **(a)** Hα continuum subtracted image of the bar region of NGC 1530. **(b)** $B-R$ colour map. **(c)** Observed projected velocity gradient map in the direction perpendicular to the bar (from Zurita et al. 2004). **(d)** $B-R$ colour map of the NW side of the bar with overlaid contours of the velocity gradients in the direction perpendicular to the bar. Images **(a)** to **(c)** show the same area of the galaxy. See Zurita & Pérez (2008) for colour versions of these snapshots. NGC 1530 rotates clockwise (Zurita et al. 2004).

(SF), or contribute to the mass of the central super-massive black hole, and to the activity around it (Shlosman et al. 1989). The properties of the bars themselves, in particular the presence and characteristics of recent SF within them, has received much less attention so far and it is not yet well understood. This is of particular interest, as bars are sites with extreme physical conditions (e.g. strong shear, shocks and non–circular velocities, significant magnetic–field strength) but there appears to be no obvious differences between H II regions of bars and discs (Martin & Friedli 1999). This makes of bars excellent laboratories for studying the physical parameters that, in general, trigger and inhibit SF.

The conditions, places and parameters which favor SF in bars are not yet well understood, partly due to the limited amount of detailed studies dedicated to the subject so far. Most of our current knowledge on the location, distribution and properties of star–forming regions has been derived from a handful of papers centered on the physical properties of the H II regions (Martin & Friedli 1999), and the global distribution of the Hα emission along the bar (e.g. Phillips 1996; Verley et al. 2007), and its relation with molecular gas (e.g. Sheth et al. 2000; 2002). While these studies provide a good overview on general properties, have proved to be insufficient for understanding the factors determining SF to occur. Moreover, it has long been associated the presence of strong shear in bars with the absence of SF. This link comes from fluid dynamic simulations of bars (e.g. Athanassoula 1992), because they predict that the highest density loci (bar dust–lanes) are also the loci of strong shear and shocks in strong bars, which could prevent the collapse of molecular clouds and therefore the formation of stars. While there is observational evidence that star forming sites are spatially anti–correlated with the loci of strong shear (Zurita et al. 2004), the above generalisation is too simplistic, as H II regions are present along strong bars. This is the case of NGC 1530 (see Fig. 1a).

2 The bar of NGC 1530: hydrodynamical simulations

NGC 1530 has one of the strongest bars ever observed (Block et al. 2004). Kinematically it is characterized by strong non-circular motions (e.g. Regan et al. 1996; Reynaud & Downes 1998), and high velocity gradients in the direction perpendicular to the bar (Zurita et al. 2004).

N-body/SPH modelling (Pérez, Fux, & Freeman 2004) has been carried out using the gravitational potential obtained from the light distribution of the galaxy. The best fit pattern speed is $\sim$10 km s^{-1} Mpc^{-1}, implying a fast bar. The model reproduces very well the main observed morphological and kinematical features of the bar, namely the presence and amplitude of projected non–circular velocities and velocity gradients perpendicular to the bar, which trace the loci strong shear (Pérez & Zurita 2009).

In spite of the strength of the NGC 1530 bar and the presence of strong shear, sites of recent massive SF are evident along its bar (see Fig. 1a). This fact strongly motivates a deep study of the H II region properties and their relation to the main dynamical features of the bar.

3 H II region properties

The H II region catalogue of NGC 1530 was presented in Relaño et al. 2005, and comprises 119 H II regions. Of these, approximately 20 H II regions are located on the bar of the galaxy (indicated with circles in Fig. 1). From the positions and projected areas of the catalogue, the B, V, R and Ks fluxes were measured using aperture photometry. Within the integration aperture, we are measuring the contribution from both the ionizing cluster and the underlying stellar population of the disc/bar of the galaxy. We are interested only in the radiation emitted by the ionizing cluster of the nebula. Therefore, we carefully measured the contribution from the underlying bar/disc stellar population, which was subtracted off from the measured total fluxes (see Zurita & Pérez 2008 for further details). The results are shown in Fig. 2. It shows the broad–band fluxes and the Hα equivalent widths ($EW_{H\alpha}$) of the bar H II regions of NGC 1530 as a function of their deprojected distance to the bar dust–lane. The most striking result comes from the Hα equivalent widths: the H II regions located further from the bar dust–lane, in its leading side (downstream), have lower $EW_{H\alpha}$, by a factor 4–5 or a 0.6–0.7 dex difference in log $EW_{H\alpha}$, than H II regions

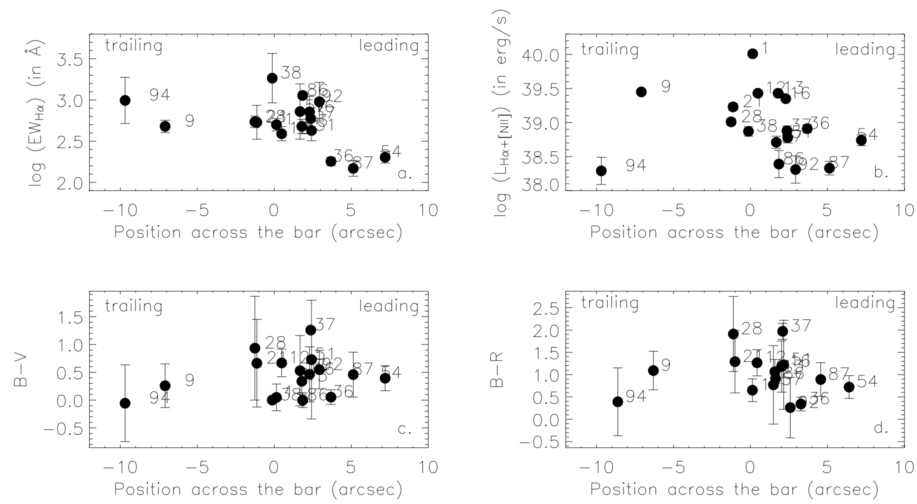

Fig. 2 Representation of (from top to bottom and from left to right) the Hα equivalent width, Hα+[N II] luminosity, B–V and B–R broad–band colors of the H II regions of the bar of NGC 1530 as a function of their deprojected distance from the bar dust–lane in arc seconds. Negative and positive distances refer to H II regions located on the trailing and leading side of the bar dust–lane respectively. Broad–band colours have been corrected for Galactic extinction (Schlegel et al. 1998).

located on the trailing side (upstream) and those closer to the bar dust lane. In terms of broad–band colors and Hα luminosities, there is no obvious difference (within error bars) between the H II regions located on the leading and trailing sides of the bar dust–lanes. We have carefully analysed the factors that could account for the observed difference in $EW_{H\alpha}$ due to differential contribution between the regions located in the trailing and leading sides with respect to the bar dust–lane: [N II] contamination within the Hα filter bandpass, Lyman–continuum photon dust extinction, escape of Lyman–continuum photons from the H II regions, differences in metallicity, IMF and age (see Zurita & Pérez 2008 for a detailed analysis). Of these, only age can account for such systematic $EW_{H\alpha}$ variation. The measured difference in $EW_{H\alpha}$ implies that the H II regions located furthest away from the bar dust–lane, in its leading side, are on average 1.5–2.5 Myr older than the rest (Fig. 3).

4 Scenarios for an H II region age difference across the bar

A time delay and a location offset of the SF burst in the bar could, in principle, explain the observed age differences. However, that would imply that the conditions triggering SF would have changed, favouring the trailing side of the bar dust–lane with respect to the leading side, in a very short timescale (a few Myrs) compared to the bar orbital time, and therefore this scenario appears unfeasible. An ageing and

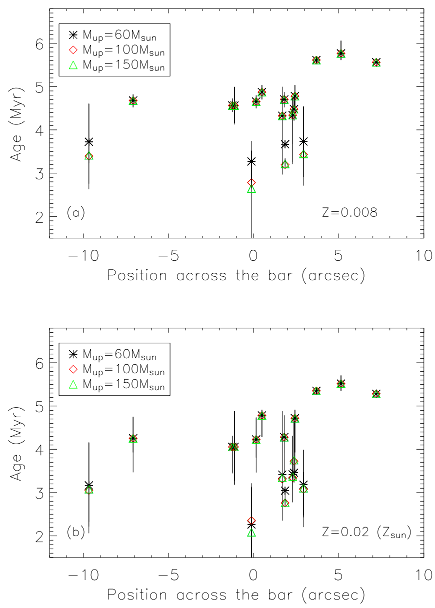

Fig. 3 Estimated age of the bar H II regions of NGC 1530 as a function of their deprojected distance across the bar of the galaxy. Negative and positive distances refer to H II regions located on the trailing and leading side of the bar dust–lane respectively. The ages have been estimated with *Starburst99* (Leitherer et al. 1999). Asterisks, diamonds and triangles indicate ages estimated from IMFs with upper mass limits of 60, 100 and 150 $M_{\odot}$, respectively. *(a)* and *(b)* show age estimates for to different metallicities.

migration effect of the stars formed initially on the trailing side of the shock region of the bar towards the leading side, can also explain the observations. This is also compatible with the time–scale, as the H II regions age difference is of the same order of the dynamical crossing–time of a cloud/star, in the frame that rotates with the bar, taking into account our measured bar pattern speed (Pérez & Zurita 2009). The hypothesis that stars could form on the trailing side of the bar dust–lane and then migrate towards the leading side, was proposed by Sheth et al. (2000). They hypothesized that stars form in *dust spurs* (observed in color maps as red feathers that extend approximately in a perpendicular direction to the main bar dust–lanes from the bar trailing side, Figs. 1b and 1d). The formed stars would then cross towards the leading side of the bar dust–lane as they age.

In addition to the H II region age difference, further evidence supporting this hypothesis comes from the Hα kinematics. Comparison of the ionized gas velocity gradients parallel to the NGC 1530 bar (Zurita et al. 2004) with our color maps shows a good spatial agreement between the location of the dust spurs and the velocity gradients in the direction of the bar major axis. This strongly suggest that the gradients are tracing gas flow along the spurs towards the main bar dust–lane. This implies that dust spurs are zones of higher gas density and lower relative velocity with respect to the bar than the surrounding regions, therefore favouring the collapse of gas clouds and the star formation (Tubbs 1982).

5 Conclusions and Future Work

The $EW_{H\alpha}$ of the H II regions located furthest away from the bar dust–lane of NGC 1530, on its leading side, is lower than the $EW_{H\alpha}$ of the rest of the H II regions by a factor $\sim 4-5$, which can only be explained in terms of an age difference between both sets of regions, being younger those located on the trailing side. This fact together with the observed spatial correlation with dust spurs and velocity gradients, provides further support to the hypothesis that SF in bars occurs in the dust spurs. The ageing of the recently formed stars as they cross the bar is compatible with the bar dynamics timescale. This result highlights the importance of taking into account the dynamics of the bar when studying SF in bar environments.

A detailed analysis of bar H II regions for a larger sample of strongly barred galaxies together to study their distribution with respect to the dynamical features of the bar, is currently being carried out. This analysis includes the study of the ionized gas kinematics and the CO content along the bars, and will confirm whether the conclusions obtained with NGC 1530 can be generalized to other bars with SF and therefore constrain the parameters which allow star formation to occur in bar environments.

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