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The Role of HI in the Star Formation Processes in Spiral Disks

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Abstract. We discuss recent work on massive star-formation efficiency parameters on 1 kpc scales in grand-design spiral galaxies. The fact that in two galaxies studied in detail, M51 and NGC 4321, the massive star-formation efficiency in the arms is larger than that outside the arms can be seen as evidence for large-scale triggering of the star formation in the arms, probably induced by a density wave system. We discuss several possible systematic effects, but infer that the conclusions on triggering are sound.

In a second part of this paper, we discuss the role of atomic hydrogen in the star-formation process in spiral arms. Rather than causing enhanced star formation, HI seems to be a product of the star-formation processes. We show that the HI in the inner parts of the disk may be produced by photodissociation from molecular gas, but that in the outer disk an important part of the HI is not a direct result of massive star formation.

1. Star-Formation Efficiency Patterns in Grand-Design Spirals

Although it is clear that stars are forming at higher rates in spiral arms than in the rest of the disks of spiral galaxies, direct comparison of these rates does not tell us too much about the physics of the massive star-formation process. This is clear if one postulates that in the arms the stars may be forming n times more quickly than in the inter-arm zones (where n is found in fact to lie in the range 1–10), whereas the underlying neutral gas density may be m times as great, where the unknown m may be much larger, or much smaller than n. Until we can compare these quantities, our knowledge of the physical constraints on the star-forming process is very limited. This problem was understood by Cepa & Beckman (1990) who formulated a massive-star-formation efficiency parameter: the Hα luminosity, $L(\mathrm{H}\alpha)$, divided by the surface density of the total neutral gas, $\sigma(\mathrm{HI}+\mathrm{H}_2)$. It is easy to show that $L(\mathrm{H}\alpha)$ is monotonically dependent on the mass of ionizing stars per unit area of galactic disk, and that for a plausible range of IMF slope this dependence is linear, while $\sigma(\mathrm{HI}+\mathrm{H}_2)$ is a measure of the amount of neutral gas available for star formation. However to use this parameter in a way which depends least on the systematic errors which can enter its computation, Cepa & Beckman (1990) used it to compute the ratio, ϵ, of the parameter in an arm, and in the neighbouring inter-arm disk. They found, for two grand-design spirals NGC 3992 and NGC 628, that ϵ varied

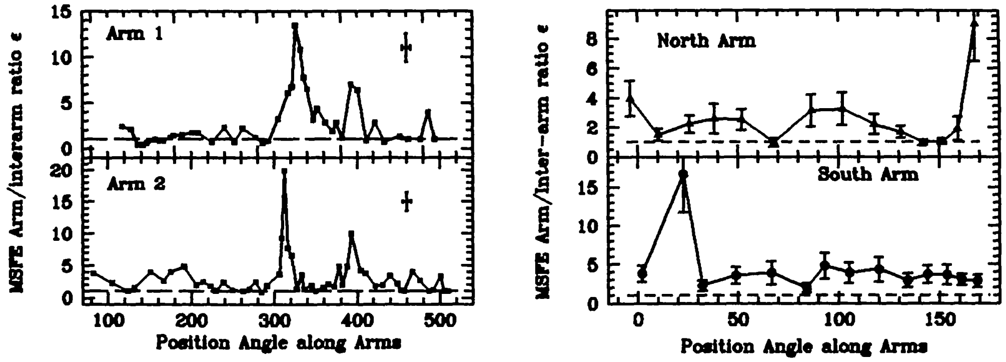

Figure 1. Arm-interarm ratio ϵ of the massive-star-formation efficiency along the main arms of M51 (left) and NGC 4321 (right).

in a strongly modulated fashion along the arms, with two peaks of amplitude ≥ 10 at well-defined galactocentric radii in each object. The fact that these peaks in ϵ occur at identical radii in both arms of each galaxy implies that they are caused by disk-wide effects, which Cepa & Beckman (1990) identified with density-wave resonances. They claimed that the dip between the peaks coincides with an efficiency minimum at corotation. The high values reached for ϵ imply triggering of star formation with a non-linear dependence of SFR on the underlying neutral gas density (untriggered formation would correspond to equal efficiencies in the arms and the inter-arm disk, *i.e.*, $\epsilon \simeq 1$).

This work was carried forward by Knapen *et al.* (1992) who applied the technique to M51, for which it was possible to make a much better estimate of the H_2 column density, which dominates the inner 5 kpc, because maps of CO emission were available for this object (Nakai et al 1991; García-Burillo & Guélin 1991). Results similar to those in the previous objects were found in M51, *i.e.*, ϵ showed peaks ranging in some cases to well over 10 in amplitude, whose radial distances from the centre of M51 were essentially the same for both arms, as were the distances of the troughs between them (see Fig. 1). Here again resonance structure in ϵ, as well as triggering of star formation by the dynamical effects within the resonance pattern, were picked out clearly.

In fact the limitation of the use of the ϵ technique is the difficulty of obtaining well resolved maps in CO, good enough in S/N ratio and in angular resolution to at least differentiate an arm readily from the neighbouring disk. The number of galaxies in the literature with good enough mapping in CO for this purpose is negligible. We ourselves, therefore, obtained a partial map of NGC 4321 (M100) for this purpose with the Nobeyama 45 m dish (see Cepa *et al.* 1992). We combined the derived $\sigma(H_2)$ values with our own VLA observations in HI (Knapen *et al.* 1993), and an Hα map with the 4.2 m William Hershel Telescope, to obtain the dependence of ϵ on radius for each arm, as shown in Fig. 1 (right). We can see that there is a notable difference between NGC 4321 and M51 in this respect. In NGC 4321 there is a lack of congruence in the modulation of ϵ with radius, between the two arms, and ϵ does not reach peaks above 7 (with the exception of one individual point on each arm, where the CO intensities are lowest, and the uncertainties highest). On the other hand the average value of ϵ for NGC 4321 is ~ 3, and this is virtually identical with the average for M51. We can conclude that there is triggering of star formation in NGC 4321 (otherwise ϵ would be ~ 1), but that the resonance pattern in ϵ is not apparent. In fact the arms of NGC 4321 are much more flocculent in appearance then those of M51, and occupy some 50% of the disk, while those in M51 occupy less than 10% of the disk surface (Beckman *et al.* 1994), so the tighter resonance structure in M51 is not surprising.

Some phenomenological questions can be raised about possible systematic effects on ϵ which could weaken the above inferences. Could the Hα peaks in M51, NGC 628 and NGC 3992 be artificial: due not to stronger Hα but to greater dust extinction between them? All the evidence in fact points against this. In optical images in the *B* & *V* bands there is no evidence of stronger dust concentrations where we detect lower Hα, nor is there evidence of a rise in $\sigma(\mathrm{HI}+\mathrm{H}_2)$ which could have been indications of greater dust column density. This absence of strong neutral gas concentrations in the arms at radii where ϵ is low also means that the low values are a result of low Hα there, and *not* of high $\sigma(\mathrm{HI}+\mathrm{H}_2)$. Similarly the ϵ peaks do correspond to points of strong star formation, and not of little neutral gas.

The use of ϵ also mitigates problems due to the need to convert observed CO column densities to H_2 column densities. While there is evidence from within our Galaxy that the CO/H_2 conversion factor does not in fact vary by large factors across the face of a galaxy, the fact that we have based our conclusions about triggering on values of ϵ consistently close to 3 in the arms means that we must be careful that conversion ratio uncertainties cannot vitiate this. The fact that ϵ contains a ratio of $\sigma_{\mathrm{H}_2}(\mathrm{arm})/\sigma_{\mathrm{H}_2}(\mathrm{inter\text{-}arm})$, with both σ at the same galactocentric radius, certainly means that radial gradients in the conversion factor will have no effect. There could be an effect due to the greater SFR in the arms, giving rise to possibly higher metallicities, which in turn would imply a lower true CO/H_2 conversion factor in the arms. If this effect were present, it would lead to an overestimate of $\sigma(\mathrm{H}_2)$ in the arms, which in turn would lead to an underestimate of ϵ. Thus our values of ϵ, if at all affected by this, would be too low rather than too high. Any conclusions about the presence of triggering will clearly remain unaffected by this possible systematic effect. One final effect might also enhance our measured value of ϵ without a genuine cause: if the CO were so optically thick that we seriously underestimate its column density, and hence that of the H_2 in the arms. However, even in the outer parts of the disks observed, where the neutral gas density is dropping below $10^{21}\,\mathrm{cm}^{-2}$, and where HI begins to compete with H_2 for dominance in column density, the behaviour of ϵ shows peaks and/or mean values consistently in the range close to 3. We feel it safe to conclude that our evidence for star formation triggering in the arms is sound.

2. The role of HI

In the inner parts of many late-type galaxies the molecular hydrogen, as measured through CO, is much more abundant than the atomic hydrogen. This effect is especially notable in barred galaxies, where the HI usually shows a clear hole in the centre, whereas the CO distribution keeps increasing inward (see

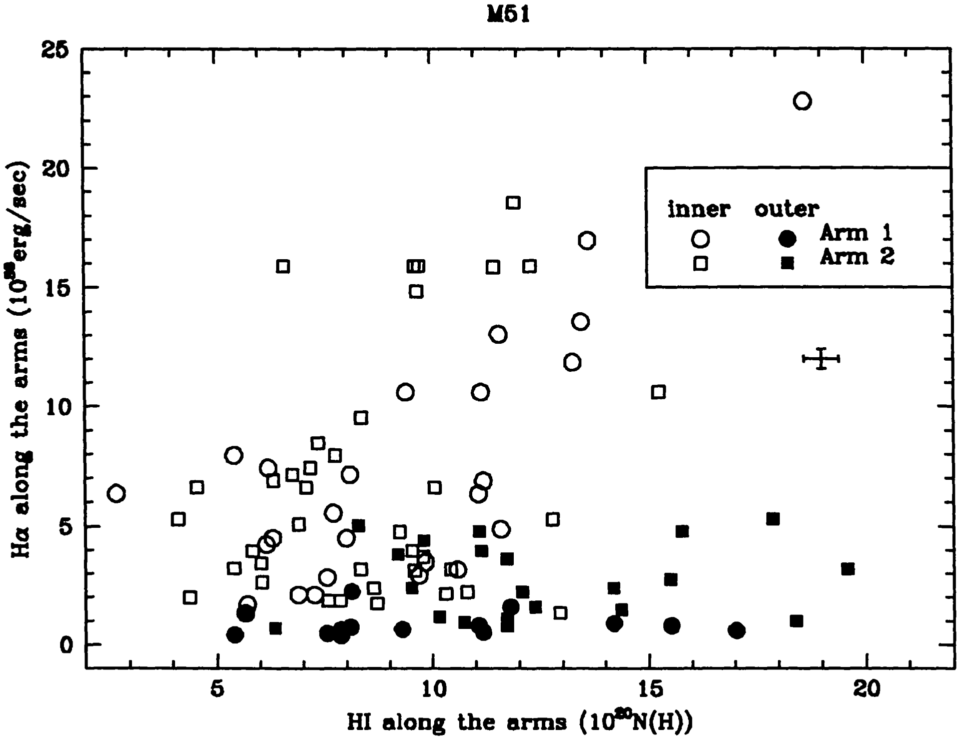

Figure 2. Relation between Hα luminosity and HI density for points along the main arms of M51. Circles indicate points along arm 1, squares points along arm 2. Open symbols are points in the inner part of the galaxy disk, filled symbols denote outer points. Typical errors are indicated.

Young & Scoville 1991 for a review). In the two galaxies under consideration here, M51 and NGC 4321, the mass of hydrogen, as expressed in N(H), in molecular form is more than an order of magnitude larger than that in atomic form over most of the optical disk. In the outer parts of the disk the HI gradually takes over as the most abundant form (Knapen *et al.* 1992, Knapen 1992).

2.1. M51

In the case of M51, we noted before (Knapen *et al.* 1992) that some of the strong peaks in Hα along the two main arms are accompanied by enhancements in the HI density at the same positions. We stated that since the molecular gas is the most abundant form of neutral hydrogen by an order of magnitude in the parts of the disk considered, these HI peaks cannot be the cause of the enhanced star-formation activity, but are more likely to be the result of that. A scenario that can be invoked to explain such a production of HI is one proposed by Allen, Atherton & Tilanus (1986) and Tilanus & Allen (1989, 1991), where atomic hydrogen may be formed from photodissociation of molecular gas under the influence of the radiation field in regions of massive star formation. This effect was originally observed from the relative displacements of tracers of gas, dust and stars in the spiral arms of M83 and M51, but in our M51 work (Knapen *et al.* 1992) we saw new evidence from the coincidence of peaks in Hα and HI along the arms.

Such an effect would work mainly in the inner parts of a galaxy, where the ionizing radiation of young, hot stars is important, and where molecular hydrogen is dominant. Apart from atomic hydrogen that is formed from molecular hydrogen by photodissociation, there is also a component of the atomic hydrogen that is not a direct result of massive star formation, and which is most visible beyond the optical disk of M51 (see Rots *et al.* 1990). We plot in Fig. 2 the HI column density against the Hα flux in points along the two main arms (named Arm 1 and Arm 2) of M51 within the confine of the optical disk. Open symbols in the Figure denote arm points in the inner part of the disk, whereas filled symbols denote arm points in the outer part of the disk. The division radius between inner and outer disk has been taken just beyond the last large HII region complexes (noted F and f in Knapen *et al.* 1992).

Fig. 2, although rather coarse, shows several interesting features. First, we see no difference in behaviour between the two arms, and will therefore not treat them separately here. Then, the points along the inner part of the arms seem to occupy a different region in the diagram than the points that lie along the outer parts. Although the scatter (which is not caused by observational errors) is large, the division seems relevant, especially since the most significant points are those with the strongest fluxes. The 'inner' points lie along a rising line (slope 0.9 ± 0.2 in the units plotted in the Figure) indicating a relationship between the Hα flux and the HI density (the correlation coefficient of a regression fit to this line is $r = 0.51$). This is caused by the fact that the HI is enhanced where the Hα shows strong peaks, as discussed before. But the 'outer' points all lie in the bottom part of the diagram. Although they do show a wide range in HI densities, their Hα flux is consistently low, and not generally higher at points with higher atomic gas density.

In the inner parts the HI is probably formed by photodissociation of molecular gas by the ionizing radiation field from massive young stars. The HI in the outer regions is not completely independent of the local Hα radiation field, as argued by Rand, Kulkarni & Rice (1992) who find evidence from radial profiles of total gas, Hα and HI that dissociation by massive young stars still plays a role at these large radii.

But even if the massive stars are the most important source of photodissociating radiation, the correlation between Hα and HI may break down. First, since the total gas density is much lower than in the inner disk, photons can travel further from the OB stars that produce them, and molecular hydrogen can be dissociated at greater distances from the radiation sources, tending to weaken the small-scale HI–Hα correlation. Also, the influence of radiation originating outside the galactic disk (extragalactic background) will be substantially higher in the outer parts since the gas density may be too low to self-shield molecular gas against destruction. Then the metallicity may be so low in the outer regions of the disk that there are not enough dust-grains for molecular gas to form on. All these processes can lead to a more widespread distribution of HI, and cause the effect seen in Fig. 2. An example may be the tidal arm observed in HI by Rots *et al.* (1990), where no Hα is detected. Some or all of the above-mentioned processes may cause the hydrogen in the arm to be predominantly atomic.

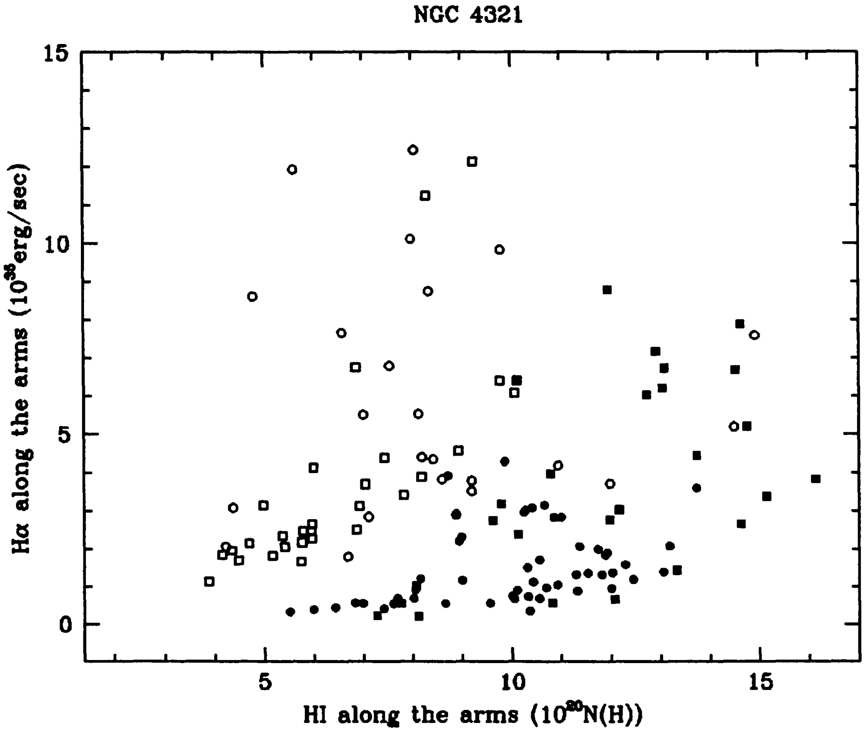

Figure 3. As Fig. 2, for NGC 4321.

2.2. NGC 4321

In Fig. 3 we present the relation between HI density and Hα flux for points along the two main arms of NGC 4321, again for the inner (open symbols) and outer (filled symbols) part of the disk. In this case we took the radius just outside the large HII region complex in the arm south of the centre as the division point between inner and outer disk. This implies, as in the case of M51, that most of the large star-forming regions are found in the inner part of the disk. Although, as shown in Fig. 1, there are no well-defined peaks in ϵ, and although there is no two-fold symmetry in the arm-interarm efficiency ratios between the two arms, we see in Fig. 3 that, as in the case of M51, the behaviour of the two arms is almost identical, and we will not discuss them separately here.

As shown by Knapen (1992), in the case of NGC 4321 it is not clear purely from the morphology of the separate Hα and HI profiles along the arms that these two tracers are related, as was the case in M51, where, as discussed above, HI peaks follow Hα peaks. But still, Fig. 3 shows that for the points in the inner part of the disk there is a similar relation between the Hα flux and the HI density, although the scatter is larger than in the case of M51. The outer points are clearly separated in the Figure from the inner points, occupying preferentially the lower and lower right parts of the diagram, again as in the case of M51. There is a clear difference however between the two galaxies, in that whereas in M51 the outer points occupy a wide range in HI density but all have low Hα fluxes, in NGC 4321 only the outer points at low HI density have consequently low

Hα fluxes. Points with higher HI densities again show a rising relation between HI and Hα, and although the scatter makes it hard to estimate a slope of this relation, it looks similar to the slope of the inner points.

This means that although the inner and outer points are separated for NGC 4321, the description given above for M51 cannot be entirely valid here. There is a relation between Hα and HI in the outer parts, but there seems to be a higher "threshold" value in atomic hydrogen. This could be interpreted in terms of two components in the atomic hydrogen: a component that is formed from molecular hydrogen due to photodissociation, and a component that is independent of massive star formation. As discussed before for M51, the relative importance of the first component may well drop when moving out into the disk of the galaxy, where the massive star-formation rate goes down. Thus the "threshold" seen in the Hα−HI relation for the outer disk may show a photodissociation component (the rising slope for $\sigma_{\rm HI} > 8 \times 10^{20}$ N(HI)) superposed on a star-formation-independent component that is more than twice as large as for the points in the inner disk. This would naturally explain the horizontal offset of the two groups of points in the diagram.

In this simple picture, many questions remain unanswered, that we will try to answer in future work. Using a full two dimensional analysis instead of the simple relationships shown in this paper, we may be able to make a more detailed model of the physical processes controlling the role of the atomic gas in the disks of galaxies. From the limited study now presented, it seems clear that in this respect there are important differences between the two galaxies studied here. The fact that NGC 4321 is weakly barred, the strength of the arms of M51, and the fact that this galaxy is interacting with its companion, may be the underlying causes of the observed differences.

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