Gas flow in barred galaxies

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Abstract. I briefly review the properties of the gas flow in and around the region of the bar in a disc galaxy and discuss the corresponding inflow and the loci of star formation. I then review the flow of gas in barred galaxies which have an additional secondary bar. Finally I discuss the signatures of bars in edge-on galaxies.

1. Introduction

Bars are elongated structures frequently present in the central parts of disc galaxies. Their formation is ubiquitous in N-body simulations, unless a sufficiently massive and sufficiently centrally concentrated spherical or spheroidal component has been added to stop or at least to delay their formation beyond a reasonable life-time of the disc. The problems relating to bar formation are far from being solved, but in this review I will leave them aside in order to concentrate on the properties of the gas flow in and around the bar region. Such a flow is intimately linked to the main periodic orbits and their structure (e.g. Athanassoula 1992a; Athanassoula 1992b, hereafter A92b). Orbital calculations (for a review see e.g. Sellwood & Wilkinson 1993) have shown that the backbones of bars are the so-called $x_1$ periodic orbits, which are elongated along the bar. If one or two inner Lindblad resonances (hereafter ILRs) are present, there are also two perpendicular families, called $x_2$ and $x_3$. Further out we find the 4:1 periodic orbits, which have rectangular-like or diamond-like shapes. These families, as well as other secondary ones, trap around them a number of regular orbits. Chaotic orbits are also present and their importance depends on the properties of the bar potential.

2. Gas flow in and around the bar

An example of the gas response to a barred galaxy potential, calculated with the FS2 code (van Albada, van Leer & Roberts 1982; van Albada, 1985), is given in Fig. 1. The left panel gives the density response in grey-scale; lighter shades correspond to higher densities and darker to lower ones. The imposed bar is at 45° to the horizontal axis, rotates clock-wise and has a semi-major axis of 5 kpc and a semi-minor one of roughly 2.3 kpc. We note that in most of the bar region the gas has very low density, while most of the gas is concentrated in two narrow strips along the leading edges of the bar. In their inner parts these density enhancements curve into a nuclear spiral or ring-like structure. There is
also considerable gas concentrated around the extremities of the bar major axis. The right panel shows the gas flow in the same model and in a frame of reference corotating with the bar. The length of the vectors is proportional to the velocity at that location and I have also superposed a number of flow lines. Comparison of the two panels, as well as cuts perpendicular to the density maxima (cf. A92b), show that the density maxima are the loci of shocks. Prendergast (1962, unpublished) was the first to associate them with the dust lanes observed along the leading edges of bars. A comprehensive study of the shape of the shock loci and of their dependence on the main parameters of the model can be found in A92b. The shock loci in strong bars were shown to be straight, while weak bars or ovals have loci which are curved with their concave part towards the bar major axis. One of the main results of A92b is that, in order for the shock loci to have the shape of the observed dust lanes, the corotation radius, $R_{CR}$, must be equal to $R_{CR} = (1.2 \pm 0.2)a$, where $a$ is the length of the bar semi-major axis.

A further result of A92b is that, in order for shocks to exist, the curvature of the $x_1$ orbits at apocenter must exceed a certain quantity, or in other words, the orbits that are elongated along the bar should be sufficiently peaked or have loops at their apocenters. Furthermore, in order for the shock loci to be offset towards the leading side of the bar, the $x_2$ orbits must not only exist, but also have a sufficient extent.

2.1. Inflow

In cases with no shocks the flow lines have simple concentric ellipse-like shapes, and there is no net inflow. However, in cases with shocks the gas flow is con-
considerably more complicated, as can be seen in the right panel of Fig. 1. At the trailing sides of the bar, where the gas density is very low, the flow is outwards, and stays so until it reaches the shock. At that point it turns abruptly inwards. Both the outwards and the inwards flow reach high values of the velocity, of the order of, or higher than, 100 km/sec. The outwards flow is over an area which is large, but has a very low gas density, while the inwards flow is concentrated around the density maxima, i.e. in a small area with very high gas density. Thus the net inflow, i.e. the density averaged radial velocity, is of the order of less than a km/sec, up to a few km/sec, depending on the model. Care has to be taken when comparing with observations since the low density regions are harder to observe and thus there is a tendency for observations to overestimate the inflow.

A maximum net inflow is found in models with thin, massive, slowly rotating bars, with centrally concentrated axisymmetric components (A92b; Piner, Stone & Teuben 1995, etc). Since these models have also the strongest shocks (A92b), we come to the conclusion that the most important inflow is in models with strongest shocks, as expected.

2.2. Can the inflowing gas reach the nucleus?

In cases with ILRs the gas is brought from regions roughly within a radius equal to the bar semi-major axis to the circumnuclear ring or pseudo-ring and little to the disc within it. On the other hand in cases with no ILR the inflow reaches the center-most area, i.e. very near the nucleus. There are indications, however, that most barred galaxies have one or two ILRs (Athanassoula 1994), so that in general the bar will not push the gas sufficiently inwards to reach the nucleus and eventually feed an AGN.

Nevertheless even in cases with ILRs gas can be pushed to the center-most radii. One possibility, which will be discussed in section 3, is that there is a second bar within the main one. Other mechanisms for breaking the ILR barrier rely on the self-gravity of the gas accumulating in the central area. Such mechanisms have been described e.g. by Fukunaga & Tosa (1991), Wada & Habe (1992, 1995), Elmegreen (1994) and Heller & Shlosman (1994).

2.3. Star formation

The shock loci are regions of high density maxima, and one could have naively thought that this might entail a considerable amount of star formation. This, however, is not the case, due to the fact that straight shock loci are also the loci of high shear (A92b). Thus a typical molecular cloud will shear out before it has time to collapse, so that no star formation will occur. This is not necessarily true for shocks whose loci are curved. The two different types can be seen when comparing e.g. the dust lanes in the bar of NGC 1300 with the corresponding ones in NGC 1566. With a similar goal, Regan, Vogel & Teuben (1997) stressed the large divergence in gas streamlines before they reach the shock, and argued that this could tear apart molecular clouds and thus inhibit star formation. It would be interesting to test whether this mechanism works for straight dust lanes as opposed to curved ones, as observations seem to suggest.

The ends of the bar are regions of high density, but not much shear. Thus one expects to find star formation there and this is indeed borne out by obser-
Figure 2. Response of the gas in the inner $2 \text{kpc} \times 2 \text{kpc}$ area of the bar, at four different times during the simulation described in section 3. As in Fig. 1, lighter areas correspond to high density regions and dark ones to low density ones.

A large number of observations have shown the existence of inner bars in different components, as the CO, the visual, or the NIR. Their formation could be due either to the existence of a bar unstable stellar inner disc (i.e. an instability similar to that forming the main bar), or to the fact that sufficient gas has been pushed inwards to form a bar unstable gaseous disc (Shlosman, Frank & Begel-

3. Bars within bars

A large number of observations have shown the existence of inner bars in different components, as the CO, the visual, or the NIR. Their formation could be due either to the existence of a bar unstable stellar inner disc (i.e. an instability similar to that forming the main bar), or to the fact that sufficient gas has been pushed inwards to form a bar unstable gaseous disc (Shlosman, Frank & Begel-
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man 1989). The main bar and the inner bar do not necessarily turn with the same pattern speed, but this does not mean that they are dynamically independent. Indeed the two pattern speeds can be different but coupled. Analytical work has predicted that the location of the ILR of the main bar should coincide roughly with that of the corotation of the inner bar (Tagger et al. 1987, Sygnet et al. 1988), and this has been nicely borne out by the simulations of Friedli & Martinet (1993). As already mentioned in section 2.2 such inner bars can help push the gas to the innermost regions of the galaxy. The mere existence of an inner bar may nevertheless not be sufficient for this task.

The response of the gas in cases with two imposed bars will of course vary with the angle between the major axes of the two bars. Thus when the two bars have different pattern speeds the response is a function of time. This is illustrated in Fig. 2, where I display the nuclear parts of the gas response at four different times during a simulation. The outer (or main) bar is always at 45° to the horizontal axis and has a semi-major axis of 5 kpc. The axisymmetric component has been chosen such that the rotation curve rises very steeply in the inner parts. The gas response in the model with only the outer bar has strong shocks along the leading sides of the bar that, towards their innermost parts, wind up in the form of a nuclear spiral, as is the case for the model shown in Fig. 1. It is this nuclear region that gets most affected by the inner bar, as expected. In the example shown in Fig. 2 the inner (or secondary) bar rotates roughly 3.5 times faster than the main bar, so that the corotation of the inner bar is situated roughly at the ILR of the main one. The gas response in the innermost parts is now bar shaped, but a given end of this gaseous bar does not always link to the same density enhancement of the outer bar. The gas response adjusts itself so that a given side of the inner gaseous bar links to the nearest density enhancement within the main bar, and in some cases one sees a nuclear pseudo-ring surrounding the inner gaseous bar. The work described briefly here is part of an extensive study of the response of gas in galaxies with both a primary and a secondary bar, which I have been doing in collaboration with G. D. van Albada. A more comprehensive description of this work will be published elsewhere.

4. Bars in edge-on galaxies

N-body simulations show clearly that stellar bars do not stay flat thin structures, but extend vertically, taking the form of a peanut if seen along the bar minor axis, and a box-like shape if seen edge-on and at an angle to it (Combes & Sanders 1981, Combes et al. 1990, Raha et al. 1991 etc). Such peanut-like or box-like protuberances are observed in many disc galaxies and are called peanut or boxy bulges. It is not easy to prove that they are indeed bars seen edge-on by using photometry alone. Thus efforts have been concentrated on kinematics. Kuijken & Merrifield (1995) and Bureau & Freeman (1999) have compared the position velocity diagrams (PVDs) of galaxies with peanut or box-like bulges, to the PVDs of galaxies with standard bulges and find importance differences, which, they argue, could well be due to the signatures of the \( x_1 \) and \( x_2 \) families of orbits in the peanuts. Bureau & Athanassoula (1999) made a detailed study of the effect of the existence and properties of the families of periodic orbits on the
structure of the PVDs. Athanassoula & Bureau (1999) have tackled the same problem using hydrodynamical simulations, and they find that the existence of a gap in a PVD, between the signature of the nuclear spiral and that of the outer disc, reliably indicates the presence of a bar. This gap is due to the fact that most of the main bar region is relatively empty, and this in turn is due to the gas flow described in section 2. All arguments seem to converge to the fact that peanut and boxy bulges are misnamed, and are in fact bars seen edge-on.

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