THEORETICAL STUDIES OF GAS FLOW IN BARRED SPIRALS GALAXIES

Kevin H. Prendergast
Department of Astronomy and Astrophysics
Columbia University, New York

We know far more about the velocity and density distributions of gas in ordinary spirals than in barred spirals. There are several reasons for this : the absence of a nearby barred spiral, the circumstance that several of the best objects lie rather far south, the necessity to map in two dimensions, and the surprisingly low intensity of the emission lines, except in the nucleus and near the ends of the bar. The older literature contains several investigations of radial velocities measured along the bars of barred spirals (cf. Burbidge, Burbidge and Prendergast, 1960 a,b for NGC 7479 and NGC 3504), and it has been known for some time that rotation curves taken in different position angles through the nuclei of barred spirals are not compatible with simple circular motion. It was not until recently, however, that attempts were made to map the velocity fields of barred spirals in two dimensions. Chevalier and Furenlid (1978) studied NGC 7723, NGC 5383 has been mapped by Peterson, Rubin, Ford and Thonnard (1978) in the optical and by Sancisi, Allen and Sullivan (1979) in neutral hydrogen, and NGC 1300 has been mapped by Peterson and Huntley (1980). The most striking result of these observations is that the isovelocity contours are elongated in the direction of the bars, or, put differently, there is no straight line through the center of a barred spiral along which the radial velocity is constant. This is clear proof that significant non-circular motions are present in these galaxies. However, as it is impossible to reconstruct a non-axisymmetric velocity field from radial velocity data alone, there is no analog for barred spirals of the reduction models which are used to estimate local mass densities for ordinary spirals from observed rotation curves.

Theoretical studies have concentrated on the problem posed by non-circular motions, and on certain morphological features of barred spirals, particularly the smooth, rather straight dust lanes often found near the leading edges of bars. The underlying mass distribution is assumed to be independent of time when viewed in a coordinate system rotating at constant angular velocity. The gravitational field is usually taken to be invariant under reflection in each of three mutually perpendicular planes, although some workers have adopted a two-armed spiral potential

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 215–220.

in the outer parts of the system. In any case, several parameters are required to specify the gravitational field, such as the degree of central concentration of the galaxy, and the strength, length, axis ratio and angular velocity of the bar. The gas is presumed to lie in the equatorial plane, and to move under the influence of gravitational, centrifugal, Coriolis and pressure forces. The theoretical problem is to find a flow pattern for the gas which is steady in the rotating coordinate system.

Before proceeding to discuss detailed computational results, it may be useful to consider certain qualitative aspects of the flow. The centrifugal and gravitational forces can be derived from an effective potential. If we imagine this potential plotted (in three dimensions) as a function of position in the equatorial plane, we would have, for an axisymmetric galaxy, a surface resembling a volcano with a level rim at the corotation radius, and all contour lines (equipotentials) would be circles. Adding a strong bar deforms the circular equipotentials into ellipses oriented along the bar inside corotation (i.e. inside the crater) and perpendicular to the bar outside. When there is a bar the rim of the volcano can no longer be level, but will have two passes (X-type equilibrium points) along the major axis of the bar, and two peaks (O-type equilibrium points) at right angles to the bar. If we ignore for a moment the pressure and inertia of the gas, the flow must be such that the Coriolis force balances the forces derived from the potential, which implies that the streamlines and equipotentials must coincide. The direction of flow must be in the same sense as the rotation of the bar inside corotation, and in the opposite sense outside. The flow speed required to give the correct Coriolis force depends on the local values of the gravitational and centrifugal forces : where these are strong the velocity is high. Near the X and O points, however, the applied forces are weak, and the inertia of the gas cannot be neglected. In particular, a stream of gas moving at high speed will overshoot the sharp bends where the equipotentials cross the major axis of the bar ; the streamlines will be skewed with respect to the equipotentials, such that the major axes of the streamlines lead the major axis of the bar. In view of the formal analogy between compressible gas dynamics and shallow-water theory, we can return to the picture of the effective potential surface as a volcano with an elliptical crater, and imagine a thin layer of water swirling at high speed within the crater. If the water does not wash over the lip of the crater (as it may near the low parts of the rim) it sloshes up against the walls ; it is not hard to imagine that a hydraulic jump forms when the flow stalls and falls back on itself. The analog of this jump in gas dynamics is a shock, and it will evidently be found near the leading edge of the bar.

The picture sketched above is probably appropriate only for galaxies with strong, rapidly rotating bars. If the bar is weak or slowly rotating the topology of the equipotentials is the same, but the features are less pronounced. In this case the gas may be expected to respond to other dynamically significant singularities of the problem, such as the inner and outer Lindblad resonances.

https://doi.org/10.1017/S0074180900032885 Published online by Cambridge University Press

The dynamics of gas flow in a barred spiral is clearly a difficult problem, and one which can be approached on several levels. The simplest theories start from the assumption that the pressure is almost everywhere negligible, which is plausible, since the random velocities in the gas are an order of magnitude lower than the streaming velocities. If there were no pressure at all the streamlines of the flow would be identical to the orbits of non-interacting particles moving in the prevailing force field. The converse is not true : that is, one cannot take an arbitrary set of initial conditions for a collection of particles, solve for their motions and identify the resulting ensemble of trajectories with the streamlines, because the trajectories will cross one another. However, there are special sets of initial conditions which give stable periodic (loop) orbits, and there may be a family of such orbits which can be nested within one another without intersections. A trivial example is the family of circular orbits in an axisymmetric galaxy. If the bar contributes only a weak tangential component to the force field a slightly distorted version of this family may exist which can serve as an approximation to the streamlines. Unfortunately, the direction of elongation of the loop orbits changes by 90° at each Lindblad resonance, as well as at corotation, and the orbits intersect one another in these regions. If there were coupling between particles moving on adjacent orbits one might hope that crossings could be avoided. Hydrodynamic computations by Sanders and Huntley (1976), Sanders (1977), Berman, Pollard and Hockney (1979) and by Sorensen and Matsuda (1982) show that this hope can be realized. The loci of closest approach of orbits forms an open two-armed trailing spiral pattern extending as far as the outer Lindblad resonance. Some of the computations show large density gradients, indicating that shocks form where the streamlines are most closely crowded together.

The stronger the bar, the less likely it is that there exists an extensive family of nested stable loop orbits, and consequently the pressure must be considered from the outset. The next simplest thing to neglecting the pressure alltogether is to include only one component of the pressure gradient : the component perpendicular to the shock, say. This is the device adopted by Roberts, Huntley and van Albada (1979). These authors derive ordinary differential equations for an equivalent one-dimensional problem which can be solved with relative ease. They find that two kinds of streamlines are possible, both of which are usually crossed by shocks. For streamlines of the first kind the shock occurs after the streamline has reached its maximum distance from the nucleus, and post-shock flow is inwards. For streamlines of the second kind, the shock intervenes while the gas is still moving outwards ; the post-shock flow is directed towards the end of the bar, but eventually returns nearly parallel to itself after a sharp hairpin ben. Thus, the post-shock region is also one of high shear. In both cases a nested family of streamlines would show standing shock waves along the leading edges of the bar. Streamlines of the first kind are frequently found in two-dimensional simulations of gas flow in barred spirals. Flows with streamlines of the second kind are extremely difficult to model, partly because of resolution problems due to finite grid spacing, and partly because most codes are afflicted with a viscosity of purely numerical origin, which can be devastating in regions of high shear. Van Albada and Roberts (1981) have reported the results of a two-dimensional calculation on a fine grid which shows a mild version of post-shock outflow. The real extent of the phenomenon is difficult to estimate, because the one-dimensional calculation which exhibits the effect most clearly is only an approximation to the two-dimensional problem that one would really like to solve.

The full hydrodynamic problem in two dimensions has been tackled by many authors, using various mass models and employing a variety of numerical techniques. It is impossible to give an adequate summary in this review of the numerous results obtained. One of the earliest investigations of this character is that of Sorensen, Matsuda and Fujimoto (1976), who used a fluid-in-cell code. This method was also used by Berman, Pollard and Hockney (1979) to investigate the influence of self-gravitation of the gas in a spiral driven by a weak oval distortion. The beam scheme (Sanders and Prendergast 1974) has been extensively used for modelling flows in barred spirals (cf. Sanders and Huntley 1976, Huntley 1980, Sanders and Tubbs 1980, Schempp 1982). The scheme is simple and rugged, but the ruggedness is achieved at the price of large effective transport coefficients : the code has roughly the same thermal conductivity, bulk and shear viscosity a real gas would have if the mean free path were equal to the grid spacing. Increasing the diffusivity of a numerical code blurs the shock transitions, increases the apparent rate of gas flow into the nucleus, decreases the sharpness of the bend between the spiral arms and the bar, increases the angle by which the gas response leads the bar, and increases the offset of the shocks within the bar. (Some of these effects can also be produced by changing the mass distribution of the galaxy or the rotation period of the bar). The influence of grid spacing has been studied by van Albada and Roberts (1981), who also compared the beam scheme and Godonov methods for the same problem and grid. The two results, shown in their figures 5 an 13, are not identical, but the agreement is rather more encouraging than otherwise. MacCormack's method has been used by Sorensen and Matsuda (1981), a flux-corrected-transport method was used by Jones, Nelson and Tosa (according to Matsuda 1981) and van Albada has experimented with flux-splitting schemes. Several of the above methods, plus others, have been intercompared by van Albada, van Leer and Roberts (1982) for a one-dimensional model of flow in a spiral gravitational field. Sanders (1977) has used a code due to Lucy which solves the hydrodynamic equations by following the motion of particles having finite radii and endowed with internal structure. N-body particle codes, supplemented with a set of rules to govern the outcome of inelastic collisions between particles, have been used by Matsuda and Isaka (1980) and by Schwarz (1981).

The main conclusions suggested by these studies are :

1) A rigidly rotating bar or oval distortion is sufficient to drive spiral structure in the gas, with or without self-gravitation ; the appearance of spirals is always accompanied by large departures from circular motion. Weak bars give open spiral patterns which extend throughout the gas ; stronger bars give spirals which emerge at sharp angles to the bar.

https://doi.org/10.1017/S0074180900032885 Published online by Cambridge University Press

2) The gas response leads the bar, by an angle which is greater the weaker the bar.

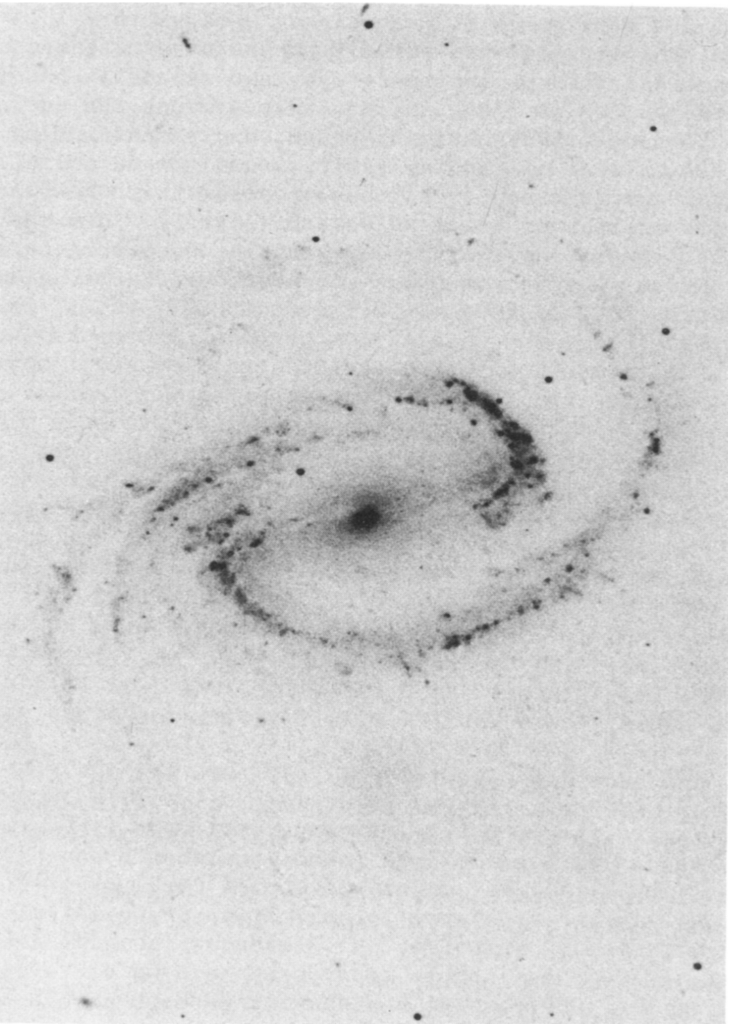
3) Strong bars favor the appearance of strong shocks within the bar. When they occur, they lie near the leading edge, which is just where they should be if the identification of shocks and dust lanes is correct.

The conclusions above are relatively insensitive to the choice of code or grid spacing. Perhaps the most important aspect of the flow that is sensitive is the rate of infall of gas towards the nucleus. Simkin, Su and Schwarz (1980) have suggested that radial inflow induced by a rotating bar or oval distortion can feed gas to the nuclei of Seyfert galaxies, and Kormendy (1982) has proposed that the flat bulges of barred spirals are formed from gas that has drifted into the central regions over the lifetime of the bar. It would be premature to estimate rates of infall from present numerical computations, but it remains a challenging problem for the future.

REFERENCES

Burbidge, E.M., Burbidge, G.R. and Prendergast, K.H. 1960, Ap. J. 132, 654, 661.
Berman, R.H., Pollard, D.J. and Hockney, R.W. 1979, Astron. Astrophys. 78, 133.
Chevalier, R.A. and Furenlid, I. 1978, Ap. J. 225, 67.
Huntley, J.M. 1980, Ap. J. 238, 524.
Kormendy, J. 1982, Ap. J. 257, 75.
Matsuda, T. and Isaka, H. 1980, Prog. Theor. Phys. 64, 1265.
Matsuda, T. 1981, Prog. Theor. Phys. Supp. 70, 249.
Peterson, C.J., Rubin, V.C., Ford, W.K.Jr., and Thonnard, N. 1978, Ap. J. 219, 31.
Peterson, C.J. and Huntley, J.M. 1980, Ap. J. 242, 913.
Roberts, W.W.Jr., Huntley, J.M. and van Albada, G.D. 1979, Ap. J. 233, 67
Sancisi, R., Allen, R.J. and Sullivan, W.T. 1979, Astron. Astrophys. 78, 217.
Sanders, R.H. and Prendergast, K.H. 1974, Ap. J. 188, 489.
Sanders, R.H. and Huntley, J.M. 1976, Ap. J. 209, 53.
Sanders, R.H. 1977, Ap. J. 217, 916.
Sanders, R.H. and Tubbs, A.D. 1980, Ap. J. 235, 803.
Schempp, W.V. 1982, Ap. J. 258, 96.
Schwarz, M.P. 1981, Ap. 247, 77.
Simkin, S.M., Su, H.J. and Schwarz, M.P. 1980, Ap. J. 237, 404.
Sorensen, S.A., Matsuda, T. and Fujimoto, M. 1976, Astrophys. and Space Sci. 43, 491.
Sorensen, S.A. and Matsuda, T. 1982, Mon. Not. R. Astr. Soc. 198, 865.
van Albada, G.D. and Roberts, W.W.Jr. 1981, Ap. J. 246, 740.
van Albada, G.D., van Leer, B. and Roberts, W.W.Jr. 1982, Astron. Astrophys. 108, 76.

https://doi.org/10.1017/S0074180900032885 Published online by Cambridge University Press



NGC 1300 (CTIO 4m, 103aO+UG2, taken by A. Bosma)

https://doi.org/10.1017/S0074180900032885 Published online by Cambridge University Press