ON THE FORMATION OF LARGE-SCALE SHOCK WAVES IN BARRED GALAXIES

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Abstract. The behavior of the gaseous phase in a barred galaxy is followed by computer simulations of the gas flow in a fixed potential formed by a bar and a disk. The results support a hypothesis that the dark lanes observed on the leading side of the bar in many SB galaxies are coinciding with the shock waves. Furthermore the results reject an outflow explanation of the arms but suggest these to be formed mechanically by the bar. Ring-shaped features were not reproduced but double arms were occasionally detected.

1. Introduction

Considerable progress has been made in the field of galactic dynamics during recent years, where especially the formation and persistence of spiral structure have been the objects of extended research. Most of this work has been concentrated on the structure of normal spirals while less attention has been given to their more complicated barred counterparts. Yet the rapid progress in the field of numerical simulation techniques has brought forward a tool which is most useful for such investigations.

The fact that there exist three stable homogeneous ellipsoidal figures of equilibrium and likewise three major morphological classes of galaxies (E, SA, SB) had a great impact on earlier models of barred systems where the bar was identified as a Jacobi ellipsoid. A probable data sample \( (\omega = 1.4 \times 10^{-15} \text{ rad s}^{-1}; \ q_{\text{bar}} = 4.2 \times 10^{-23} \text{ g cm}^{-3}) \) determines the ratio \( \omega^2/\pi GQ \) to 0.23, a value far below the limit 0.37 set for stable Jacobi ellipsoids (Chandrasekhar, 1969). As the galactic bar does not consist of homogeneous liquid but of stars, the barred galaxies have been considered to be unstable and the spiral arms were identified with matter ejected through the neutral windows at each end of the bar (Ogrodnikov, 1965; Danby, 1965; Freeman, 1966). Such a process will be self-amplifying and lead to rapid destruction of the system. However, approximately 50\% of the spirals with \( m_{pg} < 12.7 \) belong to the barred category (de Vaucouleurs, 1963a). It is therefore unlikely that barred spirals should be significantly more unstable than the SA-type.

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Using a simple model consisting of a sphere and two cylinders Aarseth (1960; 1961) constructed a bar which was stable over a time scale of $3 \times 10^9$ yr. On the basis of this model and furthermore assuming the gas to be ejected from the galactic center, Fujimoto (1963) computed the motion of test particles in the galactic field. This motion was found to be generally directed outwards along the major axis of the bar at the ends of which the gas escaped through the neutral points. After it had escaped the gas flowed approximately along the equipotential surfaces to form material arms. This outward motion was, of course, made possible by a gravitational torque due to the bar, and this in turn shrank the bar steadily. Combining the bar dynamics with an active nucleus ejecting matter, Fujimoto (1963) explained the Hubble sequence SB$_c$−SB$_b$−SB$_a$ as an evolutionary path of the SB galaxies. Freeman (1965) conducted a similar study of the outwards streaming of gas in the bar. Simultaneously, observational evidence for such gas streaming was claimed to be detected in the Magellanic-type barred galaxy, NGC 4631 (see, for example, de Vaucouleurs and de Vaucouleurs, 1963; de Vaucouleurs, 1964).

Yet there exist several items of evidence which make such an outflow explanation rather improbable. First of all, the observed rate of outflow $1 M_\odot$/yr (de Vaucouleurs and de Vaucouleurs, 1963) is insufficient to maintain the luminous arms which extend over the bar length in many cases (Mizuno and Fujimoto, 1969). Furthermore, there exist stars in the outer parts of the arms which are too young to have migrated from the bar and, consequently, must have been formed in the arms. Doubt is also cast upon the outflow explanation by the hypothesis that the dark lanes observed in the bar of several galaxies (e.g., NGC 1300, NGC 1365) are associated with shock waves (Prendergast, 1963). The positions of these lanes in the bar and their relative positions with respect to H II regions in the galaxy are very difficult to understand from an outflow model. In the present paper, the authors have used simulation techniques to follow the motion of gas in a stationary bisymmetric potential and are led to propose a model where the visual image of the galaxy is inside the neutral points. The spirals are formed here not as material arms but as a result of mechanically-induced shock waves.

2. Basic Equations and Galactic Shock Waves

2.1. Basic equations for the gas

Let us consider a model galaxy in which a test gas is moving in a background potential. On account of the fast cooling rate in a galactic system ($\approx 10^6$ yr) compared to the time of revolution ($\approx 10^8$ yr) the gas can be treated in the isothermal approximation. The following treatment will be concerned only with the dynamics of the interstellar gas while the stellar phase will be regarded only as contributing to a smooth stationary background potential. Considering the low total mass of the gas, the self-gravitation in this phase will be neglected. Likewise the effects of thickness will be disregarded and the treatment restricted to a thin disk of uniform depth. The gas is, furthermore, considered to possess no significant magnetic field.