The Structure of Barred Galaxies

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Within the cosmological scale (10^{26} m) the Universe is fragmented into a hierarchy of structures, from clusters of clusters of galaxies (10^{24} m), through clusters of galaxies (10^{23} m), to galaxies (10^{21} m). The larger the structures, the bigger their disparity and the less compact and contrasted they are. On the cosmological scale, the Universe tends to be fairly uniform, while the smallest of its structures, the galaxies, form a relatively homogeneous group of dense objects sharing common properties. They can be classified into three main morphological types: the disk, the elliptical, and the irregular galaxies.

Disk galaxies are the most numerous, irregular galaxies the least frequent. Basically, disk galaxies owe their axisymmetric shape to a fast rotation, and their flattened aspect to energy dissipation. The substantial kinetic energy of rotation reflects the fact that energy is more easily dissipated than angular momentum. Disk galaxies are thought to have remained relatively undisturbed since the early epoch of their formation. In contrast, more and more elliptical galaxies, it is now recognized, have resulted from one or several violent events, like collisions with other galaxies, the end-result of the mixing being an approximately ellipsoidal and slowly rotating ensemble of stars. Their study teaches us about fortuitous and disparate events, but nothing about the state of primordial galaxies; their far past is forever hidden behind the complexity and chaos due to more recent merging processes. On the other hand, since the history of disk galaxies has been quieter, the understanding of their structure and evolution bears more promise of unveiling facts about their primordial origin. To begin with, however, one needs to understand the specific role of the two main galaxy components, the stars and the gas, in the evolution of an ideally quiescent, unperturbed disk.

Disk galaxies may be classified into subgroups, recognising that galaxies with a smaller fraction of gas have also a larger central spheroidal concentration of stars, called the bulge whose precise origin is still controversial. Independently of this classification, an important fraction of disk galaxies present a distinct major feature which seemed bizarre for a long time, namely a fairly rectilinear structure called a bar, breaking the rotational symmetry of the disks in their central region. A bar is in reality an elongated distribution of luminous matter, consisting mostly of stars, extending typically over 6–10 kpc (2–3 $\times 10^{20}$ m) inside the plane of the galactic disk. Bars are not isolated, but are always embedded in the middle of a disk. Bars rotate in the disk plane at a high speed, high meaning that the centrifugal and Coriolis forces are essential forces in their dynamics, comparable in strength to the gravitational force. In many cases, a bar is the primary engine which, by an important gravitational perturbation of the disk, generates nice spiral arms starting at its ends (Fig. 1). The spiral arms are now recognized to be short lived density waves (a few 10^8 a) with respect to the galaxy life-time (about 10^{10} a).

The importance of bars lies not only in their non-negligible dynamical effects on disks, but also in their frequent appearance. In at least 2/3 of the disk galaxies known, a bar or an oval deformation is detected, and there must be others in the disks, whose projection angle is too edge-on for them to be detected, or, whose light as recent observations in the infrared have shown is completely blocked by remaining dust and gas. Disks have a high probability of being affected by a bar at least once in their history.

Why does nature so often prefer an apparently less symmetric state; why are bars so stable and much more robust than axisymmetric disks; and do bars reflect an unknown symmetry? Such questions have probably a broader scope than astrophysics. Complete answers are still lacking, but we shall try in the following to summarise the knowledge gained about bars in recent years.

The Self-consistency Problem

The dynamically significant energetic content of galaxies is mainly gravitational energy and the kinetic energy of the constituent stars. Other forms of energy (cosmic rays, radiations, magnetic fields, gas temperature, etc.) are more or less in equipartition and are

Fig. 1 — A galaxy forming a bar [1]. The bar is the central straight part connecting the spiral arms. The bar is recent because the spiral arms wind up in a few 10^8 a. The dark lanes consist of dust resulting from shocks in the gas.

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smaller by an order of magnitude at least. As a first approximation, therefore, galaxies are idealized as a population of stars (*i.e.* point masses), a pure Newtonian N -body problem, N being of the order of 10^{11} . The number of degrees of freedom ($6N-10$) is much too large for undertaking any direct calculation, and its precise value is certainly not relevant. A further approximation is needed.

The size and density of stars in galaxies is such that, contrary to an ordinary gas, physical collisions, or even 2-body gravitational encounters are totally negligible over the time-scale of interest, a few rotational periods. (This low density of stars is also required for the quiet development of life in the solar system!) Stars have a mean free path much longer than the galaxy radius; they interact principally with the global average gravitational field. This collisionless motion allows a drastic simplification of the N -body problem: the galactic gravitational potential can be approximated by the one produced by a corresponding continuous distribution of matter. The problem is then reduced to determining what kinds of orbit prevail in the gravitational field generated by a smooth mass distribution resembling a chosen galaxy. This problem belongs to classical Hamiltonian me-

chanics, with typically 2 or 3 degrees of freedom only. The generic phase space structure of Hamiltonian systems is known, since in particular the works of Kolmogorov, Arnold and Moser in the sixties, to contain periodic and quasi-periodic orbits, as well as chaotic orbits (Fig. 2). Stable periodic orbits are exceptional, and are always surrounded by topologically similar quasi-periodic orbits; they "summarise" the phase-space structure, as pointed out by Poincaré. Insensitive to perturbations, they contrast with quasi-periodic orbits, which are linearly amplified in time, and chaotic orbits where amplification is exponential. In bars, all these orbit types occur, as shown in Fig. 2. Bars offer a rare example of a long-lived stellar system where chaotic motion coexists with ordered motion.

The *shape* of the orbits in space is crucial. A given galaxy shape is only possible if, among all the possible star orbits, at least some have a shape resembling the global galaxy shape itself. A more precise requirement is that the *superposition* of some subset of the possible orbits indeed reproduces the chosen shape. This is a classical problem in astronomy, known as "the fundamental problem of stellar dynamics", or the self-consistency problem. It is often formulated by integro-diffe-

rential equations, and solved numerically by linear programming techniques. Except for simple cases (*e.g.* flat disks made by purely circular orbits), solutions to this problem are very hard to find by analytical means. For some other cases, a general examination can tell us immediately that no solution exists. For instance, an inhomogeneous "needle" rotating in a plane is not feasible because the only possible orbits giving the needle shape are radial, along the needle, yet radial orbits are excluded by the transverse Coriolis force.

Origin of Bars

Any equilibrium solution of the self-consistency problem has also to be stable. In particular, the flat disk model made by pure circular orbits in a plane has been recognized (in the sixties only) to be *unstable* with respect to infinitesimal perturbations. In a real galactic disk, some radial motion superposed on the general rotational motion is necessary, to play the stabilising role of heat in a gas. Self-gravitating systems always need some "pressure" in order to avoid the tendency to fragment into small scale clumps. This type of instability was first described by Jeans in 1902 for homogeneous infinite systems.

A little thought allows one to foresee that a conflict must occur if a disk galaxy builds up from an extended medium slowly dissipating its mechanical energy, while better conserving its angular momentum. Orbits tend then to be more and more circular and coplanar, forming a disk, up to the point that the disk becomes too cold to remain stable. What is not obvious, once a disk instability sets in, is its subsequent non-linear development.

If small scale instabilities allow a slow transport of angular momentum, while preserving axisymmetry at large scales, self-gravitating disks tend naturally to have a constant rotational velocity [2]. This type of rotation curve is indeed observed systematically, except perhaps in the inner part. As the angular speed varies then with radius, galaxies are said to rotate differentially.

Since the seventies, large scale N -body simulations ($N \approx 10^5$) have shown that unstable disks frequently form bars, even without dissipation. A typical example of simulation, involving 2×10^5 particles and run on a Cray-2, is shown in Fig. 3. Angular momentum is rapidly expelled to the disk outskirts by temporary, large scale, non-axisymmetric structures such as spiral arms, followed some tens of rotational periods after by a disk with an exponen-

Fig. 2 — Examples of the three types of possible orbits in bars, a periodic, a quasi-periodic and a chaotic orbit.

Fig. 3 — A typical N -body simulation producing temporary spiral arms and, a few turns later, a long-lived central bar.

tial mass distribution, in the middle of which a bar rotates. The length of the final bar is determined by the length over which stars initially rotate at a roughly constant angular speed. In the seventies, people were so convinced that the "normal", most stable state of a galaxy would be a nice axisymmetric disk, eventually with permanent spiral arms, that they first thought that the frequent occurrence of bars in the computer experiments was due to numerical artifacts, or that some other physical factor acting in galaxies had to be added. Now we realise that if a rotating disk is to be stable, one or a combination of three conditions must be satisfied: 1) it is heated sufficiently, which is hard to ensure for a long time in a dissipating medium; 2) everywhere there is a strong differential rotation, no central region with a constant angular speed, which implies a density singularity at the centre; 3) a large amount of dark mass exists in an exterior halo, which decreases the disk self-gravitation and slows down (but does not stop) instabilities; of course the dark mass would also have to be hot and collisionless.

Improved detectors and instruments increasingly confirm that barred central deformations in disk galaxies are indeed

in the majority. Both nature and computers tell us that bars occur naturally in disks containing too much circular motion. Disks with a central bar are therefore more "normal" than perfect axisymmetric disks.

Why Bars?

The immediate question arising from the frequent occurrence of bars is why such structures, and not others are so attractive? For the moment, the best explanation comes from looking at the star trajectories inside the bar and while some of the arguments which follow result from simple analytical estimates (see *e.g.* [3]), only numerical calculations can fully confirm them.

Imagine an axisymmetric, flat mass distribution sustained by circular orbits. If a small *static* bi-symmetric deformation is applied over it, the circular orbits are modified into orbits elongated in the direction *perpendicular* to the deformation (Fig. 4a). But if one perturbs the disk by a small bi-symmetric deformation which *rotates* at about the same speed as the orbits and in the same direction, oval orbits are produced which rotate and are elongated in the *same* direction as the perturbation (Fig. 4b). With small deformations of typical galactic disks, orbits become more

elongated than the mass distribution, while with very strong deformations (like a needle), it is the contrary (recall that radial orbits do not exist in a rotating needle). One can presume therefore that at some intermediate bar eccentricity, there can be a match (*cf* Fig. 2).

As with disks, a self-gravitating bar requires heat to be stable, that is, orbits can not all be periodic and concentric, some transverse component is necessary. Consequently, a real bar does not consist of pure oval periodic orbits, but mostly of fat oval quasi-periodic orbits, the superposition of which reproduces the bar, as confirmed by numerical calculations [4]. Computer simulations show that over a restricted range of eccentricities, bars are indeed possible, stable, and robust. More or less eccentric bars can be built by changing the amount of heat in transverse motions; hot bars are fatter than cold bars.

Bars and Galaxy Evolution

Now that bars are recognized to be a major feature of the evolution of disk galaxies, we must determine which secular effects are induced on the respective galactic components.

Fig. 4 — a) a static bar perturbation of the mass density (dashed ovals) deforms the circular orbits into oval orbits with a perpendicular direction (solid oval), b) a co-rotating bar perturbation deforms the circular orbits into oval orbits with the same orientation.

Orbit resonances and rings

The elongated orbits making up the bar are only one among several possible families of orbits, for example those at the transition between the bar and the disk, and which result from resonances, *i.e.* orbit frequencies commensurate with the bar rotation frequency. These resonances belong to the parametric resonance type. They occur in oscillators whose parameters are periodically perturbed (as successfully exploited by children on swings). Resonances, typically, also generate chaotic orbits in their neighbourhood.

The most important resonance occurs close to the end of the bar at the "corotation" radius, the radius at which, in an axisymmetric disk, round orbits would have the same period as the bar. The next resonances, named after the Swedish astronomer Lindblad, occur when stars oscillate radially exactly twice while making one revolution in the rotating frame of the bar. Higher order resonances occur too, but their importance decreases with the order. One of the observable effects of resonances is to focus gas and stars into nearby oval rings (Fig. 5).

The above concern motions staying close to the galactic plane, whereas bars are powerful enough to induce resonances also perpendicular to the galactic plane, an effect difficult to test observationally, but hardly avoidable from a theoretical viewpoint. As a consequence, a probable effect of bars is to thicken the inner parts of disks, and to heat up the disk. It is then tempting to associate bars with the formation of bulges. However, completely different processes, such as the infall of small dwarf galaxies, might also contribute to the disk thickening.

Gas

Contrary to stellar populations, in which stars can move in different directions without suffering significant collisions, gas in galaxies moves about like an ordinary fluid, though it differs from usual fluids by its extremely clumpy aspect, its turbulence, and its several simultaneous coexisting phases at different temperatures. Also the interstellar gas is able to undergo the "chemical" reaction of transforming itself into stars, and *vice-versa*, stars eject gas in the course of their evolution. For moving quietly in a gravitational field, gas needs to move on simple orbits without self-intersections. Otherwise shocks occur, increasing dissipation and star formation considerably.

The principal dynamical effect of bars on the gas is to expel an important frac-

tion of the initial gas outside the bar into spiral arms, and to condense some fraction towards the centre. The compression and shocking of gas leading to the formation of stars occur especially close to major resonances. For this reason very little gas is left over in "old" bars, unless some external refuelling takes place.

Fuelling the central engine

Even if only a small fraction of the total gas plunges toward the centre, at some distance away its mass density may be increased sufficiently for it to exceed the initial local density. Then the dynamics at the centre becomes dominated gravitationally by this mass supply. If the mass density is large enough, the centre decouples gravitationally from the rest of the galaxy. Typical scales for something new happening are in the 1–50 parsec range, a reduction of size from the characteristic galaxy scale by a factor of about 1000. Typical masses involved are in the 10^6 – 10^9 solar mass range, less than 1% of the total galaxy mass.

Since pure Newtonian gravitation alone has no intrinsic scale, all the phenomena of disk instability, bar formation and resonances could as well occur at other scales, as long as the collisionless approximation is valid. Once the central mass concentration is large enough there is a possibility that a small disk forms, develops its own bar instability, repeating all the process at smaller scales. A cascade of such bars then brings matter closer and closer to the centre. A bar inside a bar has indeed been observed in several instances.

Fig. 5 — A barred galaxy with rings [1].

The importance of this accretion of gas lies in the fuelling of a central black-hole or any other central engine capable of producing the jets emanating from active galaxies. By breaking axisymmetry, bars can evacuate angular momentum and simultaneously let the centre accrete low angular momentum matter. The physical conditions at the centre of galaxies and the role of these galactic nuclei on their environment are active domains of research.

Conclusions

The growth of a bar is one of the most significant events in the history of an isolated disk galaxy, strongly influencing star formation, angular momentum transport and the global galaxy shape. Its influence on the central engine and the related activity is crucial.

By breaking axisymmetry, disks are able to reach lower energetic states and to transport angular momentum. Since the physics of gravitation alone does not involve a characteristic scale, the understanding gained on self-gravitating galactic disks may have future applications on other disks at completely different scales, for instance massive disks around stars having dimensions in the 10^{16} m (0.3 parsec) range.

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