Barred Galaxies
ASP Conference Series, Vol. 91, 1996
R. Buta, D. A. Crocker, and B. G. Elmegreen, eds.

Theoretical Summary

R. H. Miller

University of Chicago, Astronomy Center, 5640 Ellis, Chicago 60637

Abstract. Why do so many galaxies have bars? Why are bars so rugged? These questions, vital to understanding barred galaxies, have not been addressed in this Conference.

Numerical studies seem to have replaced analytic theory. But the bars in numerical studies may not be good models of real galaxies.

1. Introduction

Rather than attempting to summarize the fairly wide range of theoretical presentations at this Colloquium, I'll raise some basic questions. While remarkable progress has been made toward understanding and interpreting barred and ringed galaxies, these more fundamental questions have not been addressed.

That will be followed by warnings urging caution in accepting numerical results at face value. They should be taken with a grain of salt.

2. Important Questions

Why do so many galaxies have bars? Why are bars preferred dynamically, given so many other possibilities? We rarely see a galaxy that looks like a fried egg, with a wildly off-center nucleus and little other apparent structure. Triangular systems are rare. Objects with holes in the middle are thought to be unstable, and thus transient, systems.

Bars are also very robust, a property that is not understood from first principles. That very ruggedness doubtless contributes to their frequent appearance. Once we understand why bars are so rugged, it is likely that we will also have a good idea why there are so many of them and why they seem preferred over other shapes.

3. Viewpoint

The logical relationships of various approaches to studying galaxies is summarized in a flow diagram I sketched on a blackboard at a meeting some 20 years ago, here shown as Figure 1.

Everything we know about galaxies comes from observation, but the line from real galaxies to observation is a very selective filter indeed. Not much gets through, almost none of what we really want to know: total mass, mass distribution, relative importance of various constituents, and so on. We only

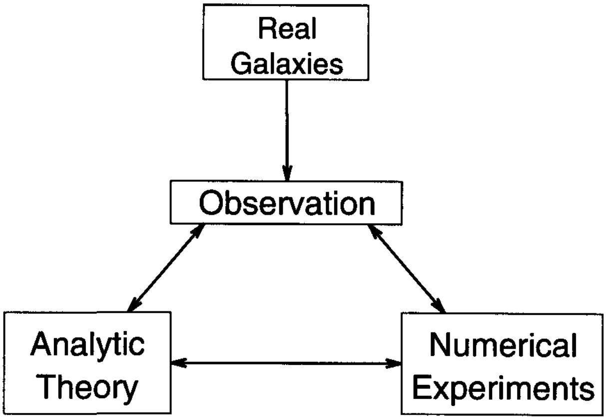

Figure 1. Logic Flow Diagram for the Study of Galaxies

collect an occasional photon, and from that we're left to infer what makes a galaxy tick.

The two boxes at the bottom are normally grouped and called "theory," but they are distinct approaches. Most of what we call "understanding" in the physical sciences is couched in the language of analytic theory, and astronomy is no exception. I'll concentrate on processes intended to clarify the physics in this summary.

In the earlier meeting, papers on numerics were rare (possibly 2 or 3 in the entire conference), while at this Colloquium I've seen only one paper I'd classify as analytic theory. The balance has shifted dramatically. The lack of analytic models for rotating barred galaxies does not help. An old model of Ken Freeman's (1966) with retrograde streaming and a strange model generated by Peter Vandervoort (which was recently studied by Contopoulos and Vandervoort 1992) essentially exhaust the list.

The arrows connecting the lower three boxes signify communication among the practitioners of these arts. In earlier times, communication was rather labored, but today it flows pretty freely among the three approaches.

4. Dark Matter

Dark matter is a giant step backwards in our attempts to understand galaxies. In the old days (before dark matter), we used to think that what we saw was the galaxy. That was the object we tried to model. Today, we don't know what it is that we're attempting to model from a dynamical point of view. It is generally accepted that a large part of the mass in a galaxy is dark, hence unobservable. That mass generates the gravitational field that keeps the galaxy from flying apart. We need to know how much mass there is and how it is distributed in space if we are to build dynamical models.

Dark matter makes the link from real galaxies to observation in Figure 1 much more tenuous. Most treatments, whether numeric or by analytic theory, are *ad hoc*. There has been little, if any, exploration to test the sensitivity of results to changes in assumed forms of dark matter halos.

5. Numerics

Numerical work on galaxies should be thought of as experiments. Matters of concern in numerical experiments are signal-to-noise, systematics, instrumental effects, equipment checks, and so on. These same issues concern any experimenter or observer. Equipment checks here consist of checking and verifying computer codes.

Given a galaxy, you'd like to go around to the other side to look at it from some different direction. You'd like to kick it to see if it bounces, shatters, or just how it would respond. You'd want to do all the things with a galaxy that you would try on any unfamiliar object. But there are practical difficulties. Numerical experiments are our only substitute. They provide the checks on analytic theory that laboratory experiments provide in physics.

The enterprise is much closer to observation than to theory. I think of myself as an experimenter, not as a theoretician.

5.1. Relation to Objects in the Sky

Is there any relation between the barred systems studied by the theoreticians and numerical types and real galaxies in the sky? This is a matter of concern both in analytic theory and in numerical experiments. It is not obvious how to verify that results of an analytic study or of a numerical experiment bear on the objects we see, principally because of the important role of the dark matter halo. It is also not clear that we always have the correct ratio of material in the bar to material in the rest of the galaxy.

Uniqueness is another concern. Are there many possible models, any one of which could equally well represent the same object in the sky? This concern is sharpened as we try to draw general conclusions on issues such as bar longevity, for example. Some models might survive better than others.

5.2. Initial Conditions

Numerical experiments are initial value calculations. They start from *something*, and that something determines the character of the entire experiment. A large part of the art of numerical experimentation lies in the design of initial conditions that will cause the experiment to mimic the physical system you have in mind. Appropriate initial conditions make the results believable, while inappropriate ones leave nagging doubts.

We used to hope, in older days, that "final states" reached in numerical studies would be more or less independent of the initial states (starting conditions), rather in the manner that stars (at least single stars) are pretty well spherical whatever the shape of the cloud from which they formed.

Counter-examples are now known, however, making it clear that final states depend, and can depend strongly, on initial states. One example is the following

(Miller 1988). Protogalaxies started from initial states that join smoothly into their surroundings rearrange themselves fairly gently and develop potentials that correspond to the flat rotation curves typical of spiral galaxies. Systems started from initial states in which matter is detached from its surroundings, by contrast, slosh around a fair bit during the collapse, and reach a mass distribution that corresponds to the de Vaucouleurs profile that characterizes elliptical galaxies. The difference has been shown, through additional experimental checks, to come from the violence of the initial collapse. A system with a flat rotation curve changes over to a de Vaucouleurs profile if shaken fairly vigorously, but it makes only a partial transition with less vigorous shaking.

Properties claimed to be generic must be reached from any of a variety of initial conditions. Issues of bar formation probably have to be addressed at the stage of protogalaxies. Bar fractions are likely to be set at that stage.

Initial states can be constructed, both in analytic theory and in numerical experiments, that could not exist in Nature. Stability studies sort these out. Stable systems might exist in Nature, while unstable systems cannot. Stability studies are not meaningful to interpret observations since the systems remember their initial states. Studies of stable systems are more profitable, since they tell us something about systems that could exist in Nature.

6. Bar Longevity

It has been suggested at this conference that bar lifetime may be limited. This would make it necessary to regenerate or replace bars, because they appear in such a large fraction of disk galaxies. Two issues arise.

6.1. Regeneration

Two mechanisms for destroying bars were suggested in the conference. Problems with bar regeneration differ between the two situations.

1. Destruction by passing objects (Athanassoula, this Conference). Debris from the destroyed bar consists of lots of stellar material with large velocity dispersion that probably takes the form of a lens. It is likely to be difficult to re-form a bar from this material because of its high velocity dispersion. A new bar could be formed in these regions if new (gaseous) material were brought in to create a new batch of stars with lower velocity dispersion. But a lot of material is needed—as much mass as was in the original bar. This does not seem terribly plausible.

2. Destruction by a point mass at the center (Sellwood, this Conference). Once the bar is destroyed, the point mass remains at the center of the galaxy. It would destroy the coherent patterns of orbits of any material that tried to organize itself into a bar. A new bar must be more massive than the original (the ratio of mass in the point to mass in the bar counts in the destruction process), and it must appear suddenly to overcome limits due to the mass ratio. It is not easy to see how to bring in enough mass, quickly enough, to regenerate the bar.

Conclusion: bar regeneration is not very likely. However, a large part of the charm of this subject is that Nature often takes routes nobody had thought of. That may be the case here as well.

6.2. Are all Bars Created Equal?

Some bars are more rugged than others. Results from studies of bar destruction by passing objects will differ if the target is fragile or robust. A different possibility for an encounter with a passing object is to nudge a fragile bar to a more robust form. For example, Sellwood's unstable thin bars are fragile, but they shift to a more robust form (the "peanut shape"). This possibility has not been addressed at this conference.

Most bars rotate. However, nonrotating bars have been seen in several kinds of experiments. An interesting aspect is that the principal axes of the three tensors that figure in the tensor virial equations need not coincide in some of these nonrotating bars. While interesting, the dynamical significance of this observation, if any, is not clear. All three virial tensors do not seem to have been explored in any detail for rotating bars.

7. Gas

Dynamic range is a problem in all numerical studies, but it is particularly severe when we try to incorporate an ISM into galaxy models. Dynamic range (in length scales) refers to the ratio of the smallest resolvable length to the system dimensions. To observers, it's the same as the number of pixels in the field of view.

The entire galaxy must be included in the calculation because of the long-range gravitational force, but important physical processes go on in the ISM at the range at which stars form, a sub-parsec range embedded within a system tens of kiloparsecs across. That is beyond the capability of present-day computers. The failure is something like the degradation in image quality we've had in movies by dropping film for video—from thousands of pixels on a frame edge for film to a couple of hundred in ordinary video.

The standard work around is to introduce some kind of sub-grid modelling. You've heard of several numerical treatments of "gas" at this conference. Basically, they differ in the treatment of sub-grid modelling. Most of them involve some heuristic picture, basically guesses. Unfortunately, those guesses are difficult to verify and, in practice, none have been adequately verified.

7.1. Gas Inflow Rates

Large amounts of gas have been reported near the centers of some barred systems at this conference. There is so much gas that its mass influences the overall dynamics (J. Turner, this Conference), and such that it's difficult to understand why there's not a lot of star formation going on in the centers of those galaxies. On the other hand theoreticians say there's a problem getting enough gas down toward the centers of galaxies to fuel AGN's and other such phenomena. There seems to be a contradiction here. Is there some way to hold lots of gas in the centers of barred galaxies without serious consequences?

Numerical models of barred systems show fairly rapid inflow of gas toward the center of the system. This result, coupled with J. Turner's observations, seem to imply that gas is transported toward the center rather too rapidly, instead of a problem of getting enough gas down there.

But a word of warning: Numerical estimates of inflow rates depend on particularly uncertain parts of CFD (computational fluid dynamics) codes.

7.2. Controlling Dissipation

Dissipation and gravitation are a dangerous mixture. Things tend to get out of control, to run away until new physics takes over. The Sun is a good example of what happens when the two are mixed. Gas in galaxies is said to act dissipatively.

The issue with dissipation is how to keep it under control. It is often suggested that angular momentum is sufficient, leading to the "problem" of getting enough gas toward the centers of galaxies. But now the observations (and numerical work with barred systems) say there's lots of gas down there. How can it be kept from forming stars in a large burst?

8. Epilogue

Notwithstanding my cautionary remarks, remarkable progress has been made toward understanding and interpreting barred galaxies. Major questions remain, however, and theoreticians and observers alike should be encouraged to ponder those questions and to ask even more fundamental questions than those that open this summary.

It is natural to concentrate on problems which we know how to tackle. That's how progress is made. But the bigger questions must be kept in mind, simmering on the back burner. Return to them from time to time, and take a stab at them. That's where discoveries will be made.

Why bars? Why are bars so rugged? Why do so many spiral galaxies contain bars?

References

Contopoulos, G. & Vandervoort, P. O. 1992, ApJ, 389, 118, (Fiche 61-E1)

Freeman, K. C. 1966, MNRAS, 134, 1

Miller, R. H. 1988, Comments on Astrophysics, 13, 1