

Matter in the universe seems to occur in the aggregates of galaxies, clusters of galaxies and clusters of clusters. It seems strange to consider very peculiar objects sitting isolated away from everything else. Where did they come from?

An example of such a curious object at lower redshift, and thus presumably closer in space to us is shown in Fig. 4. What looks on the U. K. Schmidt prints to be three small lumps in a row, turns out spectroscopically to have spectra of high-excitation emission lines on each end of the line. A photograph through an interference filter in Fig. 5 shows that in the emission line of H alpha the image

is comprised of only a double, stellar HII region on one end and a partially double HII region on the other end. The redshift of this object is around  $z = 2,600$  km/sec. Is this a very small collection of HII regions isolated in space at about 2 1/2 times the distance of the Virgo cluster? Or are there other systems at the same distance which we have not discovered yet? Or is it associated in space with other systems more nearby to our own local group of galaxies?

#### References

Arp, H. 1978, *Ap. J.*, **220**, 401.

## Why Aren't All Galaxies Barred?

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We may be accustomed to believing that most problems confronting us in astronomy involve difficult and exotic physics. In this article, I would like to draw attention to a problem, as yet unsolved, posed by some of the simplest laws of physics known, viz: Newton's law of gravity and his laws of motion. To take a familiar example, we know that these laws give a pretty good description of the motion of the planets on their orbits about the sun; even though Einstein's refinements were required to account for some very minor discrepancies.

We also believe that the gravitational attraction of a galaxy will determine the orbits of the stars of that galaxy about its centre exactly as predicted by Newton's laws. But, surprisingly, it has turned out to be remarkably difficult to show how this can be true.

In some respects, the so-called disk galaxies (which include all spiral galaxies) resemble enormously scaled-up

versions of the solar system. The name "disk galaxy" implies that the systems are highly flattened (see Fig. 1) and it has been known for many years that they rotate quite rapidly. We can measure the average speed of rotation of the stars and gas (the gas is actually much easier to measure); a typical "rotation curve" is sketched in Fig. 2. This figure shows that, moving outwards from the centre, the speed of the stars increases steadily at first but after a while remains fairly constant over a wide range of distances from the centre. This means that the galaxy is rotating differentially, since the stars near the centre take less time to complete one orbit about the centre than those further out. The typical average in the outer parts is 250 km/s, but even at this high speed a star's orbit takes somewhere between 50 and 500 million years.

The density of stars is highest in the bright bulge at the centre of all disk galaxies, clearly illustrated in Fig. 1.

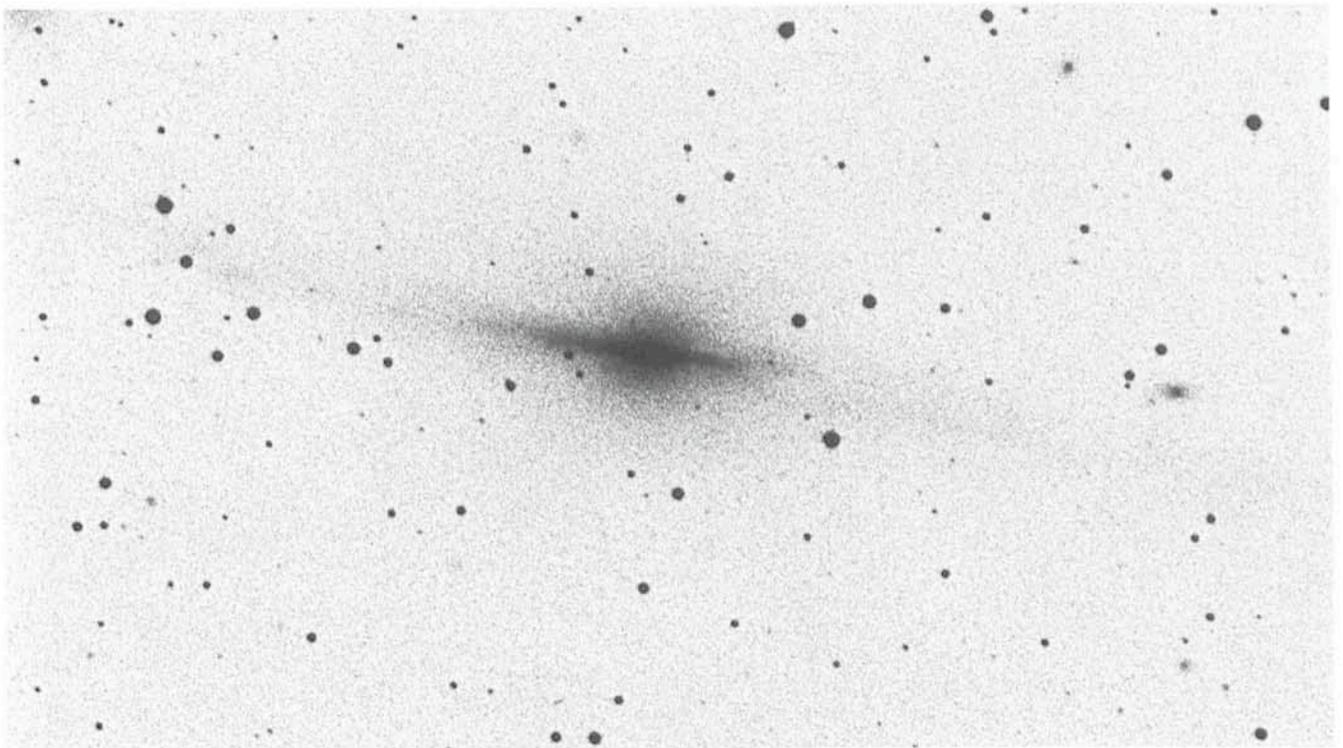


Fig. 1: A negative print of the galaxy NGC 5084 taken during the sky survey on the ESO 1 m Schmidt telescope. This galaxy is very nearly "edge-on" and we can clearly see both the very flat disk and the central bulge.

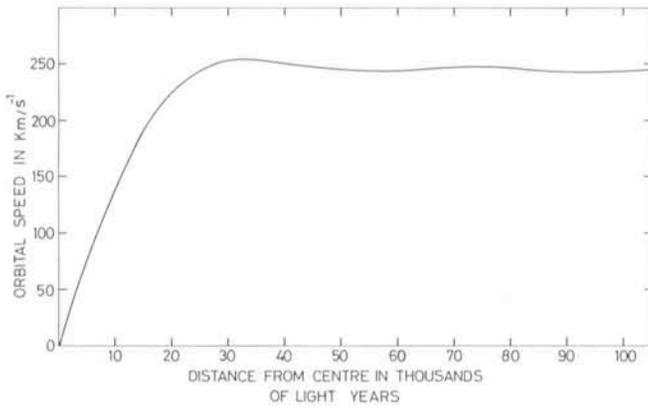


Fig. 2: Sketch showing a typical rotation curve for a disk galaxy. The basic characteristics of a gentle rise and an extensive flat part are found for nearly all spiral galaxies.

Here stars are found to be moving more or less at random, with little organized rotational motion.

In the case of the solar system, the sun is so much more massive than all the planets put together, that the orbit of each planet is dominated by the attraction of the sun, the attraction of the other planets being very weak in comparison. The situation in galaxies differs fundamentally from this, in that there is no single superstar dominating the gravitational field. The mass is divided fairly evenly amongst the one hundred billion stars that make up a typical galaxy. With so many stars in the system, the attraction of the few nearest neighbours is insignificant and the force on each star is still directed largely towards the dense concentration of stars at the centre. But prominent features such as spiral arms or a bar, apparent in most disk galaxies, contain enough stars to deflect the central attraction by an appreciable amount.

It is this aspect which makes calculation of the orbits of stars in a galaxy so much more complicated than those of the planets in the solar system, even though the relevant laws of physics are identical. One way, although not the only way, to study the behaviour of such galaxies, is to programme a computer to calculate how a given configuration of stars would develop over a long period of time. This is the approach I have followed at ESO using the CERN computers. Large, fast computers are essential, since we wish to calculate the force on each star caused by the attraction of all the others many hundreds of times. There are many short cuts and approximations which help to shorten the calculation, but such computations are still among the longest required in astronomy.

The calculation begins from a situation intended to be typical of the arrangement of stars in a disk galaxy, as illustrated in the first picture of Fig. 3. Here you can see a disk of stars viewed "face-on" in which all stars are moving in an anti-clockwise direction just fast enough to put them on nearly circular orbits. I have left out of the picture a second component of the computer model which represents the central bulge. This unseen component contains 25% of the total mass and is not rotating.

The other pictures in Fig. 3 show snapshots of the computed distribution of stars at later times, which are given in millions of years. These show clearly that the model galaxy develops a bar in a little over one billion years. This time is comparatively short on the astronomical scale, and in fact a star about halfway out in the disk of the computer model will have completed only four orbits about the centre during the entire calculation. We know that many non-barred galaxies in the sky are much older than this, so obviously they must differ from the computer model in some respect. The crux of the problem is: how can roughly half of all disk galaxies survive without forming a bar?

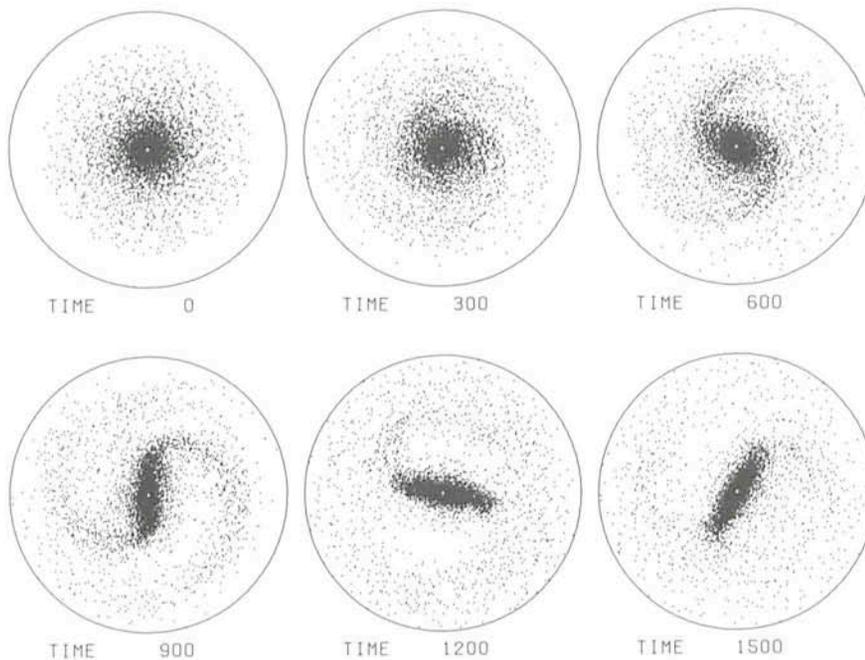


Fig. 3: These pictures show how a computer model of a disk galaxy evolves. The arrangement of stars in the disk is viewed "face-on" in every case and the times are given in millions of years from the start of the run. The computer clearly predicts that this model galaxy will form a bar in a comparatively short time.

Although the initial disk of stars in Fig. 3 was in equilibrium, the equilibrium is about as unstable as a pencil balanced on its point. Just as a tiny disturbance will cause the pencil to fall, so a slight clumping of stars will attract more, making the attraction stronger and so dragging in yet more stars. The result is a bar which forms in order to "redistribute angular momentum" among the stars: Each star's orbital motion prevents it from falling inwards towards the centre of attraction. If it could be "braked" in some way it could settle closer to the centre of attraction, but of course there is no friction in space. However, the beautiful S shape which appears during the bar-forming process is almost as effective. The stars near the centre of the S are pulled backwards by the high concentration of stars "behind" them and settle closer to the centre of attraction. This is at the expense of the outer stars which must move slightly further out to compensate, since they are accelerated by the extra density of stars in front of them. This is only a partial explanation; the full story would take too long to recount. Once the spirals, which provide the torque, fade away, no further changes occur and the bar simply rotates slowly.

There are only two ways known in which to prevent the formation of a bar. One is by increasing the amount of random motion in the disk, the other by invoking what is called a massive halo.

There is no random motion in a disk where all stars have exactly circular orbits. If the orbit of a star is not perfectly circular, then it moves alternately inwards and outwards, whilst sometimes gaining on other nearby stars and at other times dropping behind. When all stars behave in this way, we say that there is some random motion (or velocity dispersion) in addition to the orbital motion. The more eccentric the orbits of the individual stars, the greater the velocity dispersion in the galaxy.

The bar forms most readily when there is little random motion, since all stars respond similarly to any perturbation, quickly building up a big concentration. The more random motion there is at the start, the less coherent the response, hindering the growth of the disturbance. At some point there will be enough random motion to "dissolve" an arbitrary clump before sufficient nearby stars can reinforce it.

There is no simple formula to predict just how much random motion is needed to prevent the growth of a bar in all cases. In the few instances where it has been determined, it appears that the dispersion of velocities must be around 100 km/s. This is a larger value than one would expect and when compared with the 250 km/s of orbital

motion, implies that most stars would have highly eccentric orbits. We have no direct measurements of the velocity dispersion of stars in the disk of other galaxies, although we do know that close to the sun in the Milky Way, the disk stars have a dispersion of only 35 to 40 km/s. Galaxies seen edge-on, as shown in Fig. 1, have very thin disks, indicating small velocities perpendicular to the plane, which suggests little random motion in the other directions too. Thus, although the case is far from watertight, it seems unlikely that random motion in galaxies is sufficient to prevent the formation of a bar.

We are also able to inhibit bar formation by assuming the mass of the bulge to be much greater than one would guess from its luminosity. As we increase the mass of the bulge component in the computer models, we reduce the growth rate of the bar. Eventually, when the bulge is roughly twice as massive as the entire disk, we find that the bar instability is totally suppressed.

However, this again is hard to reconcile with the observed facts. The bulge of a typical disk galaxy provides about 20% of the total light and it is unlikely to contain 70% of the mass. In fact, estimates of its mass from observed rotation curves support a lower value, closer to 20% than to 70%.

(There is mounting evidence for a large quantity of underluminous material in the outer parts of galaxies, which is usually called a "massive halo". It is clear that, if it is spherically distributed, this matter cannot affect the stability of the central parts of the disk, since the gravitational field inside a spherical shell of material is zero.)

Thus, we are faced with a severe problem, although the situation may not be desperate. The only two known methods which can prevent galaxies from forming a bar, taken separately, seem inconsistent with reality. But not all possible solutions have yet been explored. My work at ESO has shown that the bar-forming region is confined to the part of the disk where the rotation curve is rising. This is precisely where we are least certain that the velocity dispersion is small. We can construct models with more random motion near the centre than further out, and reasonable fractions of bulge mass, which will perhaps not form bars. Hopefully they would be consistent with our present knowledge of galaxies.

Observational astronomers can help with this problem too. Measurements of the velocity dispersion of stars in disk galaxies are just becoming possible with the latest observing techniques. Such measurements will provide more stringent tests for our theories.

## Ring Galaxies

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Among the 338 exotic, intriguing and/or fascinating objects contained in Arp's catalogue of peculiar galaxies, two, Arp 146 and 147, are calling special attention as a presumably separate class of objects displaying closed rings with almost empty interior. It is difficult to find out when, historically speaking, attention was called first to this type of object as a peculiar class, but certainly galaxies with rings were widely found and recognized in the early sixties, under others by Vorontsov-Velyaminov

(1960), Sandage (1961) in the Hubble Atlas or de Vaucouleurs (1964) in the first reference catalogue of galaxies. The most recent estimates by Arp and Madore (1977) from a search on about 200 Schmidt plates covering 7,000 square degrees give 3.6 per cent of ring galaxies among 2,784 peculiar galaxies found. However, despite the mythological perfection associated with a circle, some ordering is necessary before trying to understand the nature of such objects. This is particularly true