The Evolution of Spiral Galaxies

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Abstract

The characteristic shapes of spiral galaxies with the manifold of different individual structures are not only noticed for the frequently shown picturesque color photographs taken with modern astronomical telescopes, the explanation of the origin of the detailed structure of galaxies is also one of the most challenging questions for astrophysics today.

A very general introduction to the rich morphology in the world of galaxies is given and it is shown how our Milky Way Galaxy fits into this picture. Starting with the most famous "deepest" images of the Universe, the so-called Hubble Deep Fields (HDFs), the concept of hierarchical structure formation and the role of merging and interaction is introduced. Comparing objects in the HDFs with galaxies in our local Universe, however, reveals that not all the structures observed today can be attributed to an early formation process of galaxies. One frequently observed typical structure of a spiral or disk galaxy is the central elongated stellar mass distribution called "bar". It is shown that our Galaxy contains such a stucture, too. This demonstrates that some typical characteristics of spiral galaxies such as bars grow with time by intrinsic processes.

All these different aspects of galaxy formation and evolution aim at a better understanding of the relation between dark and baryonic matter in a more general evolutionary description of the Universe.

Introduction

Based on their very different appearance and their very different physical behavior, e.g. with regard to the internal motions of the stellar content, we distinguish between elliptical and spiral galaxies. At least with regard to the optical appearance the latter class is the more eye-catching, appealing, and interesting kind. The outstanding feature which makes them even esthetically attractive –and a frequently used background for commercial advertisments –is their spiral structure which can be understood as a wave moving at a charateristic velocity in the density distribution of the underlying stellar disk. In Fig. 1 a typical disk galaxy with its spiral structure is shown. More beautiful images of all types of galaxies can be found on the WWW [1]. Looking at the spiral structure one has to keep in mind that the spiral itself is only a minor disturbance in a relatively smooth underlying stellar disk. In these disk or spiral galaxies the central gravitational attraction is balanced by the fast rotation around the center. As an example we can look at the surrounding of our sun where stars are rotating at a velocity of 220 km/sec around the center of our Milky Way. It is this motion that keeps the sun from falling into the direction of the Galactic center. It is also the observation of a constant circular motion of gas and stars in the outer regions of other disk galaxies which indicated the presence of dark matter in these objects: since the surface density of stars is dropping exponentially one would expect a “Keplerian” decrease (much similar to the third Keplerian law for the motions of our planets) of the rotational velocity. The contradiction between observation and theoretical prediction can only be reconciled by assuming a large scale halo of dark matter. The evidence of dark matter in galaxies now relates the study of the structure

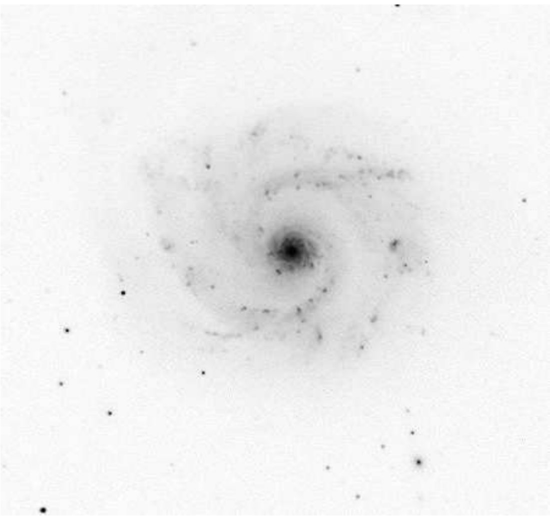

Fig.1: The disk galaxy NGC 3631 shows a prominent pattern of spiral arms (Fleenor/Lamm/Block/NOAO/AURA/NSF)

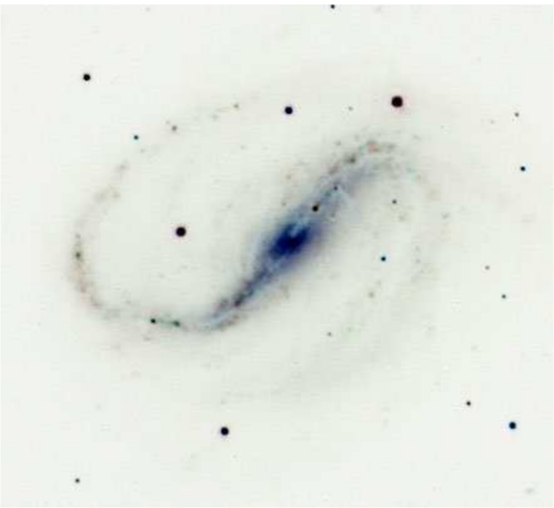

Fig. 2: The object NGC 7646 is a "bared" spiral galaxy. The bar is the elongated central structure at 45°. (Block/NOAO/AURA/NSF)

of galaxies directly to cosmological models such as those described in the contribution by Prof. Sugiyama. What we look at in the picturesque photos of todays galaxies is (just) the baryonic part of the cosmic matter that has condensed to stars and gas clouds and is trapped by the overwhelming potential of the dark matter.

Looking at a picture gallery of galaxies like those given in [1] the interested spectator will immediately notice that the complex internal structures make them individuals, each galaxy is indeed unique. Nevertheless, a more careful morphological characterization of the usually complex appearance reveals a few very general structural components. More than half of all galactic disks seen from the top – or "face-on" – show an elongated inner structure across the center connecting into the spiral armes. This structural element of disk galaxies is called a "bar". Figure 2 shows such a bared galaxy. Modern N-body simulations of disk galaxies could convincingly demonstrate that bars form in almost all numerical experiments with reasonable initial conditions. They can be understood as an instability of the system.

Fig. 3: The so-called "Sombrero" galaxy M104 is seen edge-on. This image representing the lowest light levels and the central bulge demonstrates the huge extent of the faint stellar halo.

One more very general feature should be addressed here, the central part of a disk galaxy shows a much higher concentration, i.e. density, of stars and is in many cases significantly thicker than the disk itself. If seen from the side – or "edge-on" – this central region is of spheroidal shape and called "bulge". Some of these bulges are very extended and their stellar distributions join smoothly into the faint (due to the very small number density of stars) outermost envelopes called halos. In Fig. 3 the very extended halo of the Sombrero galaxy is reproduced together with the central bulge and part of the disk. It should be noted that these faint stellar halos are different from the halos of non-baryonic dark matter. For many decades bulges and halos of disk galaxies were thought to be relics of the formation process of galaxies, left-overs from the collapse of a protocloud.

We now have introduced three morphological structures that already Hubble had used to characterize galaxies according to his famous classification scheme for galaxies: spiral arms, bars, and bulges. Hubble´s tuning fork diagramm for the classification of galaxies is reproduced in Fig.4. It is now one of the central goals of modern astrophysics to explain the characteristics of matter in the Universe observed today starting with the conditions of the Big Bang and thus to understand the formation of the observed structures in the Universe on all different lengths scales such as the filamentary distribution of baryonic matter, clusters of galaxies, and – on the smallest scales – the observed properties of galaxies.

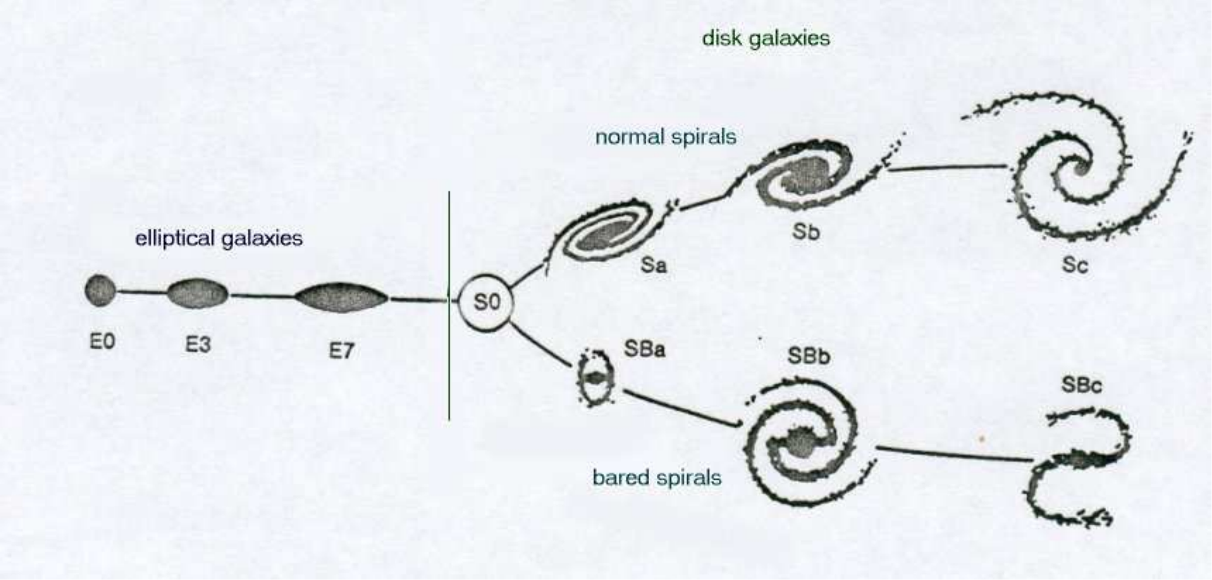

Fig. 4: Morphological classification of galaxies following Hubble. The famous tuning fork distinguishes elliptical and disk galaxies and within the disk galaxies, bared and normal spirals.

From Big Bang to galaxies observed today

This is usually done in very expensive numerical simulations where the evolution of particles under the influence of gravitation in an expanding volume representing part of the expanding cosmos is followed through time. The most important constituent in this kind of cosmological simulations is the “unkown” dark matter. It turns out, however, that only a very restricted set of parameters describing the nature of dark matter together with a specific cosmological model can reproduce typical characteristics of the observed large scale distribution of matter in the Universe. One such numerical experiment is conducted by the international Virgo Collaboration lead by astrophysicists at the Max-Planck-Institute for Astrophysics in Garching [2]. These simulations can already succesfully describe many of the observed characteristics on larger scales such as cosmic filaments, voids, or the formation of clusters of galaxies. However, up to now these kind of models fail to describe the formation of galaxies and in particular of disk galaxies. This may still partly be caused by unsufficient resolution of the simulations and other numerical effects of the algorithms used, but meanwhile astronomers consider also more physical effects such as the energy and momentum input from the first generation of stars to explain the discrepancy between theoretical modeling and observations.

These hierachical models predict that all structures shape up from the smallest to the largest scales. In this picture galaxies as observed today would have built up from the merging of smaller antecedent galaxies. And indeed, the deep images of the Hubble Space Telescope (HST) show that galaxies in the past have undergone frequent interactions and merging processes. Of course, the collisions of massive galaxies are easiest to observe and this type of "massive" mergers will most likely stimulate star formation in the participating galaxies which in turn leads to an extreme increase of their luminosities. Many astronomical problems from young globular clusters to the Ultra Luminous Infra Red Galaxies (ULIRGs) can perhaps be understood in the framework of merging. Some HST images of such local mergers as progenitors of ULIRGs are collected in Fig. 5. The scenario of hierachical structure formation also explains the observed characteristics of objects in the "deepest" images of the Universe. To obtain the Hubble Deep Fields (HDFs) the HST was pointed for 10 days of continuous integration on one position in the northern and southern celestial hemisphere, respectively [3]. These images allow us to identify galaxies at lookback times when the Universe was only one third of todays size. And indeed, the galaxies back then look different, in particular they are much smaller in size if compared to similar galaxies today. In addition, it seems that many of the characteristic structures of todays galaxies as described in the previous section such as the spiral structure, the bar, the bulge, or even the exponential disk had not shaped up yet 9 billion years ago.

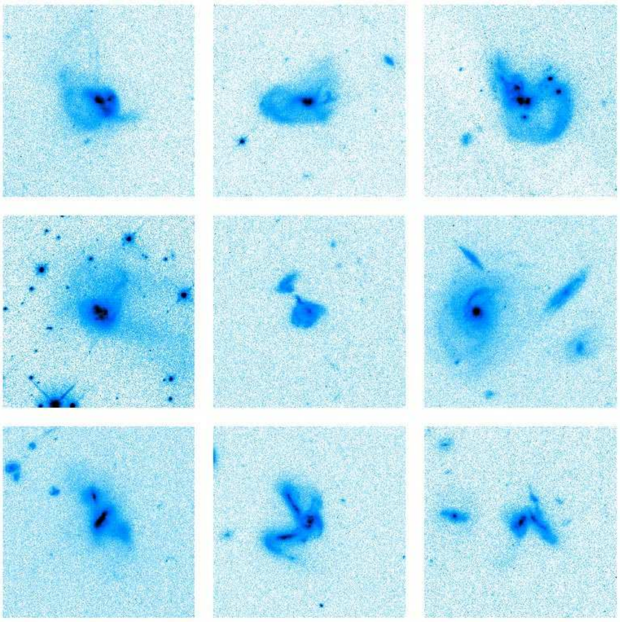

Fig. 5: Colliding and merging galaxies in the local Universe as observed with HST (Borne, Bushouse, Colina, Lucas/NASA/STScI/ESA).

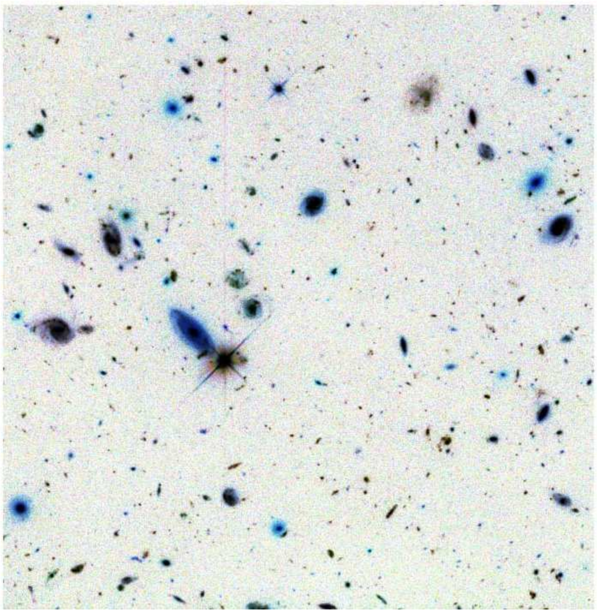

Fig. 6: Part of the Hubble Deep Field North (HDF-N), one of the "deepest" images of the Universe (NASA/STScI/ESA) Almost all of the objects seen in this 2´x2´field are distant galaxies.

Characterizing parameters of disk galaxies from CCD photometry

As demonstrated above the cosmological models are constraint by observations of cosmic structures in the local Universe and this also includes spiral galaxies on smaller length scales.

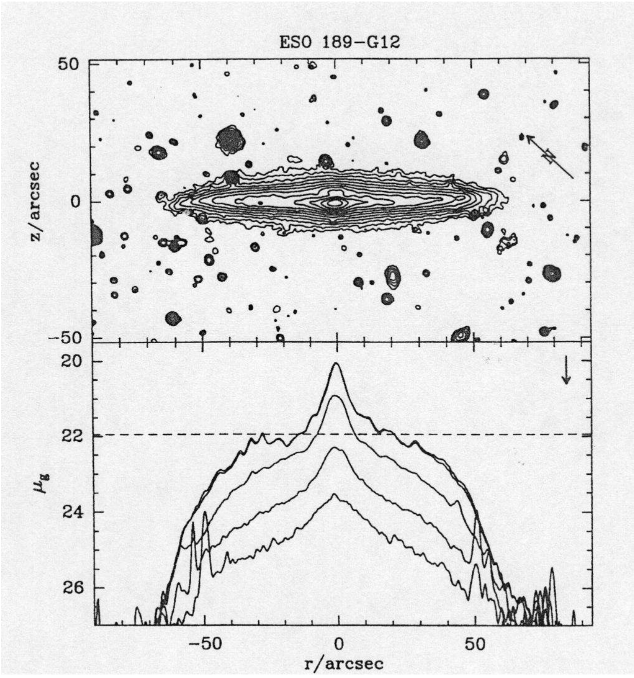

Fig. 7: CCD surface photometry of the edge-on galaxy ESO 189-G12. Contours of equal brigthness are given in the upper panel. The lower panel gives cuts through the brightness distribution parallel to the major axis. The dashed line represents the level of the night sky, here the galaxy is as bright as the night sky.

Very important contributions to a more formal description of structural parameters of galaxies came in the past from the use of the Kiso-Schmidt telescope[4]. With modern CCD cameras attached to a new generation of high-performance telescopes such as the Japanese Subaru-Telescope on Hawaii discussed by Dr. Kaifu before, it is now possible to measure and characterize the parameters of disk galaxies much better in a quantitative way than it was ever possible in the times of photographic plates.This can be demonstrated by the example of an edge-on disk galaxy shown in Fig. 7. The "textbook" exponential disk only describes the brighter innermost disk of the galaxy. Since the cuts through the brightness distribution in the lower panel of Fig. 7 are given in "magnitudes" – an astronomical measure for the logarithm of the intensity – this exponential is represented by the inner close to linear drop-off out to 40 arcsec from the center. Further out the intensity of the disk drops much faster than predicted from an infinite exponential, OR, to describe this in different terms, the disks of spiral galaxies are significantly shorter than expected.

Various parameters for disk galaxies can now be determined and in a series of papers the author and his students have applied these techniques to study, e.g., the effects of interaction and merging by "minor" mergers today [5]. In contrast to the merging of full grown disk galaxies as discussed above for the example of the ULIRGs (see Fig. 5) we are considering in the case of "minor mergers" the effects of small dwarf companions as they fall into the potential of a disk galaxy. The predicted effect is a thickening of the disk due to gravitational friction, the orbital energy of the satellite is distributed among the stellar component of the disk galaxy. This is equivalent to heating the disk and since the disk is confined by the potential well of the main galaxy this is equivalent to a thickening of the disk. In order to check this prediction we compared two samples of edge-on galaxies and measured the scale height of the disks. The first sample consisted of unperturbed objects without known or visible companions. The second sampled, representing the "minor" mergers, consisted of objects perturbed due to a recent interaction event as well as of objects with known close companions. The statistical analysis revealed that the disks of objects in the interacting/merging sample are indeed up to 1.5 times thicker than for objects in the control sample of "normal" galaxies. This result suggests, that a

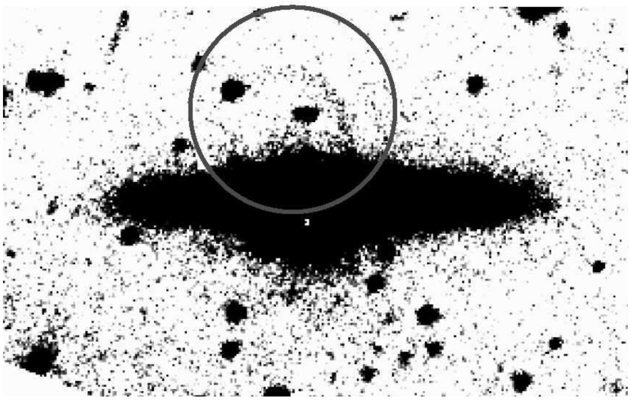

Fig. 8: The high contrast reproduction of the light distribution of this edge-on galaxy shows a possible tidal tail of a merging dwarf companion [10]

substantial fraction of galaxies still experiences so-called “minor” or “soft” merger events today.
This conclusion is corroborated by individual cases found in the course of our project. In Fig. 8 we present a high contrast image of an edge-on galaxy showing most likely the impact of a satellite companion onto the disk.

The new kid on the block…

In view of these findings with regard to the importance of merging events for the growth process of disk galaxies it is now almost no surprise if we find our own Milky Way being currently involved in such a merger process. For a long time the Magellanic Clouds were considered the typical candidates for companions that eventually would merge into the Milky Way as their host galaxy.

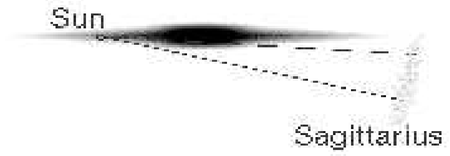

Fig. 9: Sketch of the Sag dwarf spheroidal galaxy merging into the disk of the Milky Way [6].

In 1994 the totally unexpected discovery of the so-called Sagittarius dwarf spheroidal galaxy was made: This object –one-tenth the diameter of the Galaxy but only one-thousandths of the Milky Way´s mass –sits right behind the center of our Galaxy in the middle of the Galaxy´s disk. It is of quite some importance with regard to our understanding of the dark matter in galaxies since its orbit and its decay into individual debris cannot be understood without dark matter being its major constituent. One therefore hopes that the nature of dark matter in galaxies can be better constraint from detailed observations of this ongoing “soft” merger event in our immediate cosmic neighbourhood. The sketch in Fig. 9 describes the position of the Sag dwarf with regard to the Milky Way as seen from the Sun.

The “Galactic” future

It is also very interesting to look at the “merger future” of our Milky Way considering its position in a group of galaxies. Our Milky Way teams up in the Local Group of galaxies with the closest disk galaxy of similar size, the Andromeda galaxy M31, the somewhat smaller Triangle-Nebula M33, and two dozens of smaller dwarf galaxies. Some of the more spectacular merger events in the local Universe are taking place in similar groups if two major disk galaxies eventually collide. Such a major merger event might well be in the Milky Way´s future, too. The Andromeda galaxy is moving towards the Milky Way at 80 km/sec. Therefore a collision can be predicted to happen in about 3 billion years from now. This future collision has been modelled in super-computer simulations using up to 24 million particles [7]. Figure 10 shows the expected distribution of stellar masses from the collision some 4.6 billion years into the future from one

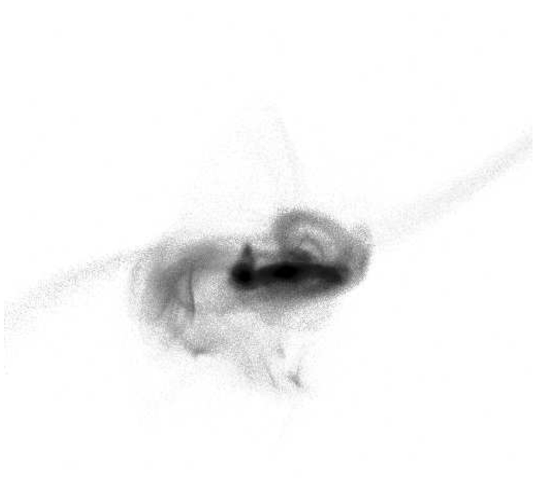

Fig. 10: The collision of the Milky Way Galaxy with Andromeda 4.6 billion years into the futurefrom N-body simulations. (Hernquist/Dubinski/NPACI)

such computer model.This major merger event of Andromeda and the Milky Way would actually be the end of our Galaxy as we know it.

Shaping up from the inside

The formation scenario discussed above seems to be able to explain the conglomeration of matter into galaxies and astronomers now hope to explain the distribution of global characteristics of galaxies in the near future [8]. A more careful look at the most sensitive surface photometries of edge-on galaxies now available from many modern CCD cameras at first class telescopes, however, resulted in a few surprises. One such unexpected observational fact comes from a detailed analysis of the shapes of galactic bulges. At the much higher signal-to-noise level provided nowadays by CCD cameras many bulges are not well described by a simple "spheroidal" intensity distribution anymore, in almost 50% of all objects observed the light distribution rather exhibits a "double-hump" or "dumble" shape, dubbed "box" or "peanut" by astronomers [9]. A typical peanut bulge from an image of an edge-on galaxy obtained with the HST is shown in Fig. 11. The very charateristic and almost X-shaped structure in the central region was actually predicted by N-body computer simulations. As mentioned before, the disks in computer simulations generally formed bars and when the computing power became sufficient to model galactic disks even in three dimensions the model disks started to "buckle" out of the disk plane. This can be understood as a complex resonance phenomenon of individual stellar orbits in the triaxial potential of the bar. As a result the superposition of all individual orbits looks X-or "peanut"-shaped, if the bar is oriented perpendicular to the line-of-sight.

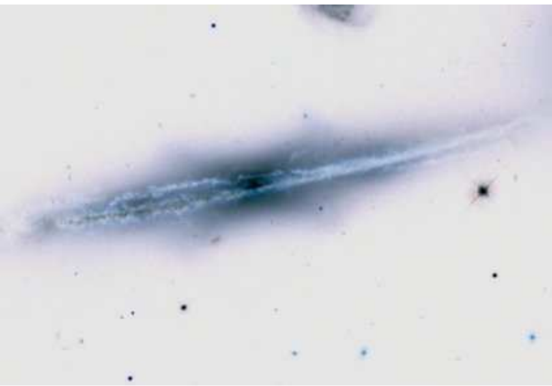

Fig. 11: A „peanut" shaped central bulge in the edge-on galaxy HCG 87a observed with HST (Hubble Heritage Team / AURA/ STScI/ NASA)

It is exactly this peanut structure that is now observed for the stellar distribution in the center of our Milky Way in infrared wavelengths which is unaffected by the absorption of interstellardust [11]. Therefore astronomers conclude that our Galaxy also harbors such a bar. Moreover, the presence of a bar also explains the observed complex gas kinematics in the central part of the Milky Way since only a non-spherical potential would allow for the large deviations from circular motions seen, e.g., in the motion of molecular gas measured by the 3mm line of interstellar CO.

For our understanding of an evolutionary scenario for disk galaxies this has one important consequence. Some of the structural components of spiral galaxies as they are observed today such as bars and bulges could be due to internal processes like instabilities and resonances. And in this respect it is tempting to think of similarities to self-organization processes in other complex systems. One should, however, keep in mind that the full physical understanding of the described models depends critically on the most mysteries unknown in physics and astronomy today: the nature of dark matter.

Acknowledgements. Research by the author in the field of galaxy evolution has been supported by DFG. Results presented here are based on thesis projects by R. Lütticke, M. Pohlen, and U. Schwarzkopf.

References:

[1] WWW based image galleries of galaxies can be found, e.g., at
http://www.noao.edu/outreach/aop/observers/galaxy.html
http://www.astro.princeton.edu/~frei/catalog.htm
http://oposite.stsci.edu/pubinfo/nearbygalaxies.html

[2] Material on the Virgo project can be found at
http://www.mpa-garching.mpg.de/Virgo
[3] The Hubble Deep Field project and its results are documented at
http://www.stsci.edu/ftp/science/hdf/hdf.html

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[6] http://www.obspm.fr/actual/nouvelle/feb02/cseresnjes.en.shtml

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http://www-brs.ub.ruhr-uni-bochum.de/netahtml/HSS/Diss/PohlenMichael/

[11] the “infrared” view of the Milky Way can be found at:
http://www.ipac.caltech.edu/2mass/gallery/showcase/allsky/index.html

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