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Turbulence, Plasma Containment, and Galaxies*

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These three exciting areas of research, apparently disjointed in content, have similar basic mechanisms in common which can be described by the same mathematical principles, concepts, and methods. Scientific problems will be discussed in all three areas. Emphasis will be placed on galaxies, where observational data are plentiful for checking the theory. A unified mathematical approach applicable to all three areas will then be described.

Key words: density wave; galactic spirals; hydrodynamic instability and turbulence; plasma dynamics; spiral grand design; WASER; winding dilemma.

1. Introduction

Dr. Dillon, Miss Smith, Mr. Tsai, ladies and gentlement, I am indeed honored by your invitation for me to speak on the occasion marking the contribution of American citizens of Pacific and East Asian heritage. I am especially pleased by the fact that I, as a Chinese-American, have been chosen to speak today, May 4th, 1979. For this day marks the 60th anniversay of the celebrated May Fourth Movement, which is generally recognized as the most important milestone of vigorous new cultural developments in modern China.

My talk will be devoted to a discussion of the similarities and differences among the three subjects mentioned in the title. By using these as examples, I also hope to explain the basic theme of an applied mathematician (physical mathematician); that is, the fundamental concepts and mechanisms that show similar mathematical characteristics are also physically similar, and *vice versa.* [These discussions were presented but omitted from this abbreviated record.]

Since my current research work is on the spiral structure of galaxies, I shall begin my discussion with this subject.

2. Galaxies

A galaxy is essentially a collection of stars. Galaxies exhibit a variety of morphological appearances: elliptical, spiral, bar-spiral, and irregular. In figure 1, we show the spiral galaxy M81 in an optical photograph. In figure 2, we show the same galaxy observed in radio-frequency at a wave length of approximately 21 cm. The latter waves are emmitted by hydrogen atoms, which exist in the galaxy (instead of the molecular form) because the medium is so rarefied. We note that the spiral structures observed in optical and in radio frequencies are quite similar. Such spiral structures are observed in many galaxies.

How do we explain these spiral features? Let me first clarify the issues by quoting from the famous Dutch astronomer, Professor Jan Oort, who has been studying galaxies for the past 50 years:

> "In systems with a strong differential rotation, such as is found in all non-barred spirals, spiral features are quite natural. Every structural irregularity is likely to be drawn out into a part of the spiral."

That is, since the galaxy is in a disc form, with a nucleus in the middle, it must be rotating, otherwise self-gravitation would have pulled it together. It turns out that the inner part is rotating faster than the outer part, in such a manner that the liner velocity of rotation is nearly constant. So the inner part, say at the distance of 5 kiloparsecs from the center, is rotating twice as fast as the outer part at 10 kiloparsecs. (One parsec is about 3.3 light years.) Since the inner part rotates faster, any material clump would be stretched out into a part of a spiral structure.

> "*But this is not the phenomenon we must consider.* We must consider a spiral structure extending over the whole galaxy from the nucleus to its outermost part, and consisting of two arms starting from diametrically opposite points. Although this structure is often hopelessly irregular and broken up, the general form of the large scale phenomenon can be recognized in many nebulae [galaxies]."

* (This is an abbreviated rendition of a lecture delivered at the National Bureau of Standards on May 4, 1979, as a part of the program to mark the Asian/Pacific American Heritage week.)

FIGURE 1. The spiral galaxy M81 according to optical observations. The line drawings show the locations of the shock wave in the interstellar medium and the minimum of gravitational potential. Both lie close to the dust lane.

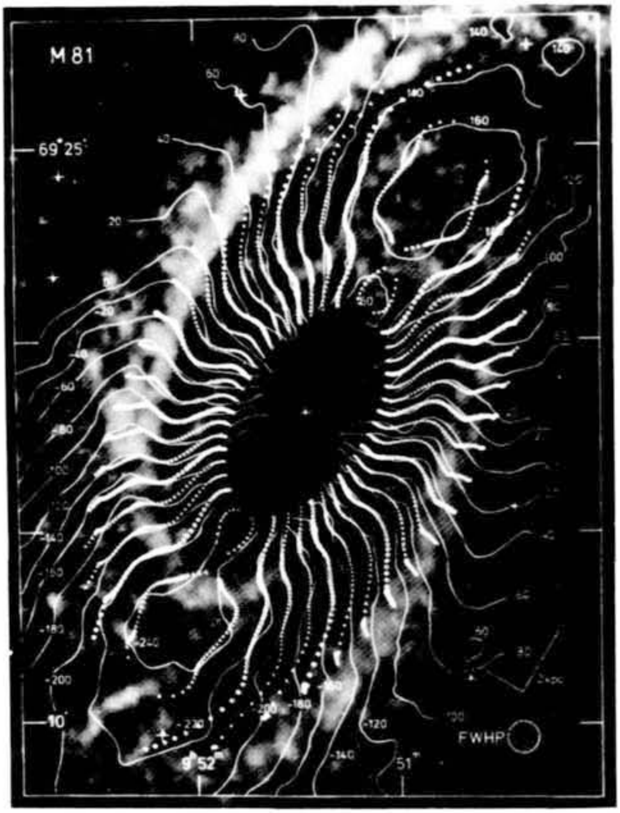

FIGURE 2. The spiral galaxy M81 according to radio observations at 21 cm. wavelength. The line drawings show the iso-velocity lines according to observations and according to theoretical calculations.

This issue is often referred to as the existence of *grand design*.

The other problem is the so-called winding dilemma, i.e., spiral galaxies, especially normal spiral galaxies, are classified by Hubble (see fig. 3) according to the tightness of winding into Sa, Sb, and Sc sprials, Sc being the most open. You might imagine that because of differential rotation, Sc galaxies would soon wind toward Sa, because the inner part is rotating faster, and like a spool of string, would therefore tend to become tighter and tighter with rotation. But this is not observed to be the case. Of course we cannot directly follow the evolution of galaxies in our lifetime: this winding would occur on the order of a few hundred million years. However, we can make a *statistical* study and show that Sc galaxies and Sa galaxies are physically different through the observation of other physical characterisitcs; for example, the gas content in Sc is much higher than in Sa. You can say that Sc galaxies would have their gas formed into stars and then become Sa at the same time. But if that were so, the average mass and the number of stars formed would be so large that Sc galaxies would be much more brilliant than they actually are. Furthermore, the mass distribution is such that there is a very small nucleus in Sc galaxies whereas Sa galaxies have more massive nuclei. It is impossible for mass to accumulate so rapidly because the angular momentum in the system cannot be adjusted so quiclkly. Thus, the evolution from Sc to Sa in a reasonable period of time is ruled out, and they must be rather permanent structures. The question is: If we have material objects arranged like that in an Sc galaxy, why does it not wind down to an Sa structure? This is the so-called *winding dilemma*.

The answer is, as it turns out, that Sc and Sa galaxies have their large scale spiral structure in the form of permanent or nearly-permanent *wave patterns*. These patterns have now been calculated by using a number of methods and the mechanisms for their maintenance have been understood. Waves over a system in differential rotation are well-known in the study of turbulence. Theory of instabilities of this kind goes back to Lord Rayleigh, in 1880, and has been developed over the years. There were mathematical difficulties, so the theory was not fully developed until much later. There were also experimental difficulties, so the

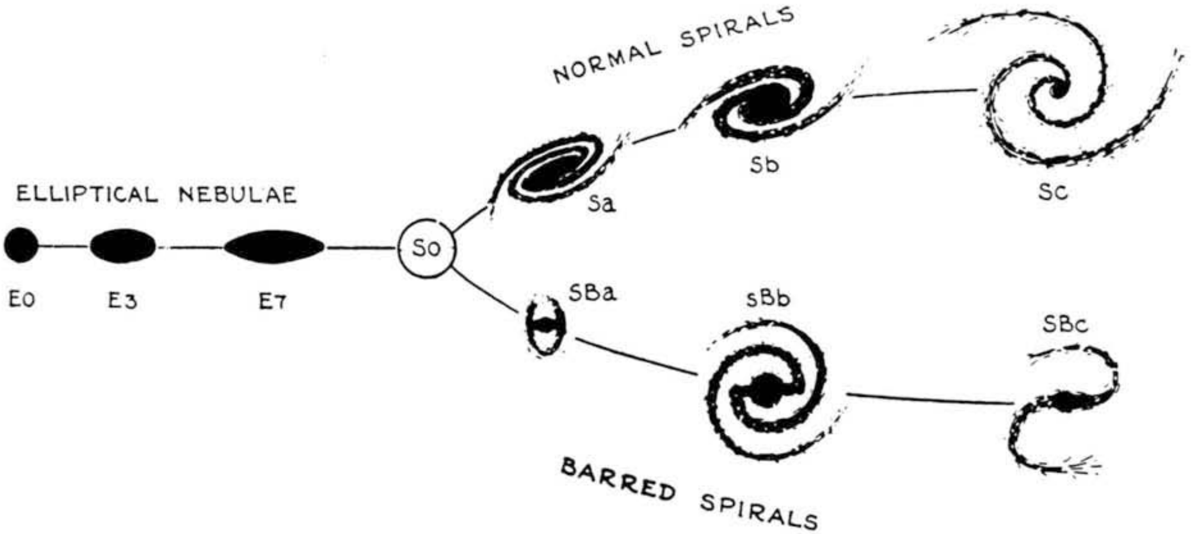

FIGURE 3. Hubble classification of galaxies.

theoretical predictions were not checked until the work at the Bureau of Standards was carried out by Dryden, Schubauer, Klebanoff and their collaborators. It is generally accepted that the calculated instabilities in a sheared boundary layer were verified by these experiments. More recently, in Japan, they have also checked the calculations for the more classical case of flow through a channel. Thus, we are applying these well-known concepts of waves of permanent structure over a system in differential motion (in shear) to the study of galaxies.

The other question is: What are those brilliant stars which mark the waves? How do they behave? They are, as a matter of fact, like the white caps on the ocean: they come and go, they are formed and then they disappear. They are now believed to form out of the interstellar medium (the gas) and then shine brilliantly by burning their nuclear fuel. After exhausting their nuclear fuel, they disappear with a bang, a supernova explosion. Can these things happen over the time period under consideration? Indeed the answer is: Yes! For the time scale for the evolution of such brilliant stars into the supernova state and then into the white dwarfs is one to ten million years, and the time of one period of revolution of the galaxy is about 200 million years. So it is during a small fraction of a period of revolution of the galaxy that the whole phenomena of star formation and star disappearance can occur, and they are no more permanent than the white caps at the crest of waves on the ocean. This is another example where the concepts used to explain the phenomena of turbulence, hydrodynamics, and galaxies get together.

Let me provide some more details. Let us assume the existence of a rotating wave pattern, and imagine ourselves in a moving system in which the wave pattern is fixed (cf. fig. 4). The flow of the interstellar medium follows the arrow, and as it enters the density peak (the gravitational minimum), the material would undergo an oblique shock

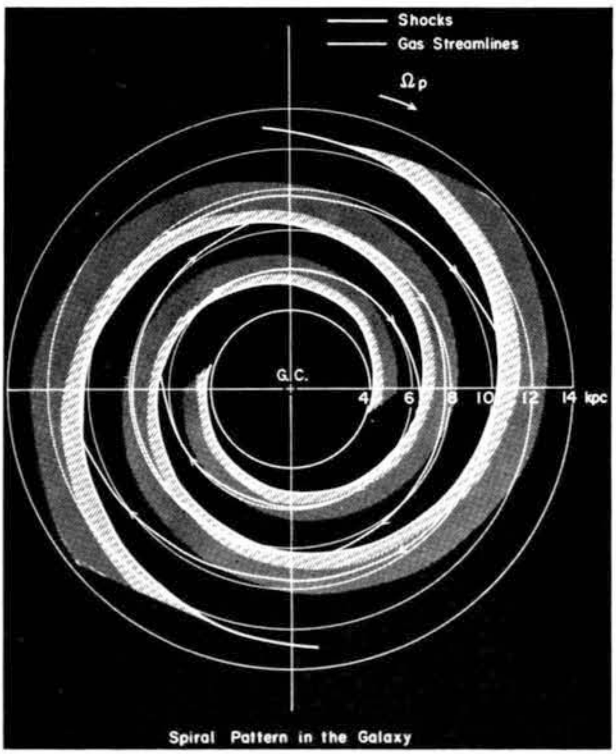

FIGURE 4. Gaseous flow in a galaxy when there is a spiral gravitational field. Streamlines are marked with arrows indicating the direction of gaseous flow. The shocks are the heavy solid lines next to the hatched regions.

which suddenly compresses the material and turns its flow direction. This oblique shock forms a part of the spiral arm. The material passing through the spiral arm follows the arm over a considerable distance, and goes to the next arm where it goes through another shock compression in the same way, and comes around and closes the loop (approximately). So the gas is going around not along a circular path, but in a slightly distorted orbit which has two shocks near the two spiral arms. At these shocks, interstellar medium is compressed, forming stars out of a part of the gas. As the stars emerge from these shocks, they go further and they disappear when their nuclear fuel is burned out. The bright part of this diagram is the region of star formation and star evolution. As the hydrogen gas is compressed by the shock, molecules are formed in the dense clumps of gas. There are also dust particles composed of elements of higher atomic weights. So one would see, at the first sign of compression, a rather dark region—the dust lanes. (See figs.

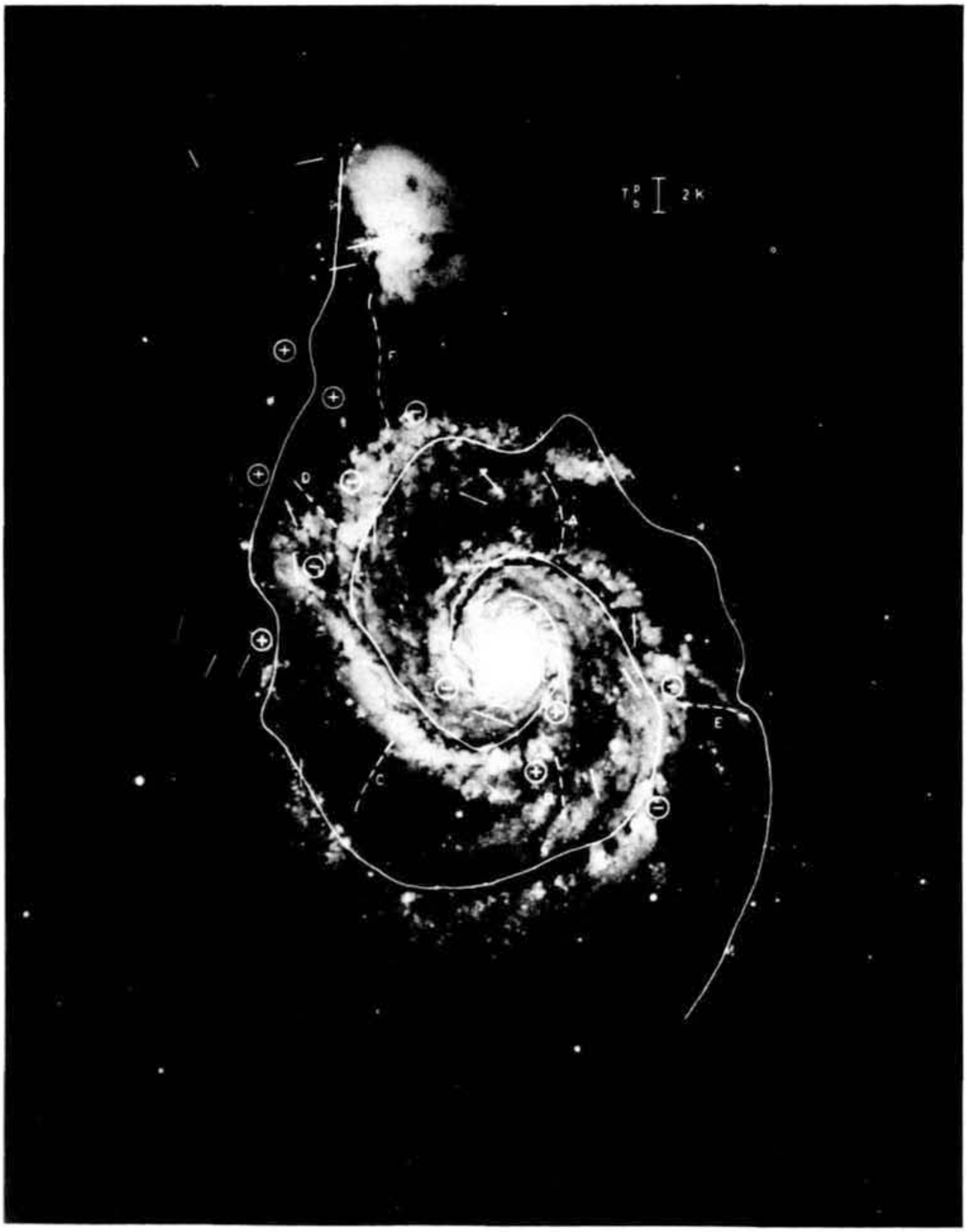

FIGURE 5. LEFT PICTURE: The location of the peak of the synchrotron emission in the right picture is shown and seen to coincide with the location of the dust lane.

1 through 5). This is followed immediately by a region of bright young stars, which are expected to be very bright, and in fact blue in color. This is indeed what is observed. In any case, in the region of compression, one would also expect to see a concentration of atomic hydrogen in the slightly less brightly shaded area.

The young stars stand out well in the galaxy M51 in blue light. These young stars are indeed in a very narrow band because their age is short and they do not move very far before they burn themselves out. Through a study of the nuclear reactions in stars, one can develop a connection between their color and their luminosity. The blue stars are very luminous, but they also burn out quickly.

The Dutch astronomer Herman Visser has constructed a model (cf. fig. 1) for the galaxy M81 based on these concepts. In Visser's model, the shock essentially matches the observed dust lanes (one is shown in dotted line and one in solid line). He calculated the flow field of atomic hydrogen

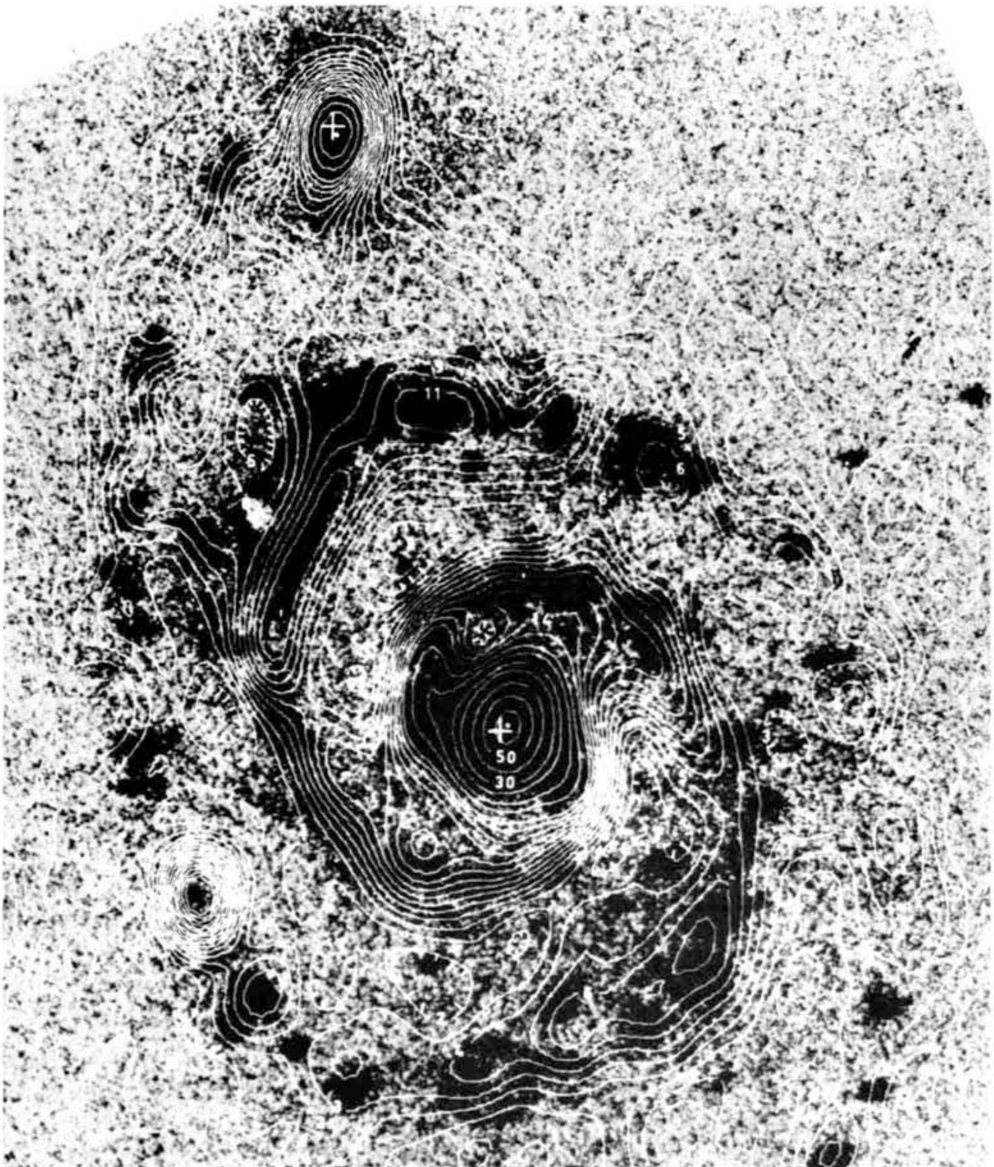

FIGURE 5. RIGHT PICTURE: The continuum radio map (at 20 cm) of the galaxy M51.

and its distribution in this galaxy, given such a gravitational field. The calculated motion of atomic hydrogen is shown in terms of iso-velocity lines; so are the data from observations (see fig. 2). Indeed, the quantitative agreement is very good.

Can we see the density variation postulated in the theory? It is not easy, but it has been done. Now, the bright young stars which we see on the spiral arms are not the ones which determine the gravitational field, because they are very few in number. We must look beyond those stars, i.e., we must filter out their light and look at the background stars which are more like the sun, a rather average, dim star. The bright stars are essentially those which are colored blue and the dim stars essentially red. The astronomer Schweitzer made the necessary observations with proper filters. When the blue color is filtered out and the color is essentially orange, one sees the fairly regular variations in the orange components from the dim stars. On the other hand, a rather chaotic variation is seen superposed when the blue components are put in. This work was done during just the past three years, so it could still be improved upon. But basically the results bear out the idea that there is a small density variation on the order of 10-20% (closer to 10%) in the actual density of the stellar mass.

There is another way to look at the existence of density waves. Roberts and Yuan made a calculation which predicted what is shown on the left hand side in the next figure (fig. 5). In this galaxy (M51), you can see very clearly the dust lane which is marked out by the dark strip side-by-side with the bright stars. The line drawn along this lane is not a physical object, but is drawn to show the location of the peak of synchrotron emission as explained below. Now we know that there is a shock, so there is a compression of gas. If there is a magnetic field, that compression would also strengthen the magnetic field because the latter is frozen into the material. So one would expect a strong magnetic field at the dust lane. This stronger magnetic field would manifest itself by the stronger synchrotron radiation from this region, because there are charged particles moving at relativistic speeds in the galaxy. Those particles would then emit at very high frequencies and one can detect them as a continuum emission. The right picture in figure 5 is an observed map of this emission by the radio telescope. The results indeed show a peak as indicated in the diagram on the left. The line was in fact drawn by the observers from the map on the right. So the results do show that there is a stonger radiation at the dust lane where the theory predicts a stronger radiation due to the strengthening of the magnetic field by a galactic shock.

We have thus seen two sets of data, one in M81 and another in M51, supporting the density wave theory. There are many other phenomena which have been observed to agree with the predictions based on the density wave theory.

3. Basic concepts and mechanisms

We record briefly some of the basic concepts and mechanisms visualized for the explanation of the observed phenomena.

(1) The above discussion places emphasis on the winding dilemma and on the existence of grand design. One should recall that the spiral structure in galaxies is indeed "often hopelessly irregular and broken-up" and hence there is *coexistence* of regular spiral patterns and spiral features in bits and pieces. Some of these may be material arms; others, waves. This situation is not very much different from that in a turbulent jet which shows both small scale chaos and large scale structures. There are only a few prominent large-scale modes, and hence at any instant the large-scale structure shows quite a deal of regularity. Hot-wire anenometer records of turbulence motions in a boundary layer (NBS) show similar behavior.

It is a matter for speculation how much regularity may be expected in the observed patterns of galaxies. In the above discussions, we assume a considerable amount of regularity and hence we conclude that it is indeed possible to have the Hubble classification in a *statistical* sense. Further detailed studies are desirable to clarify these issues.

(2) There are a number of similarities in mechanisms among the three subjects under discussion: galaxies, turbulence, and plasmas. We shall only record some of them without detailed explanation. [More details were given in the verbal presentation.]

(A) Both in hydrodynamic stability and in the study of spiral waves in galaxies, corotation resonance plays an important role in energy transfer.

(B) Analogous mechanisms may be found between the instability of the ballooning mode in contained plasmas and the instability of Couette flow with inner cylinder rotating.

(C) The WASER mechanism (wave amplification by stimulation of emitted radiation) is important for spiral wave patterns in galaxies, as well as in plasma dynamics and in the instability of supersonic shear layers. It includes the interaction of wave of positive and negative energy densities.

(D) There is similarity between the density waves in galaxies and the Bernstein waves in magentically contained plasmas. This is due to the similarity between the Coriolis force in the former case and the Lorentz force in the latter case.

(3) *A unique feature.* The maintenance of density wave patterns must depend on waves propagating in opposite directions. A naive view would then require the existence of leading waves and trailing waves, and we may expect to find

only bar-like structures. Actually, there are *two* kinds of trailing waves propagating in opposite directions (see fig. 6). Thus, one can even form pure trailing spiral wave patterns without any leading component. Obviously, there are also barred spirals, which has contributions from leading components.

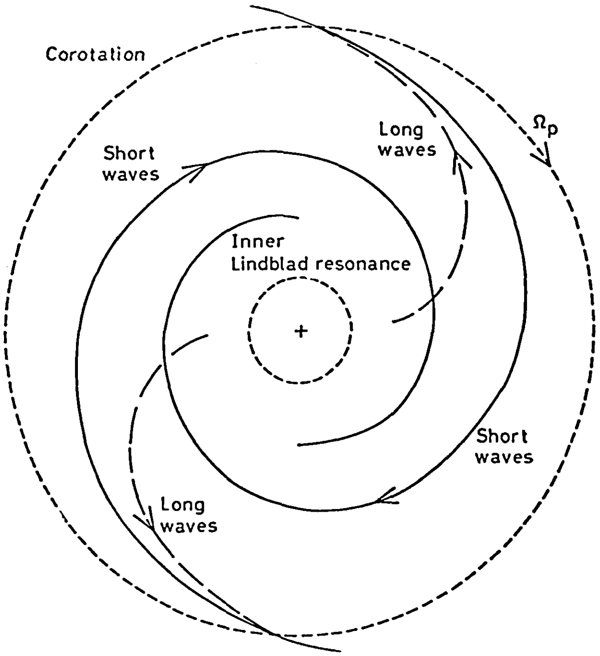

FIGURE 6. Schematic diagram showing composition of a spiral pattern by two trailing waves.

4. Concluding Remarks

Since this is an occasion to mark the contribution of Asian Americans, I should mention that a number of important contributors to the subjects under discussion are Asian-Americans. Contributors to the older subject of turbulence are too numerous to be named. However, I do wish at least to mention four persons who contributed both to plasma physics and to the study of the dynamics of stellar systems. They are James Mark, Y. Y. Lau, Linda Sugiyama, and C. S. Wu. If one examines the list of references in this subject one finds that the contribution of Asian-American scientists far outweighs the total percentage of Asian-Americans in the population as a whole. We have in this country, indeed, great opportunities for all ethnic groups, especially in science. By its very nature, science has a tendency to permeate international boundaries. Science and scientists do have a very important role to play in promoting mutual understanding among the countries in this world. American scientists with special ethnic backgrounds can contribute greatly to this effort. With this hopeful note, let me thank you again for inviting me here, and I wish you great success with the rest of your program.