Percolation and Galaxies

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A theory is presented in which much of the structure of spiral galaxies arises from a percolation phase transition that underlies the phenomenon of propagating star formation. According to this view, the appearance of spiral arms is a consequence of the differential rotation of the galaxy and the characteristic divergence of correlation lengths for continuous phase transitions. Other structural properties of spiral galaxies, such as the distribution of the gaseous components and the luminosity, arise directly from a feedback mechanism that pins the star formation rate close to the critical point of the phase transition. The approach taken in this article differs from traditional dynamical views. The argument is presented that, at least for some galaxies, morphological and other features are already fixed by general properties of phase transitions, irrespective of detailed dynamic or other considerations.

GALACTIC STRUCTURE HAS TRADITIONALLY BEEN THE DOmain of Newtonian dynamics. Although it is clear that the overall mass distribution and motions of the components of a galaxy are determined by gravity, it has not been clear what is responsible for the striking morphology of a spiral galaxy such as shown in Fig. 1. The spiral arms extend over 20,000 parsecs (1 pc equals 3.26 light-years), and the traditional view is that it is necessary to have a long-range interaction like gravity to create such long-range order. However, in condensed matter physics it is well known that long-range order can be induced by a short-range interaction, and this is a characteristic feature of a continuous phase transition. A familiar example is ferromagnetism; it is possible to create a magnet as large as one likes, even though the atomic exchange interaction responsible for ferromagnetism has a range on the order of 10 angstroms.

The structural features of galaxies that we explain are induced by the star formation mechanism operating in the galaxy; throughout this article we use the word "structure" to refer only to these features. We do not discuss the dynamic structural properties, such as total mass and angular velocity distributions, but take them as given. To account for the structural consequences of the local star formation process, we invoke a class of phase transitions called percolation. We describe this critical phenomenon and show how it applies to galaxies and how it accounts for many of their observed properties.

We emphasize that this article is an account of what we believe to be a significant mechanism responsible for the structure of galaxies. It differs from the traditional approach in which detailed gravitational dynamics is considered the dominant influence leading to global galactic structure (*1–5*). To a large extent we ignore gravity and determine what consequences the existence of a percolation phase transition has for galaxies. We show that many observed structures can be obtained as a direct consequence of this phenomenon. However, the study of galactic structure is still an active area of investigation, and it appears that some types of galaxies are well described by our theory, whereas others are better described by dynamic theories. Evaluation of relative merits, as well as possible syntheses, will have to await the outcome of observational programs that are expected to shed light on these competing mechanisms.

The message of this article is not that our mechanism is the only correct one. Rather, we show how a radical alternative point of view arising from an entirely different field (statistical mechanics) can suggest an intriguing new approach to a problem in astronomy.

The Composition of Galaxies

Galaxies exist in a number of forms; the two main groups are elliptical and disk (mostly spiral) galaxies. Elliptical galaxies are ellipsoidal distributions of old red stars; these galaxies contain little or no gas or star formation sites. Since we are primarily concerned with star formation, we do not discuss elliptical galaxies further. Disk galaxies have radii between a few hundred parsecs and 100 kiloparsecs and contain from 10^5 to 10^{12} solar masses. Their thickness is of the order of 100 to 200 pc so that the larger ones (all the spirals) have a large aspect ratio. This aspect is shown in Fig. 2, which presents a spiral galaxy seen edge-on. In the center of the galaxy is a spheroidal region called the bulge, which consists of old red stars without much gas. The bulge resembles an elliptical galaxy and has no star formation.

In a disk galaxy, the spiral arms, which are quite blue, are sites of active star formation (Fig. 1). They are blue because of the massive young stars that radiate at short wavelengths. In stars, blue always means young because stars massive and hot enough to be blue live only a few tens of millions of years—a short time on a cosmic scale.

The galaxy is pervaded with a gas of atomic hydrogen having a density of about 1 atom per cubic centimeter. Under appropriate conditions this gas can be made to condense into a molecular cloud of density 10^3 to 10^4 atom per cubic centimeter. The cloud is called molecular because it is dense enough to filter out the ultraviolet radiation of the surrounding stars; as a result, hydrogen molecules formed in the cloud will not be broken up. Regions of these clouds are dense and cool enough to undergo contraction under their own gravity and to form stars. A variety of stars is formed ranging from a tenth of a solar mass to tens of solar masses. A typical star like our sun will live about 10^{10} years and quietly end its life as a white dwarf, essentially a burnt-out cinder which remains after exhausting all the thermonuclear fuel. A massive star, however, has a completely different end. For example, a star with ten solar masses will live only about 10^7 years, after which it ends its life as a supernova. A supernova is a tremendous explosion; one can appreciate its magnitude by realizing that for a few weeks the exploding star is almost as bright as a galaxy, that is, as bright as 10^{10} suns.

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It is these massive stars that provide the trigger for propagating star formation. Their energetic processes can sweep up the dilute interstellar gas and compress it to the density typical of a molecular cloud. Stars now form in this new cloud, some of which are massive and are able to repeat the process. This chain reaction is a percolation process that fills the galaxy with stars.

Percolitis

Consider the imaginary, idealized, and benign disease percolitis. It conveys no immunity, has a low probability of transmission (1/1000), and its incubation and duration periods are each 24 hours. Mr. Smith, who lives in a susceptible community with a population of 700 and comes in contact with all other citizens every day, contracts the disease on Monday (from an out-of-town source). The expected number of percolitis sufferers on Tuesday is 0.7, and the odds of having none at all are about 1/2 (= 0.999^{700}). The chance that on the following Monday there will be any more victims is slim.

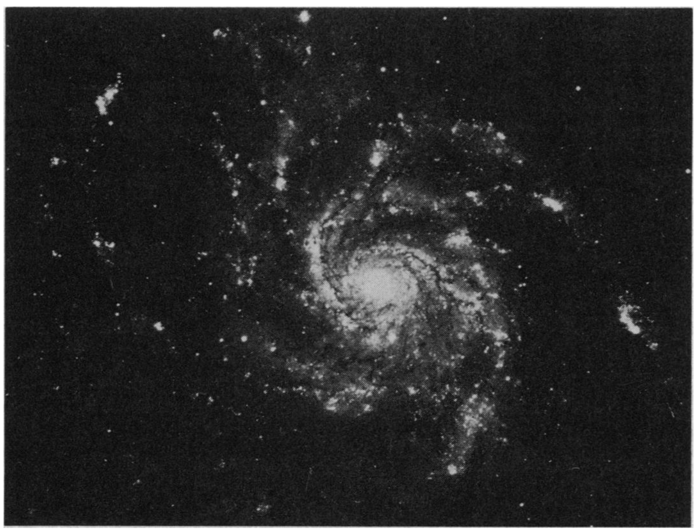


Fig. 1. The spiral galaxy NGC 5457. [With permission of the Carnegie Institution of Washington (*30*)]

Fig. 2. The edge-on spiral galaxy NGC 4565. [With permission of the Carnegie Institution of Washington (*30*)]

On the other hand, had the community numbered 2000 people (and had Mr. Smith's sociability been up to the challenge of contacting each one), the chance of a percolitis-free population on Tuesday is less than 15 percent; even more significantly, once the disease gets any kind of foothold (for example, if 12 people contract it), the odds are overwhelming that it will become ineradicable with a steady-state average number of victims of about 1600.

The foregoing is an application of percolation theory to epidemiology (*6*); the sharp contrast between possible asymptotic behavior for communities of more or less than 1000 is an example of the percolation phase transition. Many natural systems can be modeled by percolation theory (*7*), for example, fluid flow in porous media, conductor-insulator composites, dilute ferromagnets, communication networks, and the propagation of star formation in galaxies.

We provide a quantitative description of percolitis and point out not only the phase transition but also a divergence in a correlation length. This divergence is central to the evolution of global structure in a system with short-range interactions. Let N be the total population, t the time measured in days, $n(t)$ the number of diseased individuals at time t, P the transmission probability, and $\rho(t) = n(t)/N$ the percolitis density or the probability that a randomly selected individual at time t has the disease. The probability that a given individual is disease-free at $t + 1$ is $1 - \rho(t + 1)$. On the other hand (since everyone contacts everyone else each day in this imaginary community), to be disease-free at $t + 1$ requires a failure to transmit for all $n(t)$ contacts. Thus

$$1 - \rho(t + 1) = (1 - P)^{n(t)} \quad (1)$$

Defining x by $P = x/N$ and using the fact that

$$e^x = \lim_{N\to\infty} \left(1 + \frac{x}{N}\right)^N \quad (2)$$

we find

$$\rho(t + 1) = 1 - e^{-x\rho(t)} \quad (3)$$

For $t \to \infty$ this approaches an x-dependent limit that we call $\bar\rho$ and that satisfies

$$\bar\rho = 1 - e^{-x\bar\rho} \quad (4)$$

For all x this is solved by $\bar\rho = 0$, but for $x > 1$ there is a real solution that is approached for $0 < \rho(0) \leq 1$ (*8*).

The sharply different asymptotic behavior for $x < x_c$ and $x > x_c$ (where the subscript c means critical, and here $x_c = 1$) corresponds to the occurrence of a second-order phase transition. The "order parameter" is $\bar\rho$, and as a function of x it goes from zero to nonzero values. For ferromagnetism the order parameter is the spontaneous (zero magnetic field) magnetization, a quantity that becomes nonzero continuously as the temperature is lowered below the Curie temperature, about 770°C for iron. There is a second characteristic critical property that we wish to exhibit, the divergence of the correlation length. For percolitis the analogous quantity is the relaxation time, defined by the asymptotic approach of $\rho(t)$ to $\bar\rho$ through

$$\rho(t) - \bar\rho \sim (\text{constant}) \exp(-t/\xi) \quad (5)$$

Using Eqs. 3 and 4, we have shown (*9*) by a simple calculation that for x near 1

$$\xi \sim \frac{1}{|x - 1|} \quad (6)$$

What this means is that for x near 1 (either side), if some change is made in the system, the effects of these changes die out slowly (*10*).

The percolitis model allows some simple exercises, for example, finding the (nonexponential) asymptotic behavior of $\rho(t)$ for x

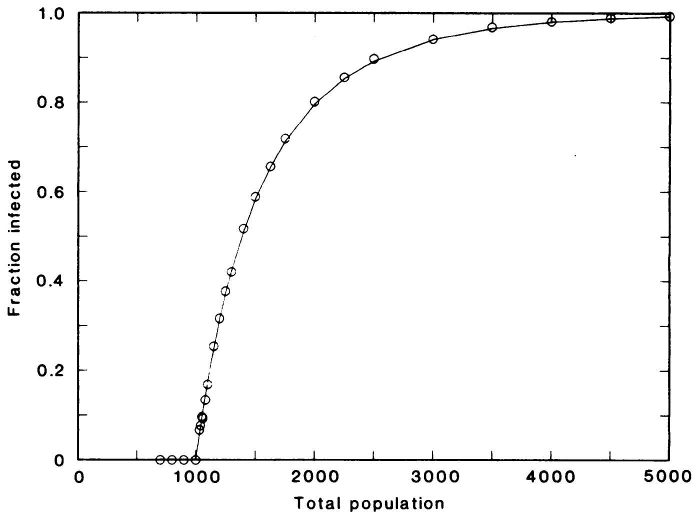


Fig. 3. The fraction of the population infected with percolitis compared to the total population (infection probability of 0.001).

exactly equal to 1. In a similar spirit we have produced computer simulations in which a random number generator is used both to determine whether successful transmission of percolitis occurs and to try numerous experimental inoculations. These results are summarized by plotting $\rho(t \to \infty)$ for various x in Fig. 3. That figure also shows the solution $\bar{\rho}(x)$ of Eq. 4, which is seen to be an excellent fit to the data.

Galaxy Models as Percolation

Perhaps the most remarkable feature of our epidemiological discussion was how little medical knowledge was needed to reach an important qualitative conclusion. If the probability of transmission is approximately equal to the inverse population, the system is very slow to settle down, and large fluctuations occur. Astrophysical details turn out to be no more essential to a qualitative derivation of galactic structure than medical details were for percolitis, although with some of these details more specific information can be extracted. This ability to make important qualitative statements in the absence of conventionally relevant details, although familiar in statistical physics, is only slowly gaining acceptance in the wider scientific community.

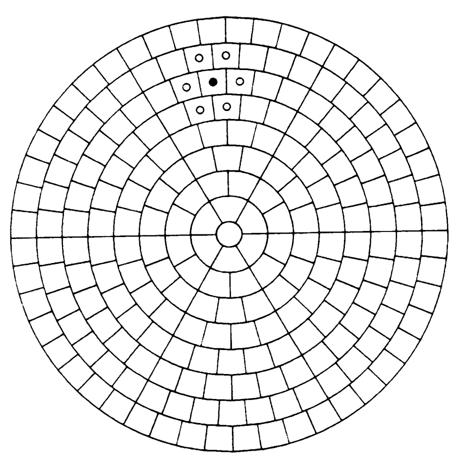
The basic astrophysical feature that allows use of the percolation model in galaxies is propagating star formation (*11, 12*). A region of the galaxy may have the ingredients needed for star formation—gas, proper temperatures, and densities—but, if left alone, nothing happens. However, if a shock wave from a supernova passes through the gas, there is a good chance a molecular cloud will form so that stars may condense (*13, 14*). That supernova is itself the result of an earlier nearby episode of star formation. Thus in a sense, a region of the galaxy is like a percolitis-susceptible individual: without a source there is no percolitis, and the source is a percolitis victim of a previous time step. This is the "propagating" part of propagating star formation. But there is another significant aspect to the model. We do not try to say exactly which individuals will get the disease. Similarly, we do not look closely at which regions have just the right gas densities or how they are oriented relative to the exploding supernova. Instead we summarize all the uncertainty and variability in a single parameter P, the probability that a supernova explosion in one region gives rise to an episode of star formation in its neighbor. This is stochastic self-propagating star formation.

Galactic Simulation

The percolitis example is a particularly simple type of percolation for which a closed form solution is possible. In general, complete solutions cannot be obtained, so either approximate solutions are constructed or computer simulations are performed.

Our structure is richer than that of percolitis since we specify the geometry on which this stochastic process occurs. A disk galaxy is mostly a two-dimensional structure, and we break it into regions with linear dimension on the order of the distance traveled by a shock wave on its way to initiate star formation. We take a polar grid (Fig. 4) of a number of rings and divide each ring into a number of cells such that each cell has the same size. A cell corresponds to a region of space the size of a giant molecular cloud or galactic stellar cluster (100 to 200 pc). The number of rings chosen depends on the size of the galaxy being modeled (five rings per kiloparsec radius). Each ring is allowed to rotate following the observed rotation velocity of the galaxy being modeled. Galaxies do not rotate rigidly; in fact, observations show that over most of a galaxy the circular velocity (rather than the angular velocity) is approximately constant (*15*). This introduces shear since the angular velocity decreases with radius. A typical region has six neighbors that will change as the annuli shear. As for percolitis, we take discrete time steps (of about 10^7 years duration). A region containing active stars (at t) has some probability P of inducing star formation in its immediate neighbors at time $t + 1$.

The simulation proceeds as follows. We start by putting some young star clusters into a small number of cells at random. (The



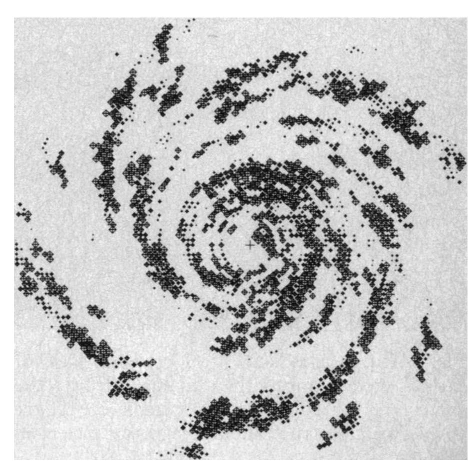


Fig. 4 (left). The polar grid used for galaxy simulations. Each cell has the same area and has, on average, six nearest neighbors (those with contiguous boundaries). The filled circle denotes an active young region of star formation. On the next time step it may induce star formation in the cells containing open circles. As time passes, the neighbors in adjacent rings will change because of the differential rotation. Fig. 5 (right). A typical galaxy simulation for $P = 0.18$, which has 49 rings, a flat rotation curve with a circular velocity of 200 km/sec, and a cell size of 200 pc.

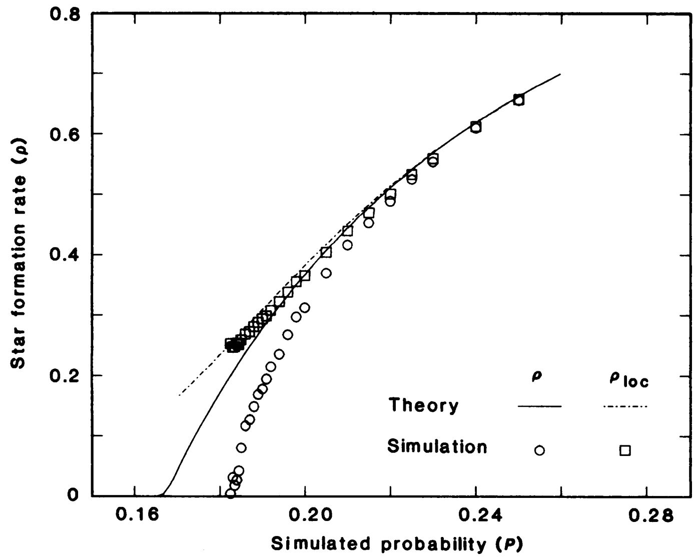


Fig. 6. Star formation rate as a function of P. Results are shown for both mean field and local models.

initial state is generally unimportant since the simulation reaches steady state rapidly.) These clusters are permitted to create new clusters in adjacent cells with a probability P. This is done for all the young clusters, and then the galaxy is rotated appropriately. The clusters just created will in turn create another set of clusters on the next time step. This process is repeated as many times as desired to simulate the evolution of a galaxy.

That is the model, or at least its simplest version. Figure 5 shows the result of a computer simulation for P near 0.18 with a velocity profile $v(r)$ = constant. The resemblance—at least at a subjective level—to galaxy photographs is remarkable. Before discussing improvements, variations, and explanations we want to emphasize just how remarkable this is. First, since our rotating galaxy has shear, one might say that the effect we get is no more than that of a cook stirring batter in which gobs of chocolate have been dropped. Not so. Within a few rotations the gobs will have been spread to unrecognizable thin strands. Something in our stochastic process is guaranteeing the appearance and reappearance of gobs as well as the occurrence of stretched antigobs—spaces between well-articulated arms. The second important aspect is that our model is local: only immediately neighboring regions communicate. And yet the structure we get spans the entire galaxy.

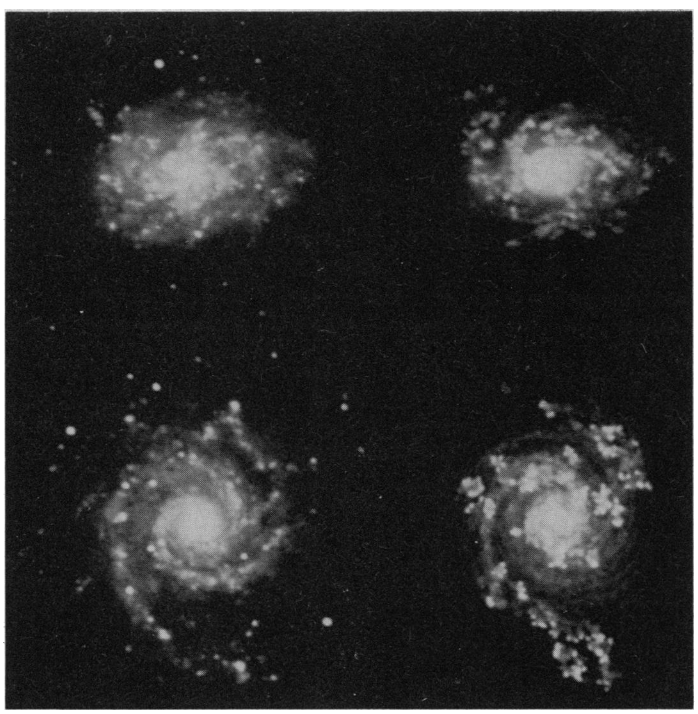


Fig. 7. The galaxies NGC 7793 (top) and NGC 628 (bottom). The left-hand images were scanned and digitized from blue plates taken by D. M. Elmegreen at the 1.5-m telescope at Cerro Tololo Inter-American Observatory, Chile. The right-hand images are propagating star formation simulations.

Propagating Star Formation as Percolation

To put quantitative teeth into the phase transition explanation of these phenomena, we first do some of the same arithmetic that we did for percolitis (*9*). Let $\rho(t)$ be the fraction of regions in which star formation is occurring at time t. For some particular region the probability that it does not have star formation at $t + 1$ is $1 - \rho(t + 1)$. But this requires failure for all attempts at ignition by any of its time t neighbors that had star formation. The likelihood that a given neighbor fails to ignite it is $1 - \rho(t)P$, since a successful ignition requires both that the neighbor have star formation and that the attempt itself succeed. Now suppose (falsely) that the presence or absence of star formation among the neighbors is mutually uncorrelated, an approach known as mean field theory. Then for the (typical) six-neighbor situation

$$1 - \rho(t + 1) = [1 - P\rho(t)]^6 \quad (7)$$

Let us continue to ignore correlations to see where our predictions lead. As for percolitis, there is an equilibrium density satisfying

$$\bar{\rho} = 1 - (1 - P\bar{\rho})^6 \quad (8)$$

Again $\bar{\rho} = 0$ is always a solution, but for $P > 1/6$ any $\rho(0)$ different from 0 tends to a positive nonzero solution so that we get a mean field critical threshold $P_c^{MF} = 1/6$. Moreover, the relaxation of $\rho(t)$ to its equilibrium value can be calculated from Eq. 7 and exhibits the same dramatic slowdown near P_c as for percolitis (Eq. 6).

Next we check the theoretical predictions of Eq. 8 against "experiment," that is, against simulations. In Fig. 6 it is seen that $\rho(t \to \infty)$ for various runs is in excellent agreement with $\bar{\rho}$ for $P \geq 0.22$, but for $P \leq 0.2$ the simulation value drops significantly below $\bar{\rho}$, and the actual value of P_c is closer to 0.18 than to 1/6. The discrepancy is easy to understand. Equation 8 was derived through the neglect of correlations. But (positive) correlations tend to reduce star formation. The expected number of descendents of two isolated star-filled regions is $12P$ while for two adjacent regions there is duplication of effort in attempting to ignite their common neighbors, and the expectation is only $12P - 2P^2$. This effect is most pronounced near P_c since it is there that correlations are largest.

Confronted with a theory that is good for large P but poor near P_c, we look to the physical phenomenon to see if a better theory is needed. At an early stage of this research we found that the best galaxies—the simulation results most pleasing to the eye, most resembling nature—were generated for P slightly above P_c. So we must concern ourselves with the critical phenomenon (the neighborhood of P_c) and also consider why nature seems to have chosen P near P_c. It has not been necessary to use the most sophisticated tools of the modern theory of phase transitions. By a simple calculation we can determine what is the most important correlation that our derivation of Eq. 8 neglects. Clearly a region with six vacant neighbors cannot form stars. But in mean field theory the actual occupation is replaced by the average $\rho(t)$ so that stars can form anywhere. Suppose we apply mean field theory only to those portions of the galaxy containing stars. That is, regions entirely devoid of neighboring stars are excluded. For these relatively more populated areas we define a local density ρ_L and derive (*9*) a mean field prediction for ρ_L. Figure 6 shows that the results are now excellent, and we deduce that the major effect of the critical enhancement of correlations is to break the galaxy into clumps of relatively populated regions (within which no criticality is evident) and large completely empty areas.

This observation is the key to galactic structure, at least for those galaxies in which the stochastic mechanism is dominant. Recalling our remarks about cooks, batter, and chocolate, we now see that P is just above P_c, which causes a clumping both of occupied regions and of completely unoccupied regions. Even as they are stretched by the shearing rotation of the galaxy, the clumps tend to re-form and to be stretched into new arms; arms form, some merge, some split, some die out, but the general pattern of arms is always present.

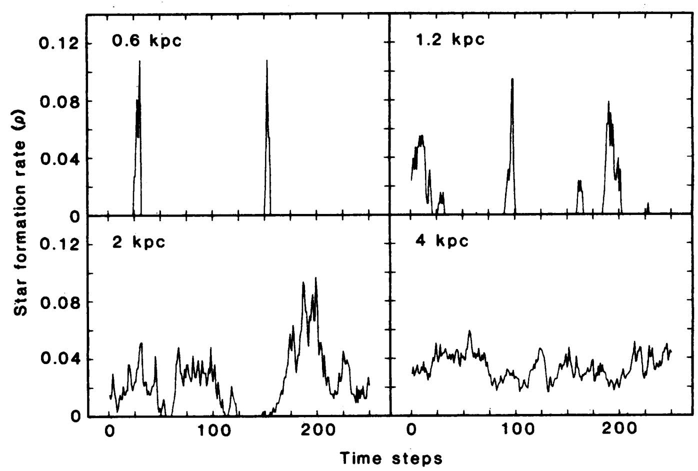


Fig. 8. Propagating star formation simulation of dwarf galaxies. The radii in kiloparsecs of the galaxies are given at the upper left of each panel.

The Full Stochastic Self-Propagating Star Formation Model

As emphasized above, we need few astronomical details to obtain the results of Figs. 5 and 6. However, the addition of such detail allows propagating star formation to make a number of statements of astronomical significance. Let us extend the model to consider matter in the galaxy to be composed not only of a disk of stars but of two disks of gas as well; one of dilute atomic hydrogen and the other of molecular hydrogen (*16*). The essential event is identified as molecular cloud formation, since this always leads to star formation. The simulation is now changed to the following sequence. A cell having a new cluster is allowed to initiate activity in its neighbors as before. However, the probability for molecular cloud formation is now taken as proportional to the density of atomic hydrogen since it is from this gas that the molecular clouds are formed. Once the gas has become a molecular cloud, it is unavailable for the creation of new clouds. The molecular clouds begin to form stars, the energetic processes of which eventually destroy the cloud (*17, 18*). A small percentage of the cloud is condensed into stars, but the rest of the cloud is dispersed into atomic hydrogen, allowing the process to repeat. This process leads to the feedback mechanism, which is responsible for keeping the galaxy near the critical point of the percolation phase transition. For example, if a region of the galaxy undergoes an increase in the cloud formation rate, a large amount of the atomic hydrogen will be converted to molecular hydrogen and the cloud formation rate must decrease locally because of the exhaustion of gas. If, on the other hand, the cloud formation rate decreases, the eventual breakup of the molecular clouds will create a region rich in atomic hydrogen and ripe for cloud formation when activity returns to the region. This feedback control results in the pinning of the cloud formation rate to the phase transition region.

For this feedback mechanism to work well, the average lifetime of a molecular cloud (*19*) should be long compared to the time step of the process. This is necessary in order to maintain the gas in this region in a form (molecular clouds) not susceptible to further sweeping up by the shock waves. Since the time step is about 10^7 years, the molecular cloud lifetime should be 10^8 years or more. The actual lifetime is not well known, but this value is consistent with most estimates (*16*).

Inclusion of the gas allows us to discuss its behavior. First, the critical region is defined by a critical atomic gas density; therefore, the atomic hydrogen content of a galaxy should be roughly a constant, independent of position in the galaxy (within the region where stars are actively being formed) (*16, 20*). This feature has been observed (*21, 22*), but no explanation had been offered before propagating star formation. Second, the molecular gas must be given by the total gas distribution of the galaxy minus this constant and must have the same distribution as the blue light from the galaxy since the molecular gas is where the new stars are being formed (*16, 20*). These features also agree with observations (*23, 24*).

Model galaxies formed by the full simulation (including gas) are shown in Fig. 7 alongside of pictures of the galaxies they are supposed to represent. The positions of the arms cannot be exactly reproduced since the evolution is random. The shape of the arms, the density of star formation, and the general appearance, however, are well reproduced by propagating star formation (*25*). The models of Fig. 7 are more realistic than those of Fig. 5; because the gas content of a galaxy decreases with radius, the luminosity also decreases with radius and terminates in a fairly sharp edge. Thus propagating star formation yields, in a natural way, an explanation for the observed sharp optical cutoff (*16, 26*); the cutoff is the radius at which the gas density drops so low that the effective value of P falls below P_c.

Dwarf Galaxies

There is another class of galaxies that illustrates the importance of fluctuations near the critical point of a phase transition (*8*). For a large galaxy it is almost always possible to find a region with enough atomic hydrogen to allow star formation to propagate. The star formation rate may fluctuate, but the chance that it will go to zero becomes exponentially small as the size of the galaxy increases. For very small galaxies, however, it is possible for a fluctuation to terminate star formation. If some phenomenon exists that can spontaneously restart the process, such as a collision of two atomic hydrogen clouds, the small galaxy will have the characteristic of a burster, which means that periods of active star formation will be interspersed with inactive periods. This behavior is shown in Fig. 8 where the evolution over time is shown for four different galactic sizes (*27*). This behavior corresponds with observations; while large galaxies fall into a few well-defined classes, dwarf galaxies vary greatly. Some are so luminous that they would consume all their gas in less than a billion years if the observed rate were constant. Other galaxies that look the same from the point of view of size, mass, specific content, and dynamical properties have had no star formation for billions of years. Bursting is the cause for this variation (*28*);

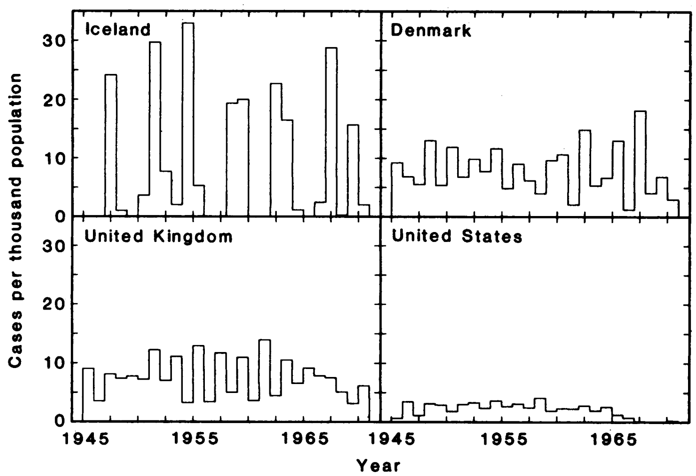


Fig. 9. Annual cases of measles per 1000 of the population for the period 1945–1970 in Iceland, Denmark, the United Kingdom, and the United States. These data are adapted from Cliff and Haggett (*29*) and are averaged over 12-month periods to eliminate seasonal variations. The decrease in the United States after 1967 is due to the large-scale introduction of a vaccine.

the active galaxies are those caught in a burst while the inactive ones are caught between bursts. Propagating star formation gives the reason for the existence of bursting.

An example of how the same percolation phenomena arise in quite different areas is given in Fig. 9. This is a study of the occurrence of measles in various size populations (*29*); it parallels the study in Fig. 8 of star formation versus galaxy size. The resemblance is not accidental.

Dynamical Effects

The main effect of gravity is to organize the mass distribution of the galaxy as a whole. After that, propagating star formation takes over and controls the conversion of gas into stars and creates the stellar distributions that we see today. This does not mean that gravity is unimportant in the determination of galactic structure. There are a number of places where gravitational dynamics plays a leading role: It is believed that in many galaxies a massive black hole exists in the center. Associated with these galaxies are highly energetic events that are driven by the gravitational energy released by mass falling into the black hole. Gas streaming is also observed in some galaxies, that is, noncircular motions of the gas. To understand these effects gravity must be directly taken into account.

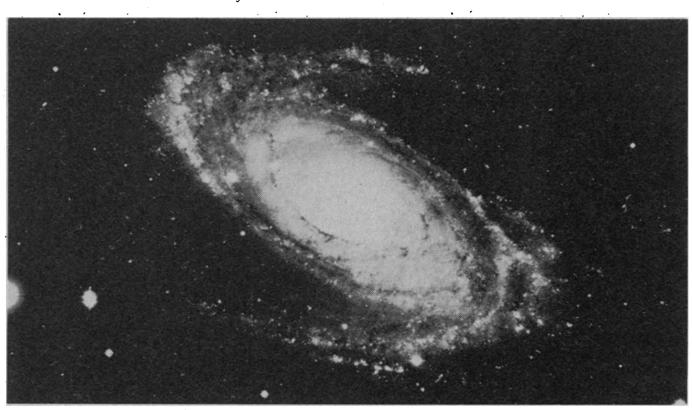


Fig. 10. The spiral galaxy NGC 3031. [With permission of the Carnegie Institution of Washington (*30*)]

The disk galaxies of Fig. 7 have many arms but are not particularly symmetric. Two-armed symmetric galaxies also exist whose arms are excited by gravitational interactions (Fig. 10). In a differentially rotating disk of gas and stars a rigidly rotating spiral perturbation, called a spiral density wave (*1, 2*), can be created. It is a rigidly rotating component of the gravitational potential into which gas and stars can fall. Therefore, the galaxy can exhibit a symmetric two-armed pattern that reflects the spiral gravitational potential. However, even in this case the young stars in the spiral density wave will go on to create more stars by propagating star formation; this is the source of the spurs and the branching of the main arms of Fig. 10.

The important point of our approach is that dynamics is not necessary for many aspects of galactic structure. Propagating star formation is able to provide many of the observed properties of galaxies and may be the dominant mechanism for converting gas into stars. Dynamic effects can also play a role and modify the form of the galaxy but propagating star formation continues over the whole star-forming life of the galaxy.

Conclusions

A contemporary theme in physics is the independent and unifying role of collective behavior. That is, systems composed of many individual constituents will exhibit common properties, even though there may be great differences in the nature of the constituents and in their mutual interaction. A striking example of such an emergent feature is the phenomenon of phase transitions and, in particular, the divergence of correlation lengths at the onset of continuous phase transitions. The divergence is a bootstrapping of local effects to scales that may be orders of magnitude greater than the basic interaction range.

In this article we have presented evidence for galactic structure being such a phenomenon. Despite ignoring details necessary for calculating the probability of induced star formation, and despite the fact that such induction is short range on galactic scales, we find that, because of the proximity to a continuous phase transition, it is enough to assume only that star formation is propagating in order to recover the main features of galactic structure.

REFERENCES AND NOTES

1. C. C. Lin and F. H. Shu, *Astrophys. J.* **140**, 646 (1964).
2. R. Wielen, *Publ. Astron. Soc. Pac.* **86**, 341 (1974).
3. A. Toomre, *Annu. Rev. Astron. Astrophys.* **15**, 437 (1977).
4. J. A. Sellwood and R. G. Carlberg, *Astrophys. J.* **282**, 61 (1984).
5. R. G. Carlberg and W. L. Freedman, *ibid.* **298**, 486 (1985).
6. This model has been simplified for the purpose of illustrating the essentials of percolation and ignores many factors entering the theory of epidemics [N. S. Goel and N. Richter-Dunn, *Stochastic Models in Biology* (Academic Press, New York, 1974), chap. 5 and references therein].
7. D. J. Thouless, in *Ill-Condensed Matter*, R. Balian, R. Maynard, G. Toulouse, Eds. (North-Holland, Amsterdam, 1979), p. 1.
8. For finite N the disease always dies out eventually, but the expected time for this grows exponentially with N.
9. L. S. Schulman and P. E. Seiden, *J. Stat. Phys.* **27**, 83 (1982); in *Percolation Structures and Processes*, G. Deutscher, R. Zallen, J. Adler, Eds. (Hilger, Bristol, and Israel Physical Society, Jerusalem, 1983), p. 251.
10. A related feature is the occurrence of large fluctuations for x near 1, and another way to look at the divergence of ξ is as the characteristic size or duration of a fluctuation.
11. M. W. Mueller and W. D. Arnett, *Astrophys. J.* **210**, 670 (1976).
12. P. E. Seiden and H. Gerola, *Fundam. Cosmic Phys.* **7**, 241 (1982).
13. B. G. Elmegreen, in *Birth and Evolution of Massive Stars and Stellar Groups*, W. Boland and H. van Woerden, Eds. (Reidel, Dordrecht, 1985), p. 227.
14. ———, in *Star Forming Regions*, M. Peimbert and J. Jugaku, Eds. (International Astronomical Union Symposium No. 15, Reidel, Dordrecht, in press).
15. V. C. Rubin, *Science* **220**, 1339 (1983).
16. P. E. Seiden, *Astrophys. J.* **266**, 555 (1983).
17. B. G. Elmegreen and D. M. Elmegreen, in *Interstellar Molecules*, B. H. Andrew, Ed. (International Astronomical Union Symposium, No. 87, Reidel, Dordrecht, 1980), p. 191.
18. B. G. Elmegreen, in *Protostars and Planets II*, D. C. Black and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, 1985), p. 33.

19. The actual time of importance is the total recycling time of the cold atomic gas. This includes the actual lifetime of the molecular cloud plus the time it takes a cloud's gaseous remnants to reach a low enough temperature to allow recollection by another shock wave.
20. P. E. Seiden, L. S. Schulman, B. G. Elmegreen, *Astrophys. J.* **282**, 95 (1984).
21. D. H. Rogstad and G. S. Shostak, *ibid.* **176**, 315 (1972).
22. M. A. Gordon and W. B. Burton, *ibid.* **208**, 346 (1976).
23. J. S. Young and N. Scoville, *ibid.* **258**, 467 (1982).
24. P. M. Solomon *et al.*, *ibid.* **266**, L103 (1983).
25. The thin wispy, almost circular, features in the simulated galaxies are due to the fact that only purely circular rotations are used in the simulations. The random noncircular component of velocities in a real galaxy smears out these features.
26. P. C. van der Kruit and L. Searle, *Astron. Astrophys.* **95**, 105 (1981).
27. H. Gerola, P. E. Seiden, L. S. Schulman, *Astrophys. J.* **242**, 517 (1980).
28. L. Searle, W. L. Sargent, W. G. Bagnuolo, *ibid.* **179**, 427 (1973).
29. A. Cliff and P. Haggett, *Sci. Am.* **250**, 138 (May 1984).
30. A. Sandage, *The Hubble Atlas of Galaxies* (Carnegie Institution of Washington, Washington, DC, 1961).

Cannibalism in the Neolithic

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Cannibalism is a provocative interpretation put forth repeatedly for practices at various prehistoric sites, yet it has been so poorly supported by objective evidence that later, more critical reviews almost invariably reject the proposal. The basic data essential to a rigorous assessment of a cannibalism hypothesis include precise contextual information, analysis of postcranial and cranial remains of humans and animals, and detailed bone modification studies. Such data are available from the Neolithic levels of the Fontbrégoua Cave (southeastern France) where several clusters of human and animal bones have been excavated. The analysis of these bones strongly suggests that humans were butchered, processed, and probably eaten in a manner that closely parallels the treatment of wild and domestic animals at Fontbrégoua.

DESPITE ABUNDANT LITERATURE ON THE SUBJECT [see bibliographies in (*1*) and (*2*)], the occurrence of human cannibalism in Old World prehistory remains an open question. We are concerned here with dietary cannibalism—the use of humans by humans as food—evidence for which is found in patterns of bone modification and discard. The key features of dietary cannibalism involve close, detailed similarities in the treatment of animal and human remains. If it is accepted that the animal remains in question were processed as food items, then it can be suggested by analogy that the human remains, subjected to identical processing, were also eaten.

Evidence of deliberate discard, cut marks, and bone breakage to extract marrow are criteria used to deduce that animal bones at archeological sites were food refuse; these same criteria have been used to interpret isolated and scattered human bones at various prehistoric sites as evidence of cannibalism (*3*). However, in many cases such an interpretation is weakened by doubts about whether humans caused the observed damage and by lack of precise contextual evidence. Poorly recorded excavation data, insufficient documentation and analysis of damage and discard patterns, and the high frequency of pre- and postdepositional disturbances by nonhuman agents at archeological sites have fueled these doubts. These are the main reasons why explanations of cannibalism are often ignored or rejected (*4–6*).

It has been suggested that human bones with cut marks are not the remains of cannibal meals but the traces of funerary rites involving the handling of corpses without consumption of human tissues (*2, 7*). Secondary burial may mimic cannibalism if it includes active dismemberment and defleshing of the body; however, the absence of bone breakage for marrow and the mode of bone disposal will set it apart from dietary cannibalism (*8*).

A hypothesis of dietary cannibalism must be based on four types of evidence: (i) Similar butchering techniques in human and animal remains. Thus frequency, location, and type of verified cut marks and chop marks on human and animal bones must be similar, but we should allow for anatomical differences between humans and animals; (ii) similar patterns of long bone breakage that might facilitate marrow extraction; (iii) identical patterns of postprocessing discard of human and animal remains; (iv) evidence of cooking; if present, such evidence should indicate comparable treatment of human and animal remains.

We studied recently excavated materials from a Neolithic cave site in southeastern France. A combination of excellent bone preservation, primary depositional context, and fine excavation techniques allows us to present evidence of cannibalism at the site.

The Site and Bone Occurrences

The Fontbrégoua Cave (*9*) is divided into three spatially discrete areas: the porch, the main room, and the lower room (Fig. 1). All areas have yielded skeletal and cultural materials: pottery, stone tools, remains of domestic and wild faunas, carbonized seeds of domestic wheat and barley, and human remains.

Stratigraphic and cultural evidence suggest that during the 5th and 4th millennia B.C. the cave was repeatedly used as a temporary

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