Articles

Star Formation in Irregular Galaxies

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Irregular galaxies can be viewed as laboratories for studying the processes of star formation. This class of galaxy, unlike the more familiar spiral galaxies, forms stars without spiral arms and does so from a chemically less-evolved interstellar medium. In this article the problems associated with star formation in irregular galaxies are outlined and their relevance to our understanding of star formation as a general astrophysical process is discussed.

IN A NORMAL DISK GALAXY STAR FORMATION IS A CONTINUOUS process that began when the galaxy first condensed from the expanding universe and will end when the galaxy runs out of gas from which to form stars. The rate of star formation determines how fast a galaxy evolves, and the star formation process can, in principle, affect the distribution of stellar masses that are formed. Hence, star formation is a fundamental, but not yet well-understood, process. Progress is being made in the study of star-forming regions on very small scales, such as the Orion region in our own Milky Way. But there is much that we do not understand about tying the local processes to the global properties of galaxies.

The best known class of star-forming galaxies is the spirals (Fig. 1). Their luminous material is organized in a flattened disk at the center of which is a spheroidal nucleus or bulge. The disk of these galaxies contains gas, dust, stars, and spiral arms that are often symmetric and generally delineated by bright regions of ionized gas that mark where massive stars have just formed. There is, however, another class of disk galaxies with ongoing star formation—the irregulars (Fig. 2). These galaxies, as their name implies, are chaotic in appearance, lacking the symmetrical spiral patterns. A galaxy can look chaotic because it has been disrupted by a collision with another galaxy. However, there exist normal, noninteracting, intrinsically irregular systems, and it is this class of galaxies that we discuss here.

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Compared to spiral galaxies, the irregulars are smaller, less luminous systems. The optical light that they emit is generally bluer in color, which indicates the relative importance of a hot, young stellar component. A larger fraction of the mass of irregulars is in the form of gas, the fuel for star formation, and this gas contains relatively less of the heavy elements (that is, heavier than He), the products of stellar evolution. These latter two characteristics indicate that the irregulars are less evolved than spirals in the sense that less of their mass has been locked up in or processed through stars. Because they lack spiral density waves, the irregulars are also somewhat simpler systems (*1*).

In the past the spiral arms that mark density waves in the disks of spiral galaxies were believed to play the key role in triggering galactic star formation. As the wave passes through the disk, it compresses the interstellar gas into dense clouds from which stars would precipitate. The irregular galaxies, however, have shown that star formation can take place without spiral density waves. As Bok pointed out many years ago (*2*), because the irregular galaxies lack density waves, they are very useful as laboratories in which to study star formation. By looking at star formation under the different conditions present in irregulars, we can learn what factors affect star formation processes in galaxies.

The disadvantage of using irregular galaxies is that they are much more distant than local star-forming regions in our own galaxy. We can study detail in our own galaxy that would not be distinguishable at all in any other galaxy because of its distance from us. Thus, we are limited to assessing the intrinsically local process of star formation in irregular galaxies from their regional or global properties. Unfortunately, the irregulars have been far better at posing puzzles than we have been at solving them. The aim of this article is to

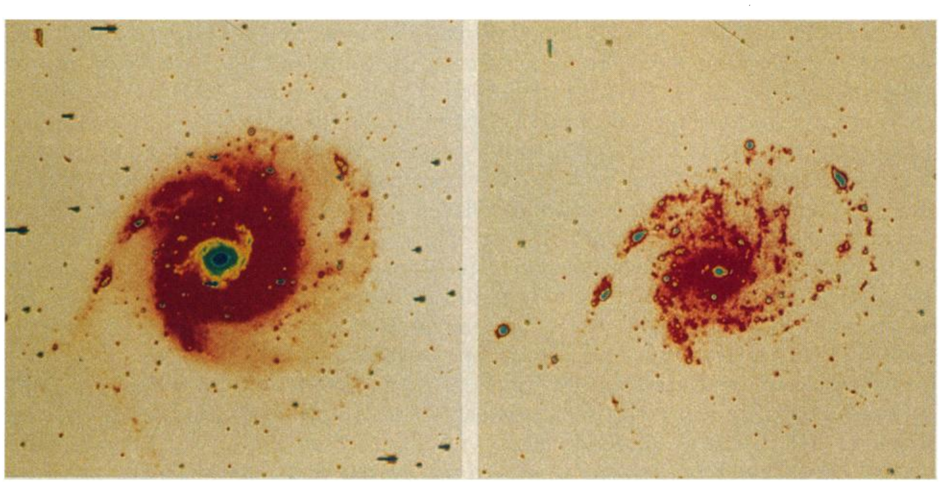

Fig. 1. M 101 is an example of a spiral galaxy. This pair of images was obtained with a charged coupled device attached to a Takahashi ϵ200 telescope that was mounted on the side of the Lowell Observatory 1.1-m telescope. (**Left**) Image taken through a filter that passes green light from stars. (**Right**) Image taken through a narrow-band filter that passes emission from ionized gas in star-forming regions. This image and several later ones are shown in false colors to enlarge the dynamic range that can be displayed.

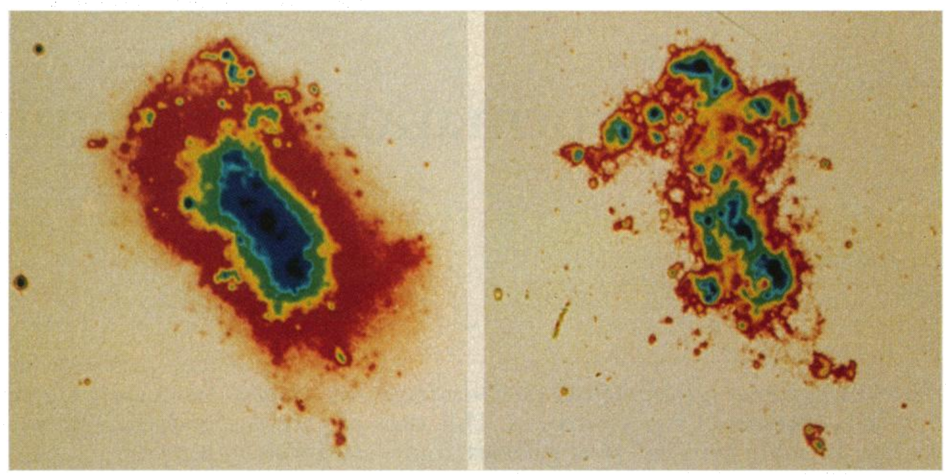

Fig. 2. The irregular galaxy NGC 4449 is shown. (**Left**) Image of the galaxy obtained through a filter that passes the blue starlight. (**Right**) Image obtained through a narrow-band filter that passes primarily emission from the ionized gas and has been processed to remove any starlight from the galaxy. Thus, the right image shows where the current regions of star formation are located. Both images were obtained with a charged coupled device on a 0.9-m telescope at Kitt Peak National Observatory.

outline the problems associated with star formation in irregular galaxies and to explain why they are relevant to our understanding of star formation as a general astrophysical process.

Star Formation Basics

It is easy to understand empirically why star formation is such a complex affair. The interstellar matter from which stars form contains gas in a wide variety of physical states, ranging from hot, supernova-heated bubbles with $T \sim 10^6$ K to dense cores of molecular clouds with $T \leq 20$ K. Furthermore, the gas is in a dynamic state as a result of energy input from stars and is interlaced with magnetic fields, fluxes of cosmic rays, and dust particles. Indeed, we should be surprised if such a medium were to prove stable against the growth of density perturbations. That the instability of interstellar gas should be so highly nonlinear, however, is a surprise. A typical galactic disk contains cool, potentially star-forming gas with a mean density of ~ 1 atom cm^{-3}. Stellar densities are of the order of 1 g cm^{-3}; so to make stars we must amplify the mean density of the interstellar medium by a factor of $\sim 10^{24}$!

Our conceptual model is that stars form in interstellar clouds where self-gravity can produce the required huge density compression factors. On the galactic scale, the cloud formation process holds the key to star formation. A number of authors have considered the types of instabilities in interstellar gas that might lead to the production of star-forming clouds. Some of these mechanisms are tied to galactic kinematic processes, such as differential rotation or spiral density waves, that are not important in most irregular galaxies, and others to the density of the gas itself (*3*).

One class of instability, gravitational instability, is certainly inescapable in any galaxy. This instability will set a minimum level of cloud formation, unless it is offset by another process, such as the ability of magnetic fields to resist compression. In general discussions of these classes of unstable processes, the time scale for cloud production, τ_{SF}, will be proportional to μ^{-1}, where μ is the mean mass surface density of the gas in $M_\odot$ $parsec^{-2}$ (a parsec is 3×10^{13} km). The star formation rate per unit area will then scale as the ratio of gas supply to time scale; $\mu/\tau_{SF} \propto \mu^2$ (*4*).

The basic model for star formation processes thus predicts that the galactic star formation rate per unit area should depend on the square of the galactic gas surface density. In this class of model, star formation rates must steeply decline over time in galaxies of fixed mass and size in a predictable way that can be tested by quantitative measurements of current and past star formation rates in galaxies. There are indications that this model is not, in fact, entirely correct.

An additional aspect of the star formation process that must be considered in global discussions is the efficiency factor, ϵ, which is usually defined as stellar mass formed divided by the initial cloud mass. The numerical value of ϵ is estimated from studies of individual star-forming complexes in the Milky Way. It varies considerably from cloud to cloud, but globally the average is $\sim 2\%$ (*5*). Since ϵ is small, it immediately follows that a typical region within a galaxy has experienced many star-forming "episodes." For a typical irregular in which the mass of stars is approximately equal to the mass of gas, more than 13 star-forming episodes must have occurred over the life of the galaxy. In a spiral more than 50 star-forming events must have taken place in typical disk locations in order to yield the observed low gas-to-stellar mass ratios. Of course, these models are based on the simple assumption that star formation in our vicinity of the Milky Way is representative of conditions in most galactic disks, which we must eventually validate.

Global Star Formation Rates

Because most irregular galaxies are so distant, we cannot readily distinguish all of their individual stars; and only in the very nearest systems can the brightest, and hence most massive, stars be identified. Therefore, we must find a means other than counting stars to learn about how fast a galaxy is forming them. The most massive stars ($\geq 10\ M_\odot$) are the shortest lived, so they act as tracers of the most recent star formation activity. They also put out prodigious fluxes of ultraviolet photons that ionize the gas around them. When stars form, most of the original gas cloud is eventually dispersed, but for a while it shines under the bath of ultraviolet photons from the massive stars that just formed.

These clouds of photo-ionized gas, called H II regions, tell us where massive, recently born stars are located. By relating the intensity of the optical atomic line cooling radiation produced by ionized gas in H II regions to the number of stellar ultraviolet photons needed to maintain the hot ionized gas, we can infer the number of massive stars that have formed in the past 10 million years or so. There are other methods of measuring the quantity of massive stars such as with the far-infrared luminosity of the dust that is heated by the massive stars, the ultraviolet luminosity of the stars themselves, and the thermal radio continuum emission of the ionized gas (*6*). These different methods agree remarkably well for irregular galaxies.

This is not the whole story, however. Stars of all masses form, down to $\sim 0.1\ M_\odot$, but only the massive stars ionize their natal gas. In galaxies that are near enough to count individual stars (including our own), the number of stars formed as a function of the mass of the star can be represented by a power law. This function, the initial

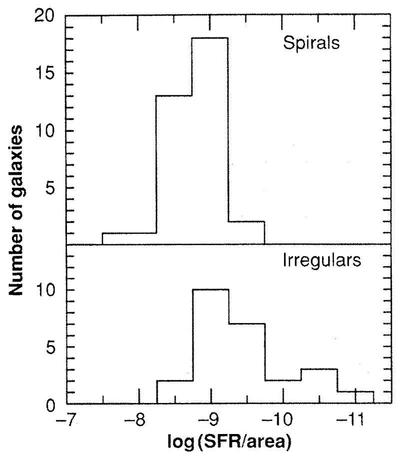

Fig. 3. This histogram shows the distribution of star formation rates (SFR) for irregular (**bottom**) and late-type spiral (**top**) galaxies. In order to compare different galaxies the star formation rate must be normalized to some measure of the size or mass of the galaxy. Here the rate (in $M_\odot$ per year) is normalized to the optical area of the galaxy, measured in square parsecs. One can see that irregular galaxies can form stars at rates comparable to those of spiral galaxies. Nevertheless, the star formation rates cover a large range in values.

mass function, predicts that the smaller the mass of the star, the more numerous they are (7). So, for example, for every 15 $M_\odot$ star that is formed, ~50 stars with the mass of our sun are also formed. Thus, if we measure the number of massive stars formed from the presence of the ionized gas, we can use the initial mass function to infer the total number and mass of stars recently formed.

The "slope" (that is, the exponent of the power law) of the initial mass function, however, is controversial. We do not understand the physical basis for it, so we do not know under what conditions it might change. Is the initial mass function different in different galaxies? The nearest galaxy outside our own is the Large Magellanic Cloud, visible from the southern hemisphere. It is an irregular galaxy, although it is also interacting with the Milky Way. The initial mass function in the Large Magellanic Cloud has been studied as far down as ~1 $M_\odot$. Stars of lower mass are too faint to observe reliably with present-day technology. Down to 1 $M_\odot$, the initial mass function seems to be like that of the Milky Way, although uncertainties are large (7). Thus, we tentatively assume that the Milky Way initial mass function is applicable to irregular galaxies and use it to infer the rate at which a galaxy is turning its interstellar gas into stars.

If we measure star formation rates in this way, we find that irregular galaxies can be just as successful as spiral galaxies at forming stars (*8*) (Fig. 3). This implies that spiral density waves, which spiral galaxies have and irregulars do not, are not necessary for a vigorous production of stars. Any model of star formation, therefore, that relies solely on density waves for producing massive stars cannot be complete. And, in recent years the role of density waves as a star formation trigger is even being questioned for spirals (*9*).

There is a second interesting inference to be made from Fig. 3. The irregulars do not all have the same star formation rate even when it is normalized to the size of the galaxy. Galaxies with otherwise very similar global properties span a range of a factor of 300 in their star formation activity. This raises the question: What governs the overall star formation activity of a galaxy? The observational evidence suggests that these galaxies have evolved at roughly constant rates over their lifetimes (*10*). What then distinguishes a galaxy with a low star formation rate from one with a high rate? Plots of star formation rates against various properties of the galaxies, such as the gas to blue luminosity ratio, the fraction of the mass of the galaxy that is in gas, and the rotation of the disk, fail to reveal any correlations. This suggests that local properties are more important than the global measurements that we have made, and the local properties somehow conspire to give us the global galaxy. For example, perhaps it is more important how the gas is distributed than how much gas is in a galaxy, or perhaps the details of the velocity field are a key. Whatever the factors are that govern the rate at which a galaxy forms stars and hence evolves, we have not yet identified them, and this is an outstanding question to be answered.

Feedback Processes

Our empirical picture of star formation in irregulars is like that of a pot of oatmeal bubbling on the stove: star formation moves around the galaxy with time. One region will form stars, deplete the gas locally, and die down; then later another region will become active (*11*). However, the "bubbling" is not entirely random. The star formation rate is not only constant over the lifetime of the galaxy; but, on average over long periods of time, it is constant as a function of radius within the galaxy.

When density waves were deposed as the sole mechanism for initiating star formation, that left the question of what does trigger a region to form stars in irregular galaxies. One model that addresses this question, the stochastic self-propagating star formation (SSPSF) model, depends on the newly formed stars themselves (*12*). When stars, particularly massive stars, are born, it is a traumatic event for the surrounding interstellar gas. The massive stars ionize the gas, put out tremendous ionic "winds," and eventually explode as supernovae. The energy being dumped back into the interstellar medium is bound to have some effect. In the Large Magellanic Cloud and in the nearby spiral M31, one can see instances where clusters of massive stars have blown kiloparsec-sized holes in the disk gas (*13*). In these cases the gas around the hole has been compressed and appears to have been induced to make stars. The SSPSF model uses this mechanism and argues that further star formation in the galaxy is induced by the current star formation activity itself. In this manner, star formation propagates around the galaxy as one region after another ignites its neighbor.

In the SSPSF model there is a causal relationship between a young

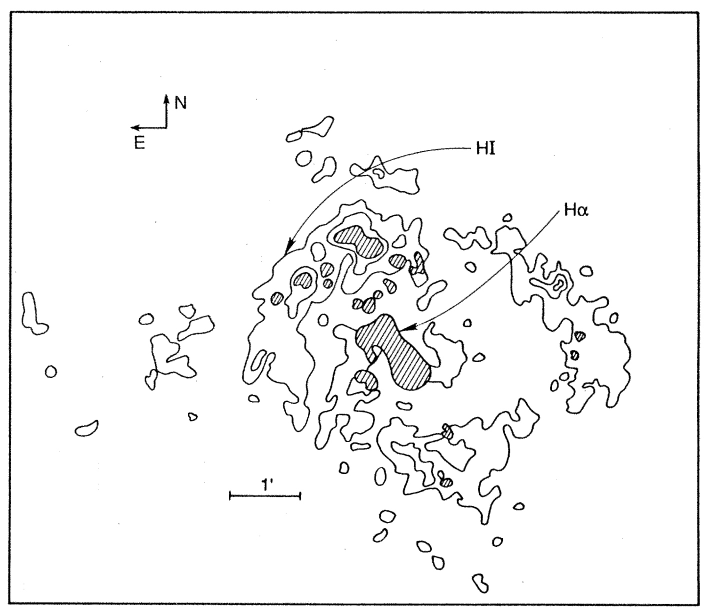

Fig. 4. The distribution of the atomic hydrogen gas within the inner part of the irregular galaxy NGC 4449 is shown. The solid line traces an outer contour of the H I map obtained with the Very Large Array radio telescope and is an indication of the location of large (~1 kiloparsec) H I cloud complexes. The shaded portion shows the location of the ionized gas and, hence, the current star-forming regions. One can see that there are regions of star formation that are not associated with the H I cloud complexes and there are H I cloud complexes without very much current star formation. [Drawing is courtesy of H. Thronson]

star-forming region and its older neighbors. Because the time scale between the initial and resulting events is unknown and can be long, star-induced star formation is hard to observationally detect except in the few cases cited above. We see that it can occur, but whether it occurs on a scale and at a frequency necessary to be the dominant mechanism in keeping a galaxy going is not known. In fact, there are other theoretical models that say that the feedback from star formation should be negative; that is, subsequent star formation should be inhibited (*14*). Detailed studies of the nearest irregular galaxy, the Large Magellanic Cloud, have been inconclusive (*15*); it is, therefore, safe to say that we do not yet know what consequences result from feedback processes.

The Interstellar Medium

Stars form out of the interstellar medium, and the physical conditions of the interstellar medium should affect the star formation process. For example, theoretical models suggest that the temperature and size of the natal clouds may influence the initial mass function of the stars formed, lower abundances of heavy elements may lower the efficiency with which a cloud of gas turns into stars, and a lower quantity of dust relative to gas and smaller dust grains may be necessary for the formation of very massive stars (*16*). By looking at the conditions in the interstellar medium, we hope to get some handle on the local processes.

The primary ingredient in making stars is gas. The irregulars are very rich in pristine atomic hydrogen (H I) and He gas; typically 20 to 50% of the mass of an irregular is in this form. These galaxies are truly "puddles of gas." What is unusual about this gas is that in irregulars it often reaches far beyond the extent of the stars in the galaxy. In one galaxy, NGC 4449, the H I extends to ten times the optical radius of the galaxy. In spiral galaxies, on the other hand, generally less than 20% of the H I lies beyond the optical galaxy (*17*).

One question this raises is why have stars not formed in this outer gas. As one goes out in radius from the center of a galaxy, the density of the gas drops. That star formation is not occurring and has not occurred beyond some radius indicates that there is a threshold gas density below which a galaxy simply cannot get a cloud together to form stars. One can measure the surface density of the H I gas at a point in a galaxy where the starlight had dropped to some well-defined low level (the density of stars and hence surface brightness of the galaxy decline radially). When we do that, we find that, at a surface brightness of 26.6 magnitudes arcsec^{-2}, which corresponds to $\sim 1\ M_{\odot}$ parsec^{-2}, the gas surface density is $\sim 3 \pm 2 \times 10^{20}$ atoms cm^{-2} and that this value seems to be the same for both irregulars and spirals (*18*). That is, the relationship between gas density and the star or cloud formation potential seems to be similar in all star-forming galaxies. The question remains whether the gas in the outskirts of galaxies can take part in the evolution of the main stellar body. If stars cannot form out there, the only way that gas can participate in the evolution of the galaxy is to move in towards the center. Such an infall of gas has been postulated but not unambiguously observed. Although this is a difficult observational problem, it is of crucial importance in understanding the long-term evolution of small galaxies.

If one looks at the distribution of the H I gas within the star-forming zones of an irregular galaxy, it is lumpy. A cloudy interstellar medium is expected because gas density enhancements are required to form stars. It is not always entirely obvious, however, how these lumps or clouds are related to the current star formation activity. In NGC 4449, for example, there are star-forming regions not connected with H I complexes and large H I complexes ($\sim$1000 parsecs in size) in which very little star formation is taking place (*19*) (Fig. 4).

The gaseous component of the interstellar medium most directly associated with the actual star formation event is molecular. It is from clouds composed mostly of H_2 that stars form in the Milky Way. The symmetric H_2 molecule cannot be directly observed in quiescent clouds. There are infrared lines as a result of fluorescence and ultraviolet lines caused by shock heating, but these are special circumstances. However, it has been found that the easily observed CO molecule, with transitions at wavelengths of a few millimeters, can be used as a tracer of H_2. A proportionality constant is applied to the observed CO flux to infer the quantity of H_2 that is present based on observations of clouds in the Milky Way.

Observations of CO emission in irregular galaxies, when taken at face value, indicate unusually low amounts of molecular material for their star formation activity compared to spiral galaxies (*20*). Exactly what this deficiency of CO emission means in physical terms, however, is not clear. It is possible that indeed the H_2 molecular content is lower in irregulars and that star formation is proceeding much more quickly and efficiently so that molecular clouds do not live very long. Or, the proportionality constant may be different in irregulars such that the CO content is low but the H_2 content is not. This latter explanation is the current favorite based on CO observations of molecular clouds in the Large Magellanic Cloud. The velocity dispersion in a cloud is also a measure of the mass of the cloud, and a plot of the velocity dispersion against the CO flux for clouds in the Large Magellanic Cloud shows a linear relationship that parallels but is offset from that for Milky Way clouds. This is

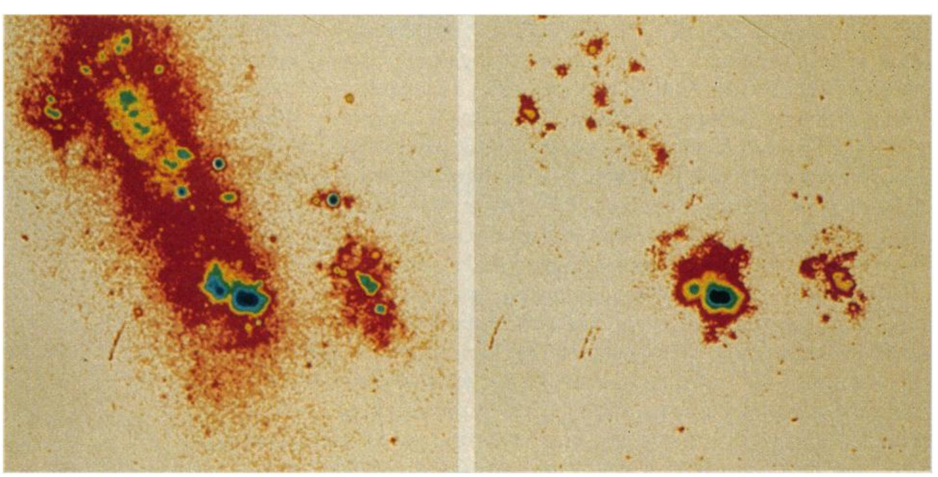

Fig. 5. NGC 2366 is an irregular galaxy with a low level of star formation activity. Nevertheless, this galaxy has produced a giant star-forming region that contains hundreds of massive stars. (**Left**) Image obtained through a filter that passes primarily starlight. (**Right**) Image showing only the ionized gas. The giant star-forming region stands out in the ionized gas image. The images were obtained with a charged coupled device on a 0.9-m telescope at Kitt Peak National Observatory. The parallel, arc-like structures on the right image are a flaw on the CCD detector. Since several images have been aligned and added, the flaw appears several times.

interpreted as evidence for a different proportionality factor necessary to convert CO fluxes to H_2 masses (*21*), and is consistent with theoretical expectations based on the overall lower abundance of heavy elements in irregulars (*22*). If the molecular clouds are indeed of normal mass in irregulars, then infrared observations show that the average global efficiency with which a cloud turns into stars is the same in irregulars as in our galaxy, ~2% averaged globally (*23*).

Dust is another component of the interstellar medium that is intimately associated with star formation in the Milky Way. In optical pictures of spiral galaxies one can see dark patches and lanes that are the result of obscuration by concentrations of dust. Such dark patches, however, are less prevalent in optical images of irregular galaxies (*24*). Dust is most easily observed in the far infrared, where it reradiates the starlight that heats it. At these wavelengths (~10 to 200 μm), however, water vapor in Earth's atmosphere hinders observation; so we must use satellites such as the Infrared Astronomical Satellite or airplanes such as the NASA Kuiper Airborne Observatory, which flies at ~12-km altitude.

We have obtained excellent measurements of far-infrared fluxes from galaxies with these instruments. We have found that globally the amount of dust relative to the amount of atomic gas is lower in irregulars than it is in spirals. Unfortunately, these global infrared and H I measurements include gas that extends radially far beyond the expected distribution of dust. The Shuttle Infrared Telescope Facility (SIRTF) and Stratospheric Observatory for Infrared Astronomy (SOFIA) planned by NASA will yield data with much higher spatial resolution that will allow local measurements of dust-to-gas ratios in individual star-forming regions.

From the global infrared fluxes we can roughly infer the characteristic temperatures of the dust in a galaxy, although there is a continuum of dust temperatures (*25*). We find that the characteristic temperature of the dust that radiates at the longer wavelengths is warmer and that which radiates at the shorter wavelengths is cooler in irregulars than in spirals. This is at least partially the result of the higher ultraviolet surface brightnesses and lower opacity of the

Fig. 6. NGC 1800, shown here, is an example of an amorphous irregular galaxy because it has a smooth optical appearance. This is in contrast to the Magellanic-type irregular galaxies exemplified by NGC 4449 (Fig. 2). This image was obtained with the video camera on the 2.1-m telescope at Kitt Peak National Observatory through a filter passing blue starlight.

irregulars. The grain characteristics, however, can also affect the temperature of the dust. All else being the same, graphite will be warmer than silicate materials and small grains will be warmer than large grains. If the average composition of the grains depends on the metallicity of the galaxy as a whole, we might expect a correlation between metallicity and average dust grain temperatures. Such a correlation is not seen and this tells us that the composition of the grains is not the dominant factor in determining the infrared properties that we see in these galaxies.

Global galactic kinematics also influence the state of the galactic interstellar medium. Most spiral galaxies rotate differentially, shearing the interstellar medium. Irregular galaxies rotate very slowly, often as a solid body, like a record turntable, so that there is little, if any, shear. Theoretical models suggest that the reduced shearing may cause stars to form more slowly than otherwise and massive stars to be favored. Another model suggests that clouds will collapse more quickly (*26*).

Thus, we find that there are differences between irregulars and spirals in terms of various aspects of the interstellar medium. The heavy element abundance is lower, the molecular content may be lower, the dust-to-gas ratios are lower, and the shear caused by rotation is lower in irregulars. Because stars are forming from the interstellar medium, we might expect these environmental differences to have observable consequences for the star formation process.

Star-Forming Regions

We cannot yet observe the detailed internal structures of star-forming regions in irregular galaxies, but we can look at their sizes and spatial distributions. The sizes of H II regions are generally related to the number of hot, massive stars contained within. Every galaxy contains a range in sizes of H II regions and hence star-forming units, with the smaller regions being most numerous (*27*). The great Orion star-forming complex in our own galaxy, in the general scheme of things, is actually rather small. It appears fairly large in our sky (~15°) because it is so nearby. But galaxies can make giant H II regions that contain hundreds of very massive stars. The most famous example is 30 Doradus, the Tarantula Nebula, in the Large Magellanic Cloud. If 30 Doradus were at the distance of Orion, it would cover ~40° on the sky and cast shadows on Earth at night.

If we compare the optical and ultraviolet properties, sizes, luminosities, and morphologies of giant H II regions in irregulars with those in spirals, we find that they are very similar (*28*). Not only can different types of galaxies make stars in similar types of units, but, once formed, the giant H II regions appear to experience similar evolution regardless of the morphological type of the parent galaxy.

One remarkable aspect of galaxies with low overall star formation rates is that they too can and do make giant H II regions. NGC 2366, which has a star formation rate one-third that of the Large Magellanic Cloud, nevertheless contains an H II region three times as bright as 30 Doradus (Fig. 5). Another galaxy, Holmberg II, has a global star formation rate one-eighth that of the Large Magellanic Cloud but contains an H II region half as bright as 30 Doradus. Why do these galaxies put so many of their star-forming eggs into one basket? And what sets the limit to the size of a star-forming region in a given galactic environment? One explanation relies on the way gas streams around central stellar potentials called bars. The gas can pile up at the ends of the bars, causing a giant cloud to form (*29*). Many irregulars do have stellar bars, but unfortunately not all giant H II regions are located at the ends of these bars.

Even though studies of star-forming regions within external galaxies are in their infancy, we find broad similarities between star-forming regions in different types of galaxies. Thus, the differences in interstellar medium characteristics described above between spirals and irregulars have not led to obvious differences in the nature of individual galactic star-forming complexes. The form of the initial mass function is probably the most crucial test of the star formation process, but it is observationally difficult. However, the data thus far available, which will soon be extended by the Wide Field/Planetary Camera on the Hubble Space Telescope, again suggest similarities between most galaxies (*30*).

Amorphous Galaxies

There is another subclass of irregular galaxies that we have not yet discussed that pose their own interesting puzzles (*31*). These are the amorphous irregulars described by Sandage and Brucato (see Fig. 6). Unlike the other Magellanic-type irregulars, these galaxies are very smooth in appearance, even though they are no more distant. They are not resolved into the many young associations and luminous clusters that give the Magellanic irregulars their distinctive jumbled appearance. They are blue and have intense emission lines, so we know they are forming massive stars. The spatial distribution of the star-forming regions is also often quite extreme: they often contain a single supergiant H II region located at the center of the galaxy. In NGC 1140, for example, the central H II complex has a luminosity 100 times that of 30 Doradus. Yet, in terms of most other global properties, the amorphous irregulars are quite similar to the Magellanic irregulars.

Why then are the clustering properties seemingly different and the star-forming units so extreme in these galaxies? We do not know, but there are hints that the extreme nature of the star-forming units is linked to the evolutionary history of the galaxy. From the statistical large variations in broad-band optical colors and emission-line equivalent widths, we see that amorphous galaxies appear to be undergoing a period of heightened star formation activity as a consequence of these central supergiant H II regions. In one model proposed by Noguchi (*32*) to explain these systems the amorphous galaxies are a result of a gentle interaction between two galaxies. Several billion years after the interaction the gas will have piled up at the center, naturally giving rise to a central concentration of the star formation as well, while stars are relatively unaffected by the interaction. In this model, amorphous galaxies originally must have been irregulars because the global properties of amorphous galaxies are so similar to those of the Magellanic-type irregulars. A crucial test of this model, mapping the H I distribution in these galaxies, remains to be made.

The existence of amorphous galaxies illustrates another important problem in understanding star formation in irregular galaxies: Does galactic star formation naturally proceed at a smooth or highly variable rate over the lifetime of the galaxy? Despite extensive theoretical and observational discussions of the possible role of epochs of globally enhanced star-forming activity or "starbursts" in small galaxies, this issue remains unresolved. Theoretical studies are now leading to well-posed questions, such as whether starbursts naturally occur as a result of internal feedback mechanisms or must be stimulated by events external to the galaxy, which will soon be subject to observational tests (*33*).

Unanswered Questions

Irregular galaxies are interesting because they present us with a different set of galactic conditions compared to spiral galaxies such as our own. Star formation in irregulars demonstrates that spiral density waves are not necessary for the active formation of massive stars, and any model of star formation must take this into account. Among the irregulars with similar global properties, there is a range in star formation rates, but the factors that govern the overall level of star formation activity in these galaxies have yet to be identified. There is a lot of energy returned to the interstellar medium by star formation events, but we do not know the consequences of this feedback. There appears to be a threshold gas density for star formation, and the relationship between gas density and star formation is similar in spirals and irregulars.

However, the relationship between H I gas clouds and current star formation activity is not clear. There are differences in the interstellar medium of irregulars compared to that in spirals in terms of abundance of heavy elements, molecules, dust, and shear, but the consequences to the star formation process are not obvious. Giant H II regions in irregulars are similar to those in late-type spirals, but even irregulars with low overall star formation rates sometimes put most of their star-forming eggs in these disproportionately large baskets. Finally, amorphous irregulars have global properties similar to those of the Magellanic-type irregulars, but we do not know why they are not peppered with many young star clusters and why their star formation activity is often concentrated in a single central supergiant region.

Clearly, there is still much that we do not understand about the star formation processes in irregular galaxies. The outstanding questions to be answered include what is the local triggering mechanism for star/cloud formation, what governs the global level of star formation activity in a galaxy, and what determines the initial mass function. Answers to these questions will require continued observational work across much of the electromagnetic spectrum to provide basic data in combination with improved theoretical models. Our reward in these tasks will be a physical understanding of a key astrophysical process that will lead us to a deeper knowledge of the evolution of galaxies and the universe.

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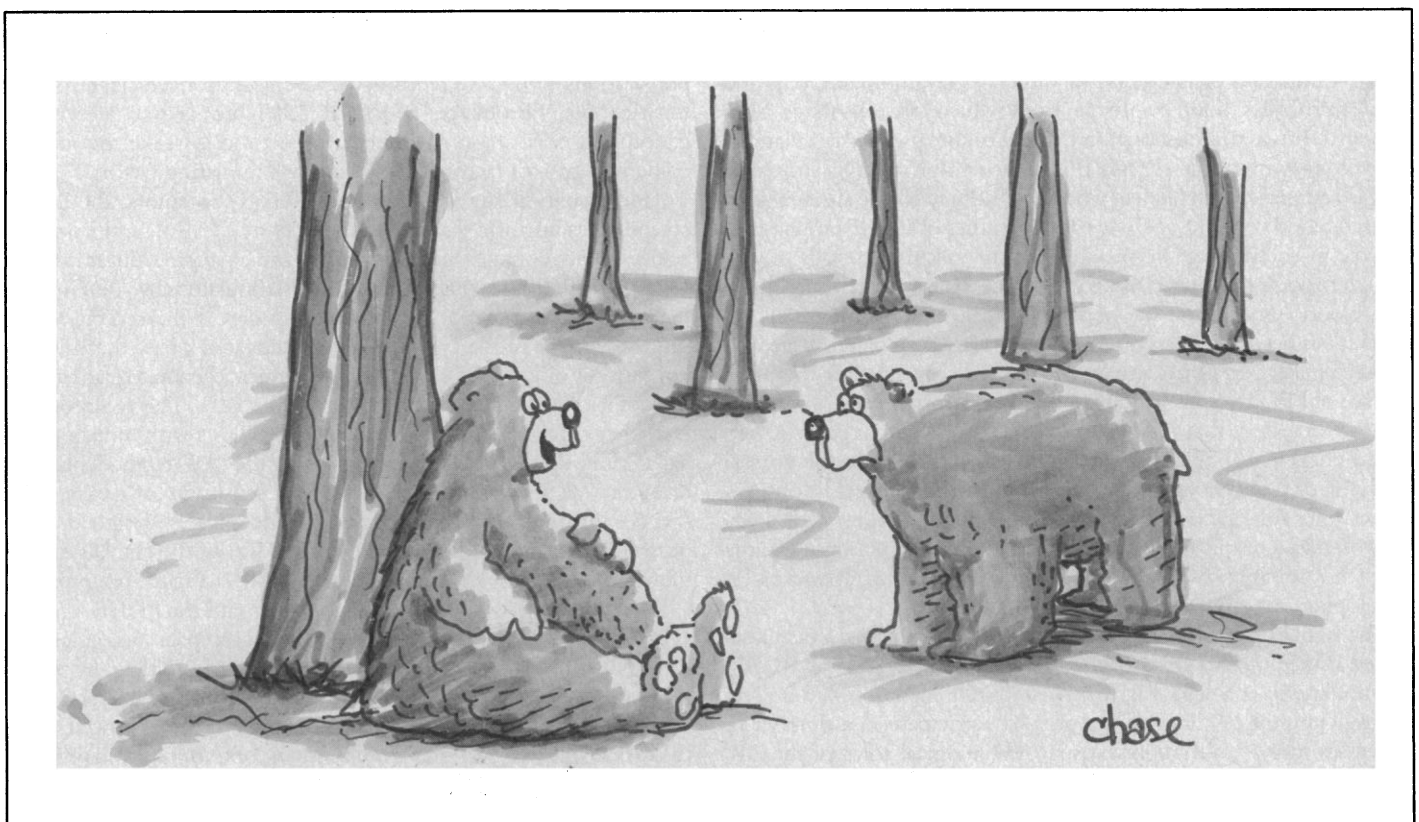

"An animal rights advocate was here today, asking questions...I ate him!"