# Galaxy Formation and Young Galaxies

According to the commonly held view, galaxies form from relatively diffuse primordial gas clouds which condense under gravity to form bound systems of stars. However, we have little understanding of the detailed processes by which this primordial matter is ultimately converted into the stellar systems which we observe. Star formation must obviously play a central role, but, until more is understood about how and when stars form, it will be difficult to evaluate the relative importance of gas dynamics and stellar dynamics in determining the structure of the resulting system. For example, if stars form very early, gas dynamics may be relatively unimportant and the collapse process may be dominated by stellar dynamics and violent relaxation; on the other hand, if star formation is less rapid, gas dynamics and the rate of star formation may be of dominant importance, as illustrated by recent model calculations (reviewed, for example, by Larson,[1,2]).

If we could observe galaxies still in the process of formation, this would help to clarify which processes are most important and how they operate. It would be particularly interesting, for example, to have empirical information about how stars form in young galaxies. Does star formation occur more or less uniformly throughout a forming galaxy, or does it first occur in dense knots or separate small galaxies which later merge into a single system, as suggested by some models? Does residual gas continue to condense and form stars in progressively smaller regions at later times, as also suggested by some calculations? How long do gas infall and active star formation continue? In the case of spiral galaxies, it is also important to understand how the gas settles into a plane to form a disc ~~dis~~component. Does this occur by the more or less uniform collapse of a rotating gas cloud, or are disks built up over a long time by infall of gas from an extended region around the galaxy? How does infalling gas interact dynamically with a forming disk? What are the dynamical effects of supernova explosions in young galaxies? These questions and others of interest might be answered, in principle, if galaxies in various early stages of evolution could be identified

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and observed in enough detail.

The characteristics by which one might try to identify young galaxies include a peculiar or chaotic structure, a large and irregularly distributed gas and dust content, and a high star formation rate, as indicated for example by large concentrations of young stars and HII regions, anomalously blue colours, or a high supernova rate. More exotic phenomena such as nuclear activity and radio emission may also be closely related to early stages of galactic evolution. For present purposes it is not necessary that *all* of the stars in a proposed "young galaxy" in fact be young, since a galaxy which contains old stars but is "rejuvenated" by the addition of fresh material or by a perturbation which triggers a major burst of new star formation may show the same phenomena and be as interesting to study as a galaxy which is just forming. Such rejuvenated galaxies might often be associated with circumgalactic gas clouds or with other galaxies showing similar peculiarities.

Since, by all indications, most galaxies have not formed recently but have ages that are a substantial fraction of the age of the universe, the most obvious place to look for young galaxies is at the large distances and redshifts where most galaxies are formed. Since it may be difficult to identify and observe such "primeval galaxies", it would be useful to have some model predictions for what young galaxies might look like when they attain maximum luminosity. Recently Meier[3] has estimated, on the basis of collapse models of Larson[4], that typical primeval galaxies of mass $10^{11} M_{\odot}$ may have redshifts in the range $2 \lesssim z \lesssim 16$, apparent magnitudes in the range $21 \lesssim m \lesssim 29$, nearly stellar images with half-light diameters of $0.5 \lesssim \theta \lesssim 2$ arsec, and UBV colors that vary strongly with redshift. Such objects would have escaped detection in the searches that have been made for primeval galaxies, but might appear as very faint semi-stellar objects near the limit of detectability in deep surveys. Primeval galaxies with larger masses or smaller redshifts would be more easily observable, although less common. At present no systematic searches for such objects have been undertaken, and this is a challenging and important observational problem.

The fact that primeval galaxies are predicted to have nearly stellar images and to overlap the magnitude and redshift range of the quasars raises the question of whether some quasars may in fact be primeval galaxies. The non-thermal emission and the rapid variability of many quasars are, of course, not explained by a system of young stars alone, but probably derive their energy in some way from the gravitational energy of collapsed objects. However, if the formation of the collapsed objects is accompanied by the formation of massive stars containing a comparable amount of mass, the nuclear energy produced by the massive stars is of the same order as the gravitational energy available from the collapsed objects, in which case one might expect to see evidence for a stellar component in the spectra of at least some quasars. In fact, two quasars at redshifts 2.9 and 3.4 have spectra which match closely the predicted spectra of the stars in primeval galaxies (Meier[5]). Thus it may be that some primeval galaxies masquerade as quasars, and a fruitful way of searching for primeval galaxies may be to look for high-redshift quasars with strong young stellar components in their spectra.

Because of the difficulty of studying in detail the primeval galaxies at large redshifts, it is also of considerable interest to look for young galaxies at smaller redshifts. Here we might expect to find mostly galaxies which are in the later stages of the formation process, or which have recently been rejuvenated, rather than galaxies which are just forming. As examples of systems that may be interesting to study in this light, we mention first some possible examples of elliptical galaxies where gas infall and star formation processes may still be actively going on. According to the model calculations, during the later stages of the collapse the residual gas tends to condense toward the center or toward the equatorial plane, where it forms new stars; thus a young elliptical galaxy in this stage of evolution might show a nearly spheroidal outer structure but irregular concentrations of gas and young stars near the center. A galaxy which resembles this description is the small peculiar elliptical NGC 5253, which contains knots of gas and young stars in its interior and is a relatively prolific producer of supernovae, having produced two recorded supernovae. Other similar galaxies may include NGC 185 and NGC 205 in the local group, both of which contain patches of dust and young stars, and NGC 3077 in the M81 group, which has a large gas content, a chaotic dust pattern and concentrations of young stars. In all cases there is evidence for active star formation in a system whose underlying basic structure appears to be that of an elliptical galaxy.

Further possible examples of elliptical galaxies with ongoing star formation are provided by the two large and very peculiar radio galaxies NGC 5128 and NGC 1275 (van den Bergh[6]). NGC 5128 resembles a giant EO galaxy with a broad, chaotic band of dust, gas and young stars orbiting around its center; patches of dust and emission nebulosity are also seen far away from the apparent equatorial plane of this system. The dust band probably represents material which is settling into a plane and forming a disk, perhaps like that of the "Sombrero" galaxy M104; if so, studies of NGC 5128 could be very important in telling us something about how disk systems form. NGC 1275 is similar to NGC 5128 in that it also resembles an EO galaxy and contains extensive dust lanes, neutral and ionized gas, and young stars as indicated by its early-type spectrum. Another possibly similar object is NGC 1510, which looks like an elliptical galaxy but has blue colors and a spectrum dominated by gas and young stars (Disney et al.[7]) Finally we mention NGC 5102, which looks like a normal SO galaxy yet has a blue color, an early-type spectrum, and a significant gas content (Gallagher et al.[8]).

Although the way in which the gas condenses into stars may be much the same in either case, it is of interest to know whether the gas in these galaxies is of internal origin, i.e. recycled from stars, or has recently fallen in from outside the galaxy, since in the latter case the observed activity may be regarded as a continuation of the galaxy formation process. At present there is no direct evidence concerning the origin of this gas, but in some cases circumstantial evidence suggests an external origin. NGC 3077, along with M82 which it resembles, is embedded in an extended hydrogen envelope surrounding the large spiral M81 (Davies[9]) and it is possible that NGC 3077 has recently acquired new material from this envelope. The similarity between NGC 3077 and M82 also suggests that some interaction with the common gas envelope is involved. Another intriguing association of galaxies with similar peculiarities involves NGC 5253, NGC 5128, and NGC 5102, which are located in a loose group (the "Centaurus chain") that also contains M83, an Sc spiral with an extended hydrogen envelope and an exceptionally high rate of star formation (see below). Again this association suggests that the anomalously high gas content and star formation rate in all of these galaxies may be due to interaction with a surrounding medium. Clearly it would be of great interest to establish whether this group contains significant amounts of intergalactic gas.

In spiral galaxies, model calculations (Larson[10]) suggest that the formation of a disk component is a relatively gradual process, and that the gas in the outer parts of a spiral galaxy may still be slowly settling into a disk, even after $10^{10}$ yr. Also, it is possible that infall of gas from an extended low density remnant protocloud will continue for a long time to add new gas to the disk. This suggests that some spiral galaxies may by dynamically young in the sense that the disk component is still being built up by the addition of new material. The question of whether gas is presently falling into our own galaxy has been vigorously debated, but we note that the two main competing interpretations of the "high velocity hydrogen clouds" (Hulsbosch[11], Verschuur[12]) share the common feature that some hydrogen outside the conventional boundaries of the galactic disk has a component of velocity directed into the disk, possibly indicating a continuation of the infall process which formed our galaxy.

Spiral galaxies which have recently acquired a large amount of new gas will have a particularly high gas content and star formation rate, and will probably also show distortions from a perfectly flat, axisymmetric structure; for example, newly acquired material with angular momentum about a different axis than the rest of the system will introduce a warp in the disk of the galaxy. Warps and other deviations from axial symmetry and circular motion are in fact commonly observed in the outer parts of spiral galaxies. A particularly striking example of a spiral galaxy with these characteristics is NGC 5236 (M83). This galaxy has a hydrogen distribution which extends out to several optical radii and is strongly warped in a way that is not easily explained by tidal effects or a residual primordial warp. (Rogstad et al.[13]) M83 also has a particularly high supernova rate (four recorded supernovae) and an anomalously blue U-B color which is most plausibly explained by a strong burst of star formation (Tinsley[14]).

Similar evidence for strong large-scale warping of the hydrogen layer has recently been found by Rogstad et al.[15] for M33. The apparent impossibility of accounting for the warps in either M83 or M33 by tidal effects or a primordial warp has led these authors to suggest that a major fraction of the gas in the outer parts of M83 and M33 has been added to these galaxies only recently. A possibly related and even more extreme example of a galaxy with outlying material rotating in a completely different plane from the inner part is the very peculiar galaxy NGC 2685, which is apparently an edge-on SO galaxy surrounded by helical filaments rotating around an axis nearly perpendicular to that of the inner disk; in this case, the evidence seems even more compelling that the outer filaments represent material accreted after the formation of the inner disk. Since modest warps are a common, if not universal, feature of spiral galaxies, this suggests that continuing accretion of new gas occurs in the outer parts of many spirals and that by studying such phenomena one can learn something about how the disks of spiral galaxies are formed.

In addition to the objects mentioned there are many peculiar galaxies (e.g., Arp[16]) whose highly distorted appearances and prominent young stellar populations suggest that they are of recent origin or have recently acquired new material. A number of examples of peculiar galaxies which may be young systems have been discussed by Burbidge et al.[17] and by Searle and Sargent.[18] Despite the fact that much progress has been made in explaining various peculiar and apparently unstable systems in terms of tidal interactions and collisions between galaxies (e.g., Toomre[19]), it is difficult to account for *all* of the proposed young galaxies in this way, and it still seems worthwhile to study some of these peculiar galaxies as possible examples of systems that may be in early stages of evolution..

Perhaps the most striking and extensively studied peculiar galaxy is M82. According to recent interpretations of this object (e.g., Visvanathan[20]), the radiation from the filaments that appear to radiate out from the center of this galaxy originates in luminous but heavily obscured HII regions near the center, and is reflected by dust grains in the filaments; in this interpretation, the velocities of the filaments are modest and the system is not exploding violently, as once believed. Instead, much evidence now points to the occurrence of an intense burst of star formation and supernova activity in dense obscured regions near the center of this galaxy. This evidence includes the presence of massive associations of young stars, luminous HII regions, strong infrared emission, large amounts of molecular gas, and possibly radio supernova remnants, all of which are characteristically associated with regions of star formation (Hargrave[21], Harwit and Pacini[22]). The high rate of star formation near the center of M82 may have been caused by recent infall of gas from the surrounding hydrogen cloud. The presence of dust in such newly acquired gas can plausibly be understood as resulting from prior contamination of the intergalactic gas by metal-rich gas ejected from galaxies in the M81 group (Larson and Dinerstein[23]). The origin of the filaments is still not understood, but they could result from interaction between M82 and the surrounding medium; a speculative possibility is that they might consist of relatively dense and cool infalling gas which is concentrated into filaments by interaction with a hot outflowing wind generated by supernovae near the center of M82. All of the peculiar properties of M82 could then be understood in terms of gas infall and active star formation occurring near the center of this galaxy. Whether or not M82 is presently accreting matter, it is possible that the present intense star formation activity in M82 is similar to that occurring during the formative phases of galaxies, and that the study of peculiar systems like M82 will be of great value in helping to increase our understanding of both star formation and galaxy formation.

R. B. LARSON
*Yale University ~~Laboratory~~*
Observatory

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