The Formation and Evolution of Galaxies

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Galaxies represent the visible fabric of the Universe and there has been considerable progress recently in both observational and theoretical studies. The underlying goal is to understand the present-day diversity of galaxy forms, masses and luminosities. Popular models predict the bulk of the population assembled recently, in apparent agreement with optical observations. However, numerous uncertainties remain, including the role that dust might play in obscuring star-forming systems. Astronomers now seek more detailed tests to verify that the Hubble sequence of types arises from transformations driven by the dynamical assembly of smaller systems. Multi-wavelength surveys and studies of the resolved internal properties of distant galaxies promise answers to these fundamental questions.

The name Edwin Hubble has become synonymous with progress in understanding galaxies. Hubble opened the extragalactic era by demonstrating that galaxies are stellar systems outside our own Milky Way\(^1\). His name now graces a most successful space observatory which has, since its refurbishment in 1993, worked in harmony with ground-based telescopes to transform our view of the distant Universe. An important goal of the Hubble Space Telescope (HST) is to directly establish the evolutionary history of normal galaxies. HST offers resolved data enabling us to perform detailed astrophysical studies on the internal properties of remote galaxies. Together with independent progress made in understanding how structure forms from initial density fluctuations soon after the Big Bang, a picture is emerging on how galaxies form and evolve.

A major question we hope to address is the origin of Hubble’s morphological sequence\(^2\). Is there any physical basis for this taxonomic scheme? Hubble noted a strong correlation between the relative prominence of the central ‘bulge’ and ‘disk’ components along his sequence. Bulge components (including ellipticals) are generally redder than spiral disks and contain less gas, which can be interpreted via the early rate of conversion of gas to stars. Ellipticals could have formed their stars during a rapid collapse leading to present-day stellar populations which are uniformly old and red. By contrast, spirals suffered a more extended star formation history retaining gas and young stars to the present epoch\(^3\). These different ‘metabolic rates’ might reflect the physical nature of the initial assembly. If primordial gas clouds had time to collide and dissipate energy, a large collapse factor would be permitted. Angular rotation associated with the primordial cloud would amplify during collapse leading to a rapidly-rotating disk. Since ellipticals are slowly-rotating,
their collapse factor would then have been modest and their high mass densities might therefore reflect a much earlier period of formation⁴.

For many years, most astronomers believed in a single ‘epoch of galaxy formation’⁵ and sought to find ‘primaeval galaxies’ e.g. the luminous star-forming precursors of present-day ellipticals. The absence of examples in deep emission line searches⁶ and faint redshift surveys was the first hint that galaxy formation might be a gradual process rather than one confined to a narrow period in time. Moreover, perhaps galaxies did not evolve as isolated objects. Local galaxies interact at a rate which is likely to have been higher in the past. Numerical simulations indicate gas-rich spirals, when they collide, can produce smooth components which look like bulges and ellipticals⁷. Upon closer examination, local bulges and ellipticals reveal a bewildering diversity. Some ellipticals have gaseous components and harbour small disks, many bulges are relatively blue. The enigmatic lenticular or ‘S0’ galaxies have disks and bulges, but without active star formation or spiral arms. Such observations may imply that disk systems were predominant at early times and that subsequent processes transformed some to give the wider range of types seen today. These conjectures can be tested by examining the morphology of galaxy populations viewed at earlier times.

**Understanding the Growth of Structure**

The most popular model accounting for the growth of structure is the cold dark matter (CDM) model⁸ which can reproduce a growing body of observations including the angular power spectrum of fluctuations in the microwave background and the large scale distribution of local galaxies⁹. Its predictive power is well-developed due to the enthusiasm and foresight of its advocates¹⁰,¹¹. However, it is conceivable that alternatives theories might still be developed which could also match the observations. We should aim to check the physical principles of a model rather than be content solely with the fact it reproduces many of the observations.

CDM theory posits that a large fraction of cosmic matter is dark and non-baryonic¹². Non-baryonic material has the advantage of decoupling from the cosmic plasma at early times with a characteristic spectrum of density fluctuations that merge hierarchically providing early seeds for later galaxy formation. A young galaxy of gas and stars is embedded in a more massive dark matter halo and its evolution is governed by the nature of that underlying halo. Baryonic gas accretes gravitationally onto the halos and is shock-heated. Stars can only form when gas has cooled and this is hindered by various ‘feedback’ processes.

The cooling timescale for primordial gas clouds provides a natural explanation for the physical sizes of present-day galaxies¹³,¹⁴. If the cooling time exceeds that for dynamical collapse, a cloud can readjust its temperature and collapse quasi-statically. However, if cooling is too rapid, then virial equilibrium is never reached and rapid collapse and fragmentation ensues. Such considerations imply that the onset of star formation in a young galaxy is a gradual process governed by gas cooling and feedback as well as the rate at which mass is assembled. For CDM, the latter is fixed by the need to match the observed abundance of present-day rich clusters which determines the epoch at which structure on
any mass scale forms. A long-standing prediction\textsuperscript{15} is that the bulk of the star formation might have occurred as recently as a redshift $z \approx 1$.

The appeal of the CDM picture lies in its ability to broadly match many of the observations of large scale structure. Whereas puzzles remain, these data sample the underlying density field and so relatively few model parameters are involved. However, in reproducing detailed observations of galaxies, a larger suite of astrophysical parameters is needed including the physical details of star formation and feedback and dynamical details of how galaxies subsequently merge to form larger morphological structures. The philosophy adopted has been to choose parameters such that the present-day distribution of galaxy properties is reproduced. A comparison of CDM predictions of how galaxies evolved to their present forms with distant data is therefore a crucial test.

Recent Observational Progress

The refurbished HST and surveys with ground-based large telescopes equipped with efficient faint object instrumentation has led to breathtaking progress. Key developments point to a remarkably recent era of galaxy formation. The results remains quantitatively uncertain and do not, by themselves, provide any theoretical insight into the processes involved. However, the empirical picture emerging is qualitatively similar to that predicted by CDM.

Until recently, the vanguard of progress has been via statistical studies at optical and near-infrared wavelengths. A remarkably simple cosmological probe of the early history of star formation is the logarithmic slope, $\gamma = d\log N / d(m)$, of the galaxy number-apparent magnitude counts. To yield a finite value for the extragalactic background light, $\gamma$ must ultimately drop below 0.4. Deep ground-based imaging surveys\textsuperscript{16,17} presented evidence for a change in slope at $B \approx 25$ and this is now confirmed from deeper counts with HST\textsuperscript{18,19} (Figure 1). A similar effect is seen at near-infrared wavelengths\textsuperscript{20,21} suggesting a transition at some redshift with the bulk of the fainter sources being drawn from intrinsically-less luminous sources at similar redshifts. Galaxies at the point of inflexion must provide a dominant contribution to the integrated background light.

Deep spectroscopic surveys conducted with ground-based telescopes equipped with multi-object spectrographs have been an indispensable tool in cosmology since the mid-1980’s. Their main task has been to determine the redshift distribution of statistically-complete samples of galaxies at various magnitude limits\textsuperscript{22–26}. Such surveys have almost reached the inflexion in the optical counts and confirm a surprisingly low mean redshift $z \approx 0.8-1$ at faint limits. Few $B=25$ sources are distant luminous young galaxies as expected for a narrowly-defined epoch of galaxy formation.

These surveys also indicate that the steeper count slope at brighter apparent magnitudes is a strong evolutionary effect representing a significant increase to redshifts $z \approx 1$ in a population of star forming galaxies with blue colours\textsuperscript{22}, intense emission lines\textsuperscript{23} and irregular HST morphology\textsuperscript{27,28}. The combination of HST morphology and deep spectroscopy has been particularly effective in pointing to an era of intense star formation at $z \approx 1-1.5$\textsuperscript{29}.
Some component of the recent decline in star formation may be associated with the slow
demise in regular spirals\textsuperscript{30,31} but a surprisingly large evolutionary signal arises from low
mass irregulars whose local counterparts are unclear\textsuperscript{19}.

There are not yet any systematic surveys beyond \( z \simeq 1 \) whose selection is based purely
on apparent magnitude. However, multi-colour imaging can be used to isolate distant
source by detecting the Lyman limit\textsuperscript{32}. Absorption by neutral hydrogen occurring in the
intergalactic medium and within galaxies produces a natural cosmic signature: a sharp drop
in flux when the absorption edge is redshifted into the observer’s frame. The technique is
simple and effective. A galaxy ‘drops out’ of view in a particular filter if the Lyman limit
(912Å) has been redshifted beyond that wavelength (Figure 2). An early application\textsuperscript{33}
suggested that most \( R=25 \) sources lie below \( z=3 \) and that such ‘drop-outs’ were rare but a
convincing demonstration awaited confirmatory Keck spectroscopy of candidates selected
by Steidel, Lowenthal and their colleagues\textsuperscript{34–36}.

A considerable amount is now known about these ‘Lyman limit galaxies’ including their
spectral properties\textsuperscript{37}, physical sizes, HST morphologies\textsuperscript{38} and clustering properties\textsuperscript{39}. Of
greatest importance here is the rest-frame ultraviolet luminosity distribution\textsuperscript{40} which yields
an estimate of the comoving density of massive star formation at early times. The activity
at \( z > 2 \) appears to be significantly less than that observed in the all-inclusive redshift
surveys at \( z \simeq 1 \), consistent with the simple interpretation of the number counts discussed
earlier. Moreover, by extending the technique to longer wavelength filters, the contribution
from Lyman limit galaxies at higher redshift can be found. A further decline in activity is
seen from \( z \simeq 2.3 \) to \( z \simeq 4 \textsuperscript{41} \).

The history delineated by these low and high redshift surveys suggests a peak in star
formation between \( z \simeq 1.2 \) and 2.5 where, currently, there is no complete spectroscopic
sample. This ‘gap’ in coverage arises because the Lyman limit technique can currently only
be located with optical facilities (including HST). Magnitude-limited spectroscopic surveys
within 1.2 < \( z < 2.5 \) are similarly challenged by the need to follow diagnostic features in
the near-infrared where spectrographs have to battle an intense sky background. Our
limited knowledge of sources in this interesting region is provided from methods based on
multi-band photometry\textsuperscript{42}.

\textbf{Is the Observational Picture Correct?}

The star formation history delineated above has attracted considerable attention both by
CDM theorists who claim vindication of their predictions\textsuperscript{15,43} and by skeptical observers
who have set out to demonstrate it incorrect\textsuperscript{55,58}. According to CDM, the Lyman limit
galaxies are precursors of massive cluster galaxies whose assembly history has been accel-
erated in the associated density peaks; the bulk of normal field galaxies are put together
later as observed\textsuperscript{14}.

The morphological appearance of the faintest sources gives qualitative support to the idea
that galaxies at \( z \simeq 1-3 \) are still assembling. Their mean physical size is small notwith-
standing redshift-dependent biases\textsuperscript{45,46} and a high proportion are irregular with evidence
of ongoing merging. Deep infrared redshift surveys sensitive to stellar mass rather than young stars find a paucity of luminous $z>1$ sources as expected if galaxies assembled late. Independent evidence for recent galaxy formation (not reviewed here - see ref. 50) arises from the low metallicity and high gas content of material observed in absorption to high redshift quasars although such interpretations depend critically on whether the available data reliably serve as representative probes of the global composition.

The star formation history will inevitably be refined quantitatively as larger surveys are conducted but a decline beyond $z \approx 2$ would represent a profound result for cosmology; less than 20% of the observed star formation would have occurred before that epoch. Recent discussions have centred on two main criticisms.

Firstly, it is possible that these optical datasets are being misinterpreted. The flux emerging from a Lyman limit galaxy will be attenuated significantly at ultraviolet wavelengths by dust clouds and thus the true star formation rate in these sources may be underestimated. The decline in activity beyond $z \approx 2$ could be entirely due to dust extinction. This cannot be addressed without making some assumptions about the intrinsic properties of the Lyman limit galaxies. If their ultraviolet properties are similar to local star forming galaxies, dust correction leads to an upward correction to the high $z$ star formation rates of between 3 and 15. A more extreme model where half of the present-day stars formed at $z > 2.5$ and were shrouded in view can be made consistent with the global history of light at various wavelengths but could overpredict the metal mass density observed in high $z$ absorbers.

A more serious possibility is that the optical samples are incomplete probes of the star forming population. Nearby starbursts output a significant fraction of their radiant energy in the far infrared region via thermal emission from dust clouds heated by shrouded young stars. Placed at high redshift they could be missed altogether by the optical observers. Satellites such as the Infrared Space Observatory (ISO) are designed to be sensitive to such radiation but at the expense of a poor angular resolution. A moderate surface density of thermally-emitting sources has been found in deep exposures of the HDF but the optically-based star formation history would only be significantly distorted if these sources were very distant.

A promising way to address this problem follows the commissioning of SCUBA, a ground-based sub-mm array detector on the James Clerk Maxwell Telescope which has a better astrometric precision. Sub-mm receivers are very effective in searching for distant dusty sources because the redshifted thermal spectrum yields a detection efficiency that hardly changes with redshift. The first genuine sub-mm source counts are now emerging and spectroscopic identifications are available for a few sources (Eales et al, in prep.).

The change to the optically-derived star formation history would be greatest if the bulk of the SCUBA sources lay beyond $z \approx 2$. The volume-limited nature of the sub-mm surveys makes a powerful point. A dusty star-forming galaxy could be viewed to $z=10$ to the flux limits now being achieved with SCUBA yet, where optical follow-up is available, a high fraction of the sources have optical detections and/or spectroscopic redshifts with $z < 3.5$. 
The quantitative form of the global star formation history (Figure 2) is likely to change, both from improved optical data and more extensive sub-mm surveys. One should not underestimate, however, the large uncertainties in converting the sub-mm fluxes into star formation rates. Conceivably the peak in activity at \( z \simeq 1-2 \) will shift to higher redshift. However, the detailed shape of this curve is less important in testing models than the question of whether there is a sizeable population of massive star-forming galaxies at \( z > 3 \). At the time of writing, there is no convincing evidence to challenge the notion that galaxy assembly occurred gradually over \( 1 < z < 3 \) as predicted by CDM.

**Testing Hierarchical Models for Galaxy Formation**

To what extent does a similarity between the predicted star formation history and that observed imply support for the hierarchical models? The global history integrates over the evolutionary behaviour of galaxies of all luminosities and morphologies thereby hiding many details. More precise tests must take advantage of the resolved properties of distant galaxies available with HST to probe directly the physical processes that lead to the diversity of the present day galaxy population.

The dissipative collapse of primordial gas clouds in the CDM picture leads to rotating disk systems. External factors govern the structural and morphological evolution\(^{64} \). Disks formed at high redshift slowly merge providing a continuous supply of newly-born ellipticals and lenticulars.

One of the most fundamental observations relating to the origin of the Hubble sequence is the ‘morphology-density relation’\(^{65} \) (Figure 3). Ellipticals are predominantly found in cluster environments and noticeably scarce in the low density ‘field’. Does this indicate that ellipticals were produced at high redshift only in those regions destined to become clusters (e.g. via a rapid initial conversion of gas into stars), or can ellipticals be produced subsequently through the mergers of spirals as postulated by CDM?

Early ground-based work\(^{66} \) tracked a rise with redshift in the fraction of star-forming galaxies in rich clusters and HST images show this is accompanied by a radical shift in galaxy morphologies\(^{67,68} \). By \( z \simeq 0.5 \) spirals are almost as frequent in proportion in dense cluster cores as they are in the field. A particularly striking result is the rapid increase with time in proportion of lenticular (or ‘S0’) galaxies, strongly suggesting they are transformed spirals.

Hypotheses advanced for the remarkably recent demise of cluster spirals include dynamical friction in the cluster potential\(^{69} \), gas stripping of infalling field galaxies by a dense intracluster medium\(^{70} \) and galaxy-galaxy merging\(^{71} \) induced perhaps by the hierarchical assembly of clusters. Strong radial gradients observed in diagnostic spectral features in distant clusters\(^{72,73} \) support the idea that gas-rich field galaxies suffer truncated star formation as they enter the cluster on radial orbits. Although these transformations are not yet understood, the observations demonstrate that recent environmental processes shaped the morphology-density relation urging us to take seriously the suggestion that morphology may be the result of dynamical processes including ones associated with merging of
dark matter halos.

The important test objects here are the elliptical galaxies. Traditionally their uniform red colours and smooth isophotes of ellipticals indicate a rapid collapse at high redshift\(^{74,4}\). An appealing argument in support of this picture is that homogeneous populations of old cluster ellipticals can be found at high redshift\(^{75,76}\) suggesting that at least some completed their star formation before \(z \simeq 3\). However, in view of the accelerated evolution expected in dense environments\(^{44}\), a more critical test would be to examine the age distribution of field ellipticals.

Unlike clusters where the majority of sources are being seen at a single epoch, redshifts are necessary for each object in a field sample. Using optical colours to select candidate ellipticals from ground-based redshift surveys\(^{22}\), Kauffmann et al\(^{77}\) claim only a third of the present day comoving density of ellipticals at \(z \simeq 0.8\) are following evolutionary paths consistent with long-lived stellar populations formed at \(z > 3\). Such a rapid decline in established red field ellipticals is consistent with calculations which equate morphology with the bulge/disk ratio produced in a dynamical merger\(^{78,64}\).

Such dramatic evolutionary trends should be easy to test with HST data. Through a study of areas for which extensive ground-based spectroscopy had already been completed\(^{22,23}\), HST images are now available for over 300 field galaxies of known redshift\(^{30}\). A significant scatter is seen in the correlation between colour and morphology indicating the crucial advantage of HST in distinguishing morphologically between ellipticals and early spirals\(^{79}\). Although the samples remains small, field ellipticals do seem to be a less homogeneous population than the clustered counterparts\(^{80}\). A more powerful test of the merger hypothesis would be a direct estimate of the comoving number density of evolved (red) ellipticals as a function of redshift. Early results suggest a significant paucity of luminous red objects at faint magnitudes\(^{40,81,49}\).

A more complex topic is the history of disk formation. Gas cooling onto pre-existing dark matter halos produces rotating disks but star formation must be delayed until late times in order to avoid an over-production of small spirals which would merge too readily. Early formation also leads to a tidal transfer of angular momentum from the baryonic gas to the outer dark halo. To match the observed properties of local spirals, gas cooling has to be delayed to \(z \simeq 1-2\)^{82}. Again, recent formation is preferred and strong evolutionary effects are predicted.

However, the deepest HST images show no obvious decline with redshift in the abundance of spirals; well-formed examples are found at \(z \simeq 1\)^{30,31}. Unfortunately, a detailed census is not trivial to construct because evolutionary effects in stellar luminosity and disk scale size both affect the selection process. Surface photometry parameters such as the bulge/disk ratio, disk scale lengths and central surface brightnesses can be extracted from HST images\(^{83}\) and these indicate large well-formed spirals were as abundant at \(z \simeq 0.8\) as they are today\(^{31}\) with only modest changes in surface brightnesses over \(0.3 < z < 1\). A more detailed population analysis of HDF spirals further supports the suggestion of well-established stellar populations at \(z \simeq 1-1.5\)^{80}. 

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Ultimately one wishes to characterise evolution in terms of the assembling mass. The Keck telescope has provided the first rotation curves for HST-selected spirals to $z \simeq 1^{84.85}$ and such dynamical data could be combined with independent photometric estimates of luminosity changes to yield mass growth rates for direct comparison with theoretical models. At present, such analyses are confused by the possibility of different selection criteria and it has been argued that both datasets are consistent with significant recent growth.$^{86}$

Ellipticals and spirals account for only half of the global evolutionary trend between $0<z<1^{41.42.56}$. The remainder arises from smaller, more numerous, star-forming galaxies of irregular morphology$^{27-29}$ whose role remains unclear.$^{19}$ As their fraction increases with redshift, it is tempting to postulate these are ancestors of more regular systems. Numerical simulations in which the gas is clumped make this an attractive hypothesis.$^{87}$ However, so many irregular sources are seen, even at $z<1$, this seems unlikely. Their existence alongside well-formed spirals and ellipticals is evidence for continued star formation governed by processes in addition to gravitational collapse of gas into dark matter potentials.$^{88}$

Where Next?

HST has revolutionised this field by providing resolved images of faint galaxies. Allied ground-based spectroscopy has not only provided distances and luminosities, but long-slit techniques have supplied the first rotation curves at high $z$. A new generation of actively-controlled large telescopes are nearing completion and their image quality at near infrared wavelengths will approach that of HST.$^{89}$ *Integral field* spectrographs$^{90}$, where the sampling of a contiguous area of sky is reformatted to fit a long-slit instrument, will considerably extend the capabilities. For example, high redshift irregulars imply an erratic star formation history consistent with a time sequence of bursts associated with each physical component.$^{91}$ (Figure 4). Are these merging systems in a chaotic dynamical field or clumps in a well-established disk? Resolved 2-D spectroscopy will lead to an explosion of new data on the dynamics, excitation and dust content of young galaxies similar to that opened up with HST itself. The excitement generated by this year’s SCUBA results shows how dangerous it may be to rely on a narrow wavelength range. More extensive sub-mm and mm surveys including those with the proposed new millimetre arrays will provide more detailed information on the nature and extent of star formation in distant sources.

Our first glimpse of the history of galaxies to redshifts $z \simeq 5$ leads to the tantalising question of what happened before. The optimum strategy for probing the “dark age” beyond depends on the amount of dust at early times. If, as the limited SCUBA data currently suggests, dusty sources share a similar redshift-dependence to those probed by young stars then the early Universe may be relatively dust-free and searches based on emission lines from neutral hydrogen will be promising.$^{92}$ Such territory will be explored with projected facilities such as the Next Generation Space Telescope and large ground-based radio arrays.

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Figure Captions

Figure 1: [Main panel] The Hubble Deep Field: the deepest exposure undertaken at optical wavelengths\(^{18}\) and an inspiration to other instruments which have followed suit and imaged this undistinguished \(2 \times 2\) arcmin patch of sky in Ursa Major (see panel below). Despite the considerable exposure time, the rate of increase in galaxy surface density with optical faintness appears to decline beyond a certain level (inset) suggesting optical and infrared images reach to epochs before most galaxies had formed their stars. [Bottom panels] Whether the HST image offers a representative view of the deep Universe is a hotly contested issue. The same field studied with different instruments can address this question although none can yet match its depth and resolution. From left to right: ground-based near-infrared (Dickinson, Kitt Peak), mid-infrared (Infrared Space Observatory\(^{58}\), sub-mm (SCUBA, James Clerk Maxwell Telescope\(^{61}\)). [Inset: Galaxy number magnitude counts - a simple but powerful cosmological tool (see ref 19 for a recent summary). The logarithmic slope of the count-magnitude relation is a measure of the rate of evolution of the population with look-back time. The steep slope at moderate magnitudes contrast with a slightly flatter one at fainter limits. Galaxies near the point of inflexion contribute most to the integrated background light of the night sky.]

Figure 2: (Centre panel) The history of star formation inferred from optical and near-infrared ground-based surveys\(^{31,41,42}\). Below a redshift \(z \approx 1\), magnitude-limited surveys define the luminosity density by direct census. Above \(z=2\), the Lyman-limit imaging technique (left inset) locates those sources which reveal the characteristic signature of a ‘drop-out’ in flux in a short wavelength filter\(^{32,33}\). At intermediate redshifts, redshifts are estimated by fitting the spectral energy distribution defined by 4-7 colours\(^{42}\) (right inset). It is argued that the empirical data validates an early prediction of late galaxy formation central to the cold dark matter model of structure formation\(^{15,43}\). The key issue is whether the optical data includes most of the flux from star forming galaxies. [Insets: (left) Finding distant galaxies by the Lyman-limit ‘drop out’ technique (after Dickinson\(^{40}\)). Absorption by neutral hydrogen produces a characteristic signature at 912 \(\AA\) which, when redshifted, extinguishes a galaxy in a short wavelength filter. By locating that wavelength where the galaxy is no longer visible, an approximate redshift can be obtained. The technique is useful for sources with redshifts \(z > 2.3\)^{35}. (right) Photometrically-determined redshifts: By fitting the spectral energy distribution of a galaxy observed in many filters, the approximate redshift can be found\(^{42}\). The technique remains controversial since it is largely untested against the spectroscopic values (abscissa) in the region of interest \(1.2 < z < 2.5\)]

Figure 3: Nature versus nurture: did galaxies transform from one morphological type to another and if so, what physical processes were involved? (left panel) Local spirals and ellipticals defined according to Hubble’s original scheme\(^2\) contrasted with images of fainter, more distant galaxies taken with HST. A surprising fraction of high redshift galaxies appear disturbed and irregular indicating they are being seen in a juvenile state\(^{30,47}\). (right panel) The morphology-density relation; clustered regions today contain many ellipticals and lenticulars (S0s) but relatively few spirals\(^{65}\). Does this trend reflect primordial conditions
or recent environmental evolution? Systematic studies of clusters at earlier times\textsuperscript{66–68} have tracked the evolution in this relationship confirming that environmental effects shape the present-day appearance of many galaxies.

**Figure 4:** Determining the physical state of a young galaxy: Beyond $z \approx 1$ a typical galaxy is physically small consisting of numerous knots of activity. Does this represent chaotic activity in a well-established system\textsuperscript{87} or are we witnessing the active merger of numerous components as implied in hierarchical models? Integral field spectroscopy\textsuperscript{90} (top panel) offers the opportunity of sampling the dynamical and astrophysical properties of each component of a young galaxy. This can be coupled with detailed stellar population analyses based on multi-colour HST data which age-date physically-distinct sub-units\textsuperscript{80,91} (bottom panel). Such techniques will be exploited for the brightest galaxies with $1 < z < 3$ using the new generation of large telescopes, but such studies of more distant sources, including those in the ‘dark age’ beyond $z > 5$ await the Next Generation Space Telescope.
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