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Anna Pasquali *Editors*

Environment and the Formation of Galaxies: 30 years later

Proceedings of Symposium 2 of JENAM 2010

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Preface

The publication of the *morphology–density* relation by Alan Dressler in 1980 brought into the limelight the role played by environment in the formation and evolution of galaxies. During the following three decades, we have learned that galaxy evolution is driven by both intrinsic processes (typically controlled by galaxy mass, also known as *nature*) and environmental effects (usually referred to as *nurture*). At present, we still have to understand the details of the interplay between nature and nurture. The advent of large, homogeneous redshift surveys has been a major step forward in this direction, since it has allowed us to quantify environment in a more consistent way, sampling a large variety of galaxy environments (from voids to massive galaxy clusters, through different size galaxy groups). Large galaxy surveys at different wavelengths have enabled us to study how different galaxy properties (e.g. morphology, star formation, stellar populations, AGN activity) depend on environment. The comparison between the observations and the predictions from state-of-the-art semi-analytical models and numerical simulations of galaxy formation in a cosmological context has proven essential in disentangling the mass assembly history from the star formation history of galaxies, in connection with the environment where they live.

The year 2010 represents the 30th anniversary of the *morphology–density* relation, and we took this opportunity to organize the symposium *Environment and the Formation of Galaxies: 30 years later*, with the purpose of establishing the impact of environment on the evolution of galaxies and its dependence on look-back time. Special emphasis was given to the physical mechanisms that are responsible for transforming galaxies once they are accreted by a group or a cluster (e.g. ram pressure and tidal stripping), including the observable imprint left in the galaxy HI distribution. Other major topics of the symposium were the environmental dependence of galaxy properties at $z \geq 1$ and the implementation of environmental effects in cosmological models of galaxy formation and evolution.

This symposium was hosted by the 2010 Joint European and National Astronomy Meeting, held in Lisbon on 6–10 September 2010. We thank André Moitinho de Almeida and the 2010 JENAM Scientific and Local Organizing Committees for their support and help with the logistics of the symposium.

We warmly thank the other members of the Scientific Organizing Committee of this symposium: Alan Dressler (Carnegie Observatories), Gabriella De Lucia (INAF – Trieste), Sadegh Khochfar (MPE Garching), Bianca Maria Poggianti (INAF – Padova) and Frank van den Bosch (Yale University), for their priceless help in planning such an interesting symposium, and all the speakers and participants for making it successful.

Last, but not least, we would like to gratefully acknowledge financial support from The Royal Astronomical Society of the UK, and the Max Planck Institut für Astronomie (Heidelberg, Germany). Their support has been essential for the organisation of this symposium.

Heidelberg and London
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The Morphology–Density Relationship: Looking Back, Thinking Back

A. Dressler

Abstract The work I did in the late 1970s leading to the morphology–density relation was done in a time of rising interest in how galaxies acquired different morphological types. I describe briefly here how I contributed to this effort by adding a large number of morphologies for galaxies in rich clusters and the field. The strong correlation that I discovered between galaxy type and local galaxy density ran counter to ideas at the time that emphasized processes tied to the global cluster environment. Instead, it provided some of the first evidence for a hierarchical picture – one in which the density of the environment into which a galaxy was born would be its lifetime legacy. Though often cited as a relation between galaxy morphology and the influence of present-epoch environment, the morphology–density relation was interpreted by me, from the first, as the influence of the early environment of galaxy formation, passed down by the hierarchical growth of structure. In fact, it seems increasingly likely that the more fundamental correlation of galaxy morphology is with galaxy mass, and that the morphology–density relation is basically an expression of the prevalence of more massive galaxies in regions of higher galaxy density.

1 Destiny

In the film "Back to the Future" a hyper-nervous George McFly is pushed by his time-traveling son to invite Lorraine – Marty's future mother – to the *Enchantment Under the Sea* dance – a crucial event in Marty's own existence which his visit to the past has apparently endangered. A nerd of the first magnitude, George predictably botches the "you are my destiny" line his Cyrano-playing son has written for him – "you are my density," he flusters.

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As it turns out, density is destiny – in a hierarchical universe. We recognize today that the environment into which a galaxy is born is the one it will experience for the rest of its life. A galaxy residing in one of today's rich clusters is likely to have been bumping elbows with its siblings since birth, while one out in the boonies has grown accustomed to the lack of company. For most of the attendees of this symposium, these are common ideas – younger astronomers have grown up within the cold-dark-matter paradigm that has cemented such notions. But, around 1980, when the first steps were taken to integrate galaxy formation into a cosmological context, this was certainly not the common picture. On the contrary, astrophysicists believed that galaxy formation was a relatively rapid process that happened before large-scale structure had a chance to develop. A forming galaxy, it was said, could not "know" whether its *destiny* was to live in a cluster, a group, or a void. This was the context within which my discovery of a remarkably good correlation of galaxy morphology with the present-day *local* density of its surroundings was surprising, if not suspicious. What seems natural today was hard to fit into the work that was shaping the field, at a time when the first real progress was being made in this important subject.

In reading the abstracts submitted for this JENAM symposium, *Environment and the Formation of Galaxies*, I was surprised how many claimed they would show that local density was not the real driver of galaxy evolution, as (they apparently thought) I had argued in my 1980 paper [6].

Of course, I am ridiculously grateful to the conveners of this Symposium, Anna Pasquali and Ignacio Ferreras, for recognizing the work I did three decades ago, but especially glad as well that I have a chance to come here and explain why the morphology–density relation ran counter to this field's prevailing winds. In fact, I interpreted what I had found as evidence for the importance of *early* environment in shaping a galaxy's morphology and was almost strident in arguing that the later environment where I had found these galaxies was not likely responsible.

Perhaps I should have called it "the morphology-destiny relation" – maybe that would have made clearer what I thought it was all about.

2 Galaxies and Their Environments: History on a Budget

References to a connection between different kinds of nebulae, presumably the extragalactic ones, and the crowdedness of their surroundings can be found back to the eighteenth and nineteenth centuries, in the work of William Herschel and son John. But, with the limited depth of visual observations, and confusion about what nebulae actually were, it was not until the 1930s when these impressions were formally acknowledged, at least in a qualitative sense. In 1936 Edwin Hubble wrote, in the "Realm of the Nebulae" [13]

> There are some indications of a correlation between characteristic type and compactness, the density of the cluster diminishing as the most frequent type advances along the sequence of classification.

and, somewhat less obtusely,

> ...dominance of late typed among isolated nebulae in the general field.

In their famous 1931 paper showing the correlation of distance and redshift, Hubble and Milton Humason [14] had taken note of the fact that, in the Virgo Cluster

> Nebulae of all types except irregular are represented, but elliptical nebulae and early spirals are relatively much more numerous than among nebulae at large.

In 1936 Clyde Tombaugh [29], discoverer of Pluto – once a planet – was the first to map the Pisces-Perseus supercluster, and he noted that, in the richest clusters of this vast structure, elliptical galaxies were more concentrated than spirals. Always with the eye for detail, Fritz Zwicky [32] reported in 1942 that S0 galaxies in the Virgo cluster are distributed like the elliptical galaxies, not like the spirals – a prelude to what was to come.

I want to emphasize that these early references to galaxy morphology and environment were not linked to ideas about how galaxies had formed and achieved different types – the common reference to Hubble's belief that the morphological sequence was one of galaxy age is a myth. The credit for motivating the field to think about galaxy origins goes, I think, to Walter Baade [2] for his work in the 1940s relating the different stellar populations of the Andromeda galaxy to the Milky Way's Population I and Population II stars – stellar populations with known histories. In 1962 Olin Eggen, Donald Lynden-Bell, and Allan Sandage [9] took Baade's work a step further when they proposed a link between metal abundance and kinematics in the Galaxy that argued for an early and orderly collapse phase of the gas cloud that became the Milky Way, a breakthrough that also led a decade later to the picture of a more chaotic collapse, by Leonard Searle and Bob Zinn [27]. Thinking along similar lines, but with a different approach, Morgan sought a connection of these earlier galaxy correlations to stellar population types in his 1962 Russell Lecture, by comparing galaxy types with old and young star clusters and emphasizing how these are distributed within galaxies (bulge, disk, and halo) [19]. In retrospect, perhaps the first morphology–density relation was Morgan's "discovery" of cD galaxies and his conclusion that they were only found in the dense centers of rich clusters.

These were great steps forward. Unfortunately, before the 1970s there was no clear way to connect either galaxy morphology or stellar populations to galaxy formation, that is, there was no cosmological model like ΛCDM to help explore how different types of galaxies might arise. Without a starting point for galaxy formation models, the only ideas that could reasonably be put forward and tested were things that could happen to galaxies later in their lives that might force a differentiation. For example, in 1951 Lyman Spitzer and Baade [28] proposed that galaxy collisions in clusters make S0 galaxies, stripping the disk gas as the stars in two galaxies pass through each other. The idea died as the Hubble constant fell, but, with the advent of X-ray astronomy and the remarkable discovery of hot dense gas in galaxy clusters, Jim Gunn and Richard Gott [12] revived the stripping model in 1972 by inserting the hot intracluster medium (ICM) as the agent of change. They predicted that ram pressure would strip the gas from infalling spirals as they plowed through the ICM of a dense cluster core. In the same year, successful modeling of strong tidal interactions of merging spirals by Alar and Juri Toomre [30] suggested a mechanism for the formation of elliptical galaxies – another process that could happen late in a galaxys life. A few more ideas followed for turning spiral galaxies into S0s, for example, Richard Larson et al. [16] suggested that the stripping of gas reservoirs in the cluster environment simply shut down star formation in a spiral, and Len Cowie and Toni Songaila [4] and Paul Nulsen [20] suggested that – in the dense environment of a cluster center – hot X-ray gas would "boil away" a spiral's intragalactic gas.

While these somewhat piecemeal attempts to explain the origin of galaxy morphologies were being advanced, a more substantial assault on the problem began. Jim Peebles and Marc Davis were interested in pushing back to the early universe to provide a physical context for galaxy formation and the growth of large scale structure. Ironically, this bold new step only reinforced the idea that galaxy differentiation into morphological types was a late-in-the-game process. Their framework for studying structure formation was what Tjeerd van Albada [1] had called *gravitational instability*, the simple idea that fluctuations in density in the early universe would irreversibly grow in amplitude as the universe expanded over cosmic time. The question was, how to describe these fluctuations at some early time, so that they could be evolved and compared with the present-day structure of the universe – the only real data available at the time. In 1977 Davis and Peebles [5] presented an analytical solution of the statistics of such an evolving gravitation system and compared it to the "counts in cells" of faint galaxies in the Shane-Wirtanen catalog – from observations done with the Lick Observatory astrograph and stored on *sheets of paper(!)* in Santa Cruz. The formalism used by Davis and Peebles was general, relying on the power-law distribution of the fluctuation amplitude at some early time. Based on statistics of the *correlation function*, they derived a power-law spectrum of initial fluctuations with an index of $\eta = 0$ – what is commonly called "white noise," in effect, equal power at all "wavelengths" of structure. In such a universe, smaller structures (galaxies and very small groups) formed and matured much earlier than larger ones, e.g., rich clusters. In this context, and assuming that galaxies began to coalesce early, differences among galaxies would logically be the result of later processes – galaxies, it was often said, could not "know" when they were forming where they were going to wind up. The pioneering work of Davis and Peebles seemed to seal the deal: galaxies "differentiated" later in life, or again – in the lingo of the day – it was "nurture, not nature."

3 Grad Student Seeks Exciting Career Opportunity

From 1970 to 1976 I was a graduate student at Lick Observatory, UC Santa Cruz. I had the very good fortune of being at a department that was "on the map" and so many of the principals in the studies I have just talked about passed through and gave colloquia. For my own part, I was working on a PhD thesis project that involved taking photographic plates of clusters of galaxies with the Lick Observatory Crossley telescope, and scanning them with a machine that had been modified by me for the purpose, using one of the very basic computers of the day, a Digital PDP-8. This photographic photometry served as the basis for a study of the luminosity functions (LFs) of a dozen clusters of galaxies, specifically aimed at the question of the universality of the cluster LF that George Abell had suggested. In the end, the differences I found were small, and the few cases that seemed to depart from the "universal" form were arguably due to the gobbling of other bright cluster galaxies by a central cD. The universality of cluster LFs was another piece of observational data that supported the idea that all galaxies had formed in more or less the same way – environment independent, but my evidence was not as strong as Paul Schechter's comparison of field and cluster LFs [25] (the work in which Schechter developed his irreplaceable parameterization of the LF). Schechter's finding that cluster galaxy and field galaxy LFs were the same, within the errors, was yet further evidence that galaxies were born in common conditions.

In hindsight, we all really missed something here, something that turned out to be relevant to the work I would do a few years later that led to the morphology–density relation. Yes, the luminosity functions of field and cluster galaxies were in close agreement, but luminosity is a time-dependent parameter that changes with aging stellar populations. A galaxy's mass, by comparison, is more fundamental, and not subject to the rapid changes that are possible in galaxy luminosities. Mass can change as well, as with major mergers, of course, but that activity has died down considerably in the last half of the Hubble time. By the end of the 1970s kinematic measurements were already being combined with accurate photometry to determine visible mass-to-light ratios (hereinafter M/L), and it was becoming clear that elliptical galaxies typically had M/L values 2–3 times higher than late-type spiral galaxies, as reviewed in 1979 by Faber and Gallagher [10]. Combining this with what was known about the difference in morphological mix of cluster and field, it should have been apparent that the *mass* functions of the field and cluster could not be the same if the luminosity functions were. But, I know of no astronomer, me included, who put two and two together, so to speak, and drew this important conclusion from Schechter's work. If this had been recognized, it would have thrown a curve into the straight line thinking that galaxies were born in ways that were independent of larger-scale environment, because – on average – clusters of galaxies contain more massive galaxies than the field. I will return to this subject and its relevance to the mophology-density relation in my closing.

4 Making the Morphology–Density Relation

Around 1973 Olin Wilson of the Mt. Wilson staff came to visit the astronomers at Santa Cruz. At an informal sit-around, he was asked about the new du Pont telescope that Carnegie was building at the Las Campanas Observatory. What was special about this new telescope, he explained, was the Ritchey-Cretien design that gave it a well-corrected 2-sq-deg field, intended for first use with 20-in. photographic plates. The plate scale would match the 200-in. Hale telescope prime focus, 11-arcsec per mm, but the du Pont would have a field size more like a Schmidt telescope. A couple of years later, when I applied for a Carnegie Fellowship, this came up in a discussion with my thesis advisor Sandy Faber, who, in helping me come up with a research proposal for the application, asked me what were the most important "missing" data for understanding clusters of galaxies. This was, of course, galaxy morphology – the telescopes that could photograph wide enough areas of sky to study clusters had too small a plate scale for robust classifications, while those with a suitable scale typically had small fields. The relatively new 4-m telescopes at Kitt Peak and Cerro Tololo offered the right combination, but more relevant for this conversation was the du Pont telescope that Wilson had described. Following the work of Augustus Oemler in his PhD thesis at Caltech, I proposed to make a more extensive and more accurate (because of the high plate scale) study of galaxy morphology and its relation to other properties of clusters and their galaxies. Thanks to Faber's insight and guidance, I was able to write a proposal that won me a Carnegie Fellowship, an opportunity I had not thought possible at the time.

The du Pont was not quite ready when I arrived at Carnegie in the fall of 1976, but by the following spring Horace Babcock – Director of the Hale Observatories and the driving force behind Las Campanas and the du Pont – had taken the first photographic plates and demonstrated the excellence and power of the new camera. Because other instrumentation for the new telescope was still months away, I was given a generous allotment – what amounted to two full dark runs – in August and October of 1977. Armed with hundreds of "finder charts" of clusters of galaxies, I became the first astronomer to begin a science program with the du Pont. The television guide cameras were not ready either, so I had to use the main eyepiece of the telescope to verify the fields and to guide by hand paddle, scrunched underneath the telescope on long, cold winter nights and bleary-eyed, and then half asleep trying to develop all the plates in the afternoons. The August run was almost completely clear and by the end I was a wreck – but that is another story.

Over the next 2 years I accumulated plates of some 40 clusters in seeing of 1 arcsec or better with the du Pont, and added another dozen or so clusters with plates I took at the Mayall telescope and the Palomar 60-in. telescope. Carnegie had a carpenter on the shop staff in those days and he built a large light box for me, copying a design he had made for Allan Sandage, who was also an early, intense user of the du Pont camera. I fitted the light box with a drafting machine that would allow me to scan the plates with an eyepiece, measure positions, and compare to images of galaxies and galaxy bulges for a rough magnitude scale – a technique that was called flyspanking. Although imprecise, the systematic errors from this approach seemed to be small enough to yield useful data; this work served as the basis for a later paper by Schechter and myself [26] where we estimated the global bulge-mass/disk-mass in the present-day universe to be about unity, a result I think has stood up all these years.

It took about 8 months, as I remember, to do a raster-scan by eye of all the plate material; I recorded the data by hand on accounting paper that was later transcribed to IBM computer cards, one per each of the ∼6,000 galaxies [7]. I then started to investigate the data, starting with a comparison to Gus Oemler's [21] result of three characteristic population ratios. In the 1980 paper there is a plot of where each of the clusters I studied falls on this plane of the percentage of ellipticals and percentage of spirals – these were global measures of the total population out to an "effective radius." I interpreted Oemler's result as three discrete population types, but Oemler later told me that the distribution was probably continuous and the three types were only meant to be representative. He was more right than he knew, unfortunately: I found only a spread of points all over the map, scratched my head and moved on.

I next looked at the work of Jorge Melnick and Wal Sargent [18] on the populations of six X-ray emitting clusters, for which they found a rising S0 fraction with increasing velocity dispersion (a global relation), and a rising spiral-to-S0 ratio as a function of radius, a semi-global relationship. Both were consistent, they claimed, with ram-pressure stripping of spirals to make S0 galaxies. However, the scale and slope of this relationship was sufficiently variable in their six-cluster sample that "consistent" was about all one could say – and the same could be said for the radial correlations for my eight clusters that were strong X-ray emitters.

I searched further for meaningful correlations, basically following the "plot anything against everything else" approach. This seldom works and it did not here. I was somewhat distressed by this point; it seemed that several years of very hard work might be leading nowhere. Almost in desperation, I tried the one thing that seemed ridiculous given the notions we all had about cluster formation. I had noticed, as I sloughed through the examination of each and every galaxy in my 55 clusters, what seemed to be discrete clumps of galaxies – they looked like real physical associations. From the dogma of the day, I also knew that this was not thought to be possible – I reasoned that perhaps these were just foreground and background groups superposed on my clusters. One reason for this shared prejudice was Donald Lynden-Bell's slick answer to the baffling question of how clusters of galaxies could have such steep radial density profiles [17], when two-body relaxation was far too slow, a paradox Zwicky had raised decades before [31]. Lynden-Bell described a process he named with the oxymoron "violent relaxation," in which massive galaxies exchanged kinetic energy with light ones through the intermediary of the violently changing gravitational potential of the collapsing cluster. This reproduced cluster profiles very well, but it also was sure to scramble galaxies in the cluster and break up any loose groups, as can be seen in the 1970 simulation of the violent relaxation of the Coma cluster by Peebles [22]. Then, too, there was the prevalent belief that galaxy morphology had to occur late and that "galaxies could not know where they were going to end up" idea. It just did not seem reasonable that there were distinct subgroups in rich clusters and that they had unique population mixes.

Nevertheless, clueless of what else to do, that is exactly what I decided to look into, writing a computer program that calculated the local projected density of each galaxy by measuring the rectangular area over which its ten nearest neighbors were

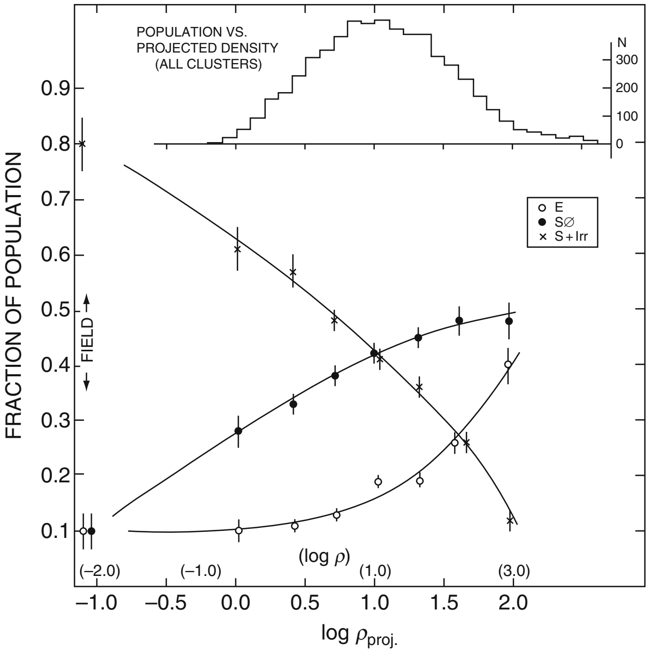

Fig. 1 The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster and field galaxies in the 1980 sample. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density. Figure from [6]

distributed. The program ran on one of the central mainframe computers at Caltech, with the two boxes of punchcards that recorded the data. A few minutes of CPU time on the IBM mainframe computer of the day was required to do this millisecond's of work on my Powerbook. I ran the first half one night and plotted up the data. Barely able to contain my excitement and to resist telling anybody what I thought I had found, or even to sleep, I ran the second half over the following night.

What emerged was the now familiar diagram of Fig. 1. What I had found astonished me, especially given the weeks of casting about for some correlation good enough to think about. I had the greatest enjoyment and satisfaction in my astronomical career trying to figure out what this excellent correlation meant. Although this was early in my career, I somehow knew already that moments like this were rare – I wish that every scientist could have this good fortune. In short order I had compared the morphology–density relation to the morphology-radius relation for the same clusters and found, unsurprisingly, that in very regular clusters with little substructure the results were very similar, but that the morphhology-density relation held even in very clumpy, irregular clusters, where population correlated poorly with radius. Clearly, it seemed that the clumps were real physical associations and the correlation of morphology was with a local rather than global parameter. The implication was that galaxies had gotten their morphological type from some process that had more to do with their local environment than some global process such as ram-pressure stripping. I did look to see if I was missing any "second parameter" to the morphology–density relation, but the only one I found was that the strong X-ray emitting clusters seemed to have slightly offset curves, meaning fewer spirals and more E's and S0's at a given density – perhaps that was a second-order global effect.

I am still surprised that through these many years there have been occasional papers arguing that the morphology-radius relation is the fundamental relation, not the morphology–density relation. My own work aside, what I find decisive is the remarkable study by Riccardo Giovanelli et al. [11] of the Pisces-Perseus superclusters in which they show maps across a wide swath of sky sliced by morphological type. Figures 1 and 6 of that paper show a vivid correlation in pictorial form of galaxy morphology with local-density over a wide range of environments, from rich clusters, through rich groups, to poor groups, to isolated field galaxies. The rich clusters – where global effects might plausibly dominate – look to be part of smooth, continuous relationship, rather than a special environment. In their study of the *low-density group* regime of the morphology–density relation, Marc Postman and Margaret Geller [23] found the same behavior as did Giovanelli and collaborators. I still find the evidence from these studies to be compelling, but by now there is also the well accepted paradigm of the hierarchical growth of structure that seems to me to obviate global processes as the primary driver of morphological differentiation.

5 What Did It Mean? For That Matter, What *Does* It Mean?

It seems amazing to admit that even 30 years later we are still not sure why there is a strong correlation of galaxy type with local density. From the start, many in the field pointed to it as further evidence for mergers or ram-pressure stripping in the shaping of galaxy morphology. Qualitatively, of course, the disappearance of spirals in the dense regions of rich clusters looked like evidence for ram pressure stripping, or perhaps the Larson et al. stripping of gas reservoirs from spirals. But, a more careful look at the morphology–density relation showed that the S0 fraction rises more slowly than the spiral fraction plummets – no one then (or now) expected that some of those supposedly stripped spirals were adding to the elliptical population. Furthermore, the upturn in the elliptical fraction – coming as it does for the densest regions – is certainly not what is expected if late mergers were responsible, because the high velocity dispersions of such regions strongly discourage them. So, right from the start, I thought that the morphology–density relation was in conflict with these popular ideas.

For me there was one other point that was compelling for the question of late processes transmuting galaxy types. How could the fractions change so slowly, I wondered, over two or three orders of magnitude in space density? What kind of physical process was so weak and yet apparently so effective? I expressed the points