The Role of Astronomy in Society and Culture
Proceedings IAU Symposium No. 260, 2009
D. Valls-Gabaud & A. Boksenberg, eds.

doi:10.1017/S1743921311002109

The growth of astrophysical understanding

Martin Harwit
Cornell University 511 H street, SW, Washington, DC 20024-2725, USA
email: harwit@verizon.net

1. Introduction

Since this symposium commemorated Galileo's discoveries and was concerned with astronomy and culture, I thought I might examine the extent to which culture affects how we view, depict, and ultimately come to understand the Universe around us. Twenty-five years ago, Andrew Pickering, wrote *Constructing Quarks – A Sociological History of Particle Physics*, (Pickering 1984) a book that enormously annoyed the high-energy physics community, perhaps because it contained a disquieting dose of truth. Pickering argued that the theory of fundamental particles, the particles that make up the atomic nucleus, and break up or fuse into myriad other particles when smashed into each other, was a construct that physicist had pieced together, through a process he termed a "*communally congenial representation of reality*". Physicists, he claimed, had arrived at a so-called "standard theory" of particle physics that was not an inherent description of Nature, but "*deeply rooted in common-sense intuitions about the world and our knowledge of it*". Instead, Pickering surmised that a better depiction of particle physics would eventually be found, which would appear unrecognizably different from what had come to be the accepted way of viewing Nature's fundamental particles. Today, many particle physicists would be more likely to agree with Pickering than they were then. Although the standard theory has successfully survived a quarter of a century of testing, its scope is known to be limited. It fails to properly accommodate gravity. And the string theories, brane theories, and other attempts of particle physicists to produce a coherent theory of all the known forces of nature have so different a structure from the standard theory, topologically, as well as in terms of numbers of spatial dimensions, that they share little recognizable resemblance. So, we may ask, was Pickering right? Are physicists and astronomers just constructing congenial representations that bear little relation to the inherent structure of the Universe we inhabit? In astronomy, we have by now embraced what we term the "concordance model" based on general relativity, which we assert has led to tremendous strides in understanding the evolution of the Universe. But we find ourselves forced to postulate a new form of matter, dark matter, the existence of which is supported by little independent evidence, and we find ourselves forced to postulate the existence of a new form of energy, dark energy, for which there is similarly little independent evidence. Perhaps both these postulates will someday soon be justified. But we may equally well find a need for viewing the Universe in a totally different way that encompasses general relativity only as a limiting case, but embraces dark matter and dark energy as a natural consequence. Such a depiction might then be just as mind-bogglingly different from what we conceive today, as Einstein's postulate was, when he first annunciated it, that the speed of light would always appear the same no matter how fast an observer was moving toward or away from its source. How could that be, it violated every conceivable human intuition?

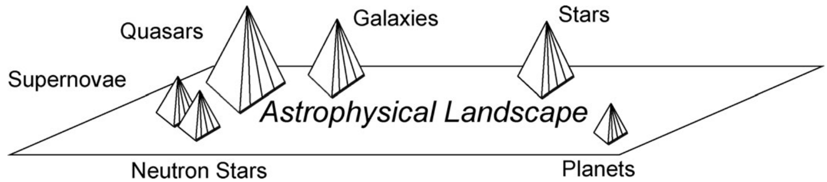

Figure 1. The astrophysical landscape.

One might argue that such drastic changes in how we view Nature are just a natural progression of science, whether physics or astronomy – that ultimately, after a long series of revision after drastic revision, we come ever closer to accurately describing the nature and evolution of the world around us. But when we look back at the history and sociology of science over past centuries, it is obvious that different cultures saw the world we inhabit in very different ways, judging the validity of their worldviews on grounds that we today dismiss as unscientific and therefore irrelevant. But even within the established scientific community heated arguments can arise because different factions dismiss one form of evidence while emphasizing another. The conclusions reached by antagonists can then lead to totally different worldviews, each the product of a very different cultural approach to science, as Ludwik (Fleck 1935) first taught us in a long-neglected book, where he documented convincingly the extent to which a scientific community conforms to cultural authority and resists new ideas and concepts, often remaining wedded to prevailing thought until long after it has outlived its usefulness. A quarter century after Fleck, Thomas Kuhn, echoed the same theme in his depiction of The Structure of Scientific Revolutions (Kuhn 1962). So, if we wish to examine whether or not our cosmologies are just a "*communal construct*", we should begin by looking at whether or not Pickering, Fleck, and Kuhn, might be right, that we astronomers work under a tightly coordinated, culturally-imposed authoritarian system. This is what I will now try to do (Figure 1).

The everyday work of astronomers and astrophysicists takes place within a well-defined landscape that represents the astrophysicist's view of the Universe (Figure 1). It mirrors the interaction of stars with their surroundings, the interplay of galaxies within their clusters, and our heritage from an earlier phase in the evolution of the Universe in which some of the chemical elements we see around us today were first forged at temperatures of the order of billions of degrees. The everyday task of the astrophysicist is to gather additional information and make the new pieces of observational and theoretical evidence fit neatly into this landscape, making sure that nothing is missing and, to the extent possible, everything is tidy and explained. This can be an arduous process. Each newly gathered piece of evidence clamors for a place in the landscape but often will not fit. To accommodate it, other pieces of the landscape have to be moved around, and so the landscape continually changes. But although the astrophysicist often thinks it is, this landscape is not totally isolated. Occasionally, some other form of human activity intrudes drastically altering the landscape (Figure 2).

Astrophysics is then in temporary disarray. Unrecognizably disfigured, the landscape then needs urgent reconstruction. (Note how the word "construct" hides within "reconstruction"). In the post-World War II era, radio, X-ray, gamma-ray and infrared observational discoveries shook up the field, time after time reconfiguring the landscape. Often we did not even have time to pick up the pieces and reassemble them before the next discovery disrupted our efforts. Each major discovery came as a surprise because the landscape that had previously been assembled had meticulously attempted to exhibit continuity and coherence, leaving little room for unexpected external influences.

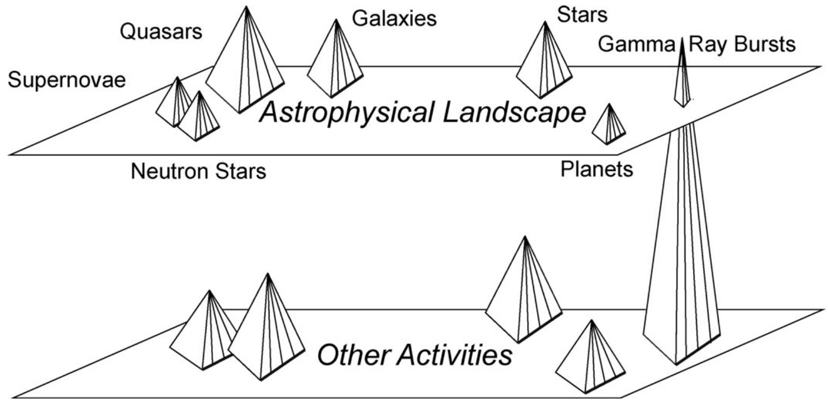

Figure 2. The landscape of some other human activity.

Until World War II, our astrophysical theories had been too narrowly defined by observations gathered almost exclusively at visible wavelengths. The War introduced new technologies that led to the discovery of phenomena, which had left no imprint of themselves at visible wavelengths. Viewed in isolation, these technologies constituted a totally different, previously largely ignored world – a landscape of their own – from which time and again disturbances emanated to alter the astrophysical landscape. The tools these technologies could provide had – and even today have – no assigned place in the astrophysical landscape, i.e. in our views about the world we live in. But, if you are cognizant of the technological landscape, you possess information about all the conceivable ways in which the Cosmos might ultimately be studied and have a map which tells you where observational astronomy has thus far failed to take a foothold. This is where new observations will most likely produce novel insights. The Universe is so complex that theoretical predictions have usually failed to extrapolate from known observations into areas where observations are still lacking (Harwit 1981). Novel technologies, however, are not the sole external influences that shape the astrophysical landscape. Mathematical models of the underlying cosmic topology and geometry, and the ability to compute complex interactions or analyze vast accumulations of data can similarly lead to new world views. Discoveries of novel physical or chemical processes, or advances in mineralogy can similarly elucidate astronomical processes. And, certainly, governmental decrees, often based on a nation's current economy or military priorities, can command new directions of research. Control of the purse channels scientific projects. Investigations that looked promising are dropped for lack of funding; new projects are started because they can be financed. Rarely do scientists swim upstream against the budgetary flow. Most astronomers follow the money. Any of these external influences can overnight determine that work on tidying one domain of the astrophysical landscape will stop, while some other, more remote, less developed domain that had been too difficult to investigate under previous external influences becomes accessible. Astrophysicists then revise their efforts, and begin to re-order, re-configure, and tidy this new domain of the landscape to possibly gain further insights on the workings of the Universe. From this we see that the direction of our research is at least partially influenced by outside cultural forces.

2. Landscapes and communities

To a large extent, the different landscapes I have described mirror the work of different professional communities. Mark Newman of the University of Michigan has looked in

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press

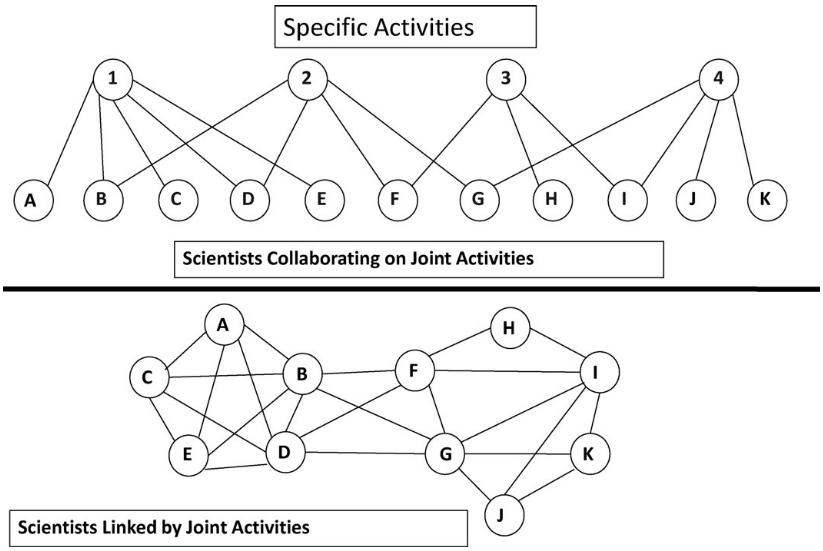

Figure 3. Scientists linked through joint activities, after Newman, Strogatz & Watts (2001).

some depth at the links that tie these communities. Two types of activity tend to provide astronomers the opportunity to establish mutual respect, trust, and influence. The first is through collegially-conducted research, as indicated by jointly published papers. The second is through joint service on professional boards or committees, or other close contacts. These links can be represented in two ways (Figure 3).

One indicates the specific activities involved. The upper half of the figure shows four activities, say four scientific papers numbered 1 to 4 on which some eleven scientists A through K worked in groups. Scientist D was a co-author with A, B, C, E, F and G, and thus had direct links to them. Author H is directly linked only to I and F, and via F is linked through a second step to D. The lower half of the figure drops all reference to the linking activities and merely shows which scientists are linked to each other, albeit making the linkage between them more explicit.

Within any one professional group, astrophysicists, instrument makers, theoretical physicists, or government officials, the interaction between individuals can be close because they have worked together on some form of activity (Figure 4).

Links across different professions generally are relatively infrequent but can be among the most influential (Figure 5). Although only a few astrophysicists have close ties to government officials and perhaps rather more of them to instrument builders or theoretical chemists, these few links between members of different professions suffice to bring all the different communities into effective working contact. Across the entire community of scientists, the network of astronomers is merely part of a much larger network.

Newman has analyzed some of these networks by tracing the collaboration between astronomers on research papers, as reflected by `ArXiV/astro-ph` entries over a five-year period from 1995-99, by when `astro-ph` had become a widely used pre-publication forum (Newman 2001a). He argues convincingly that two astronomers who have completed a co-authored paper must know each other very well, particularly if the number of co-authors is small. Studying co-authorship then becomes a way of assessing the extent of cross-linkage across our profession. Three interesting characteristics emerge from Newman's work:

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press

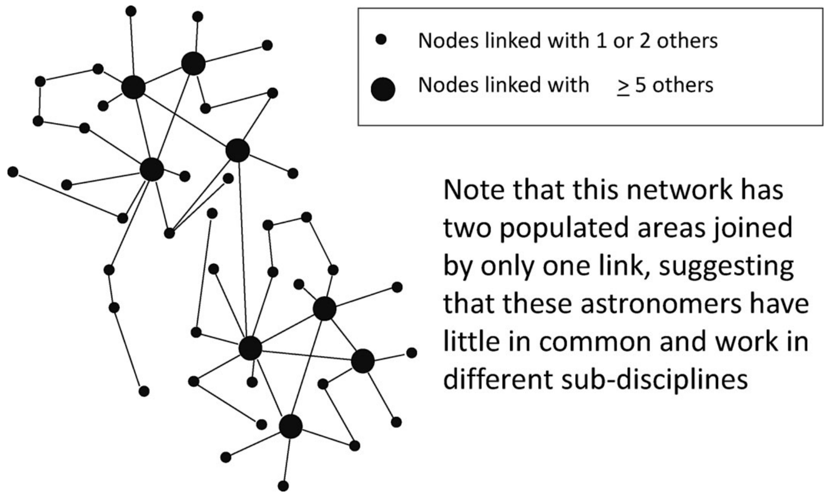

Figure 4. Scientists linked through joint publications sit at nodes in a network.

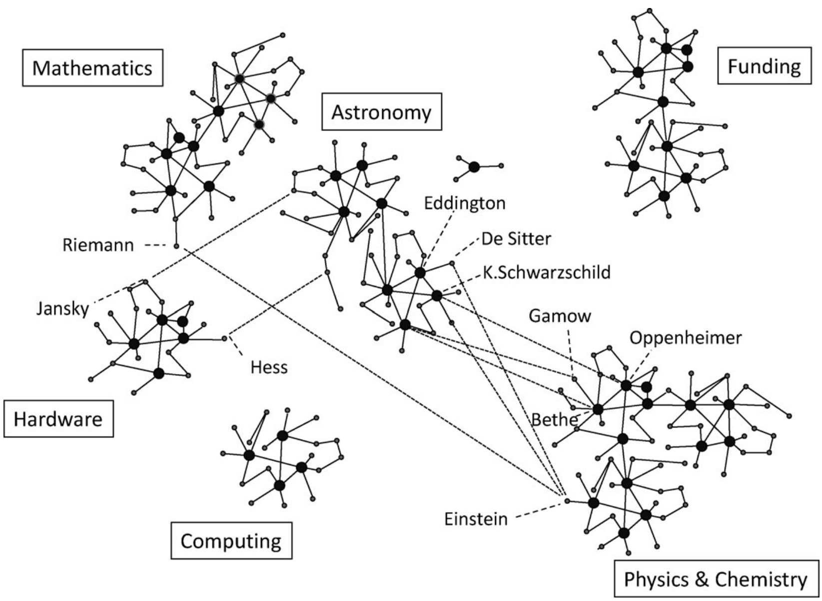

Figure 5. Astronomy is merely part of a larger network.

First, the existence of a giant component of the community consisting of roughly 90% of all astronomers who are so closely linked through joint publications that, on average, it only takes 4 or 5 steps, or 3 to 4 intermediaries, for any one member of the community to contact any other whom he or she might not personally know through joint authorship but who could be reliably contacted through just a short chain of intermediaries who have co-authored papers. This giant component arises through a phase transition from what might, at the left of Figure 6, have begun as a gas of weakly linked individuals who, through increasing collaboration, gel into larger liquid assemblies, in the center,

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press

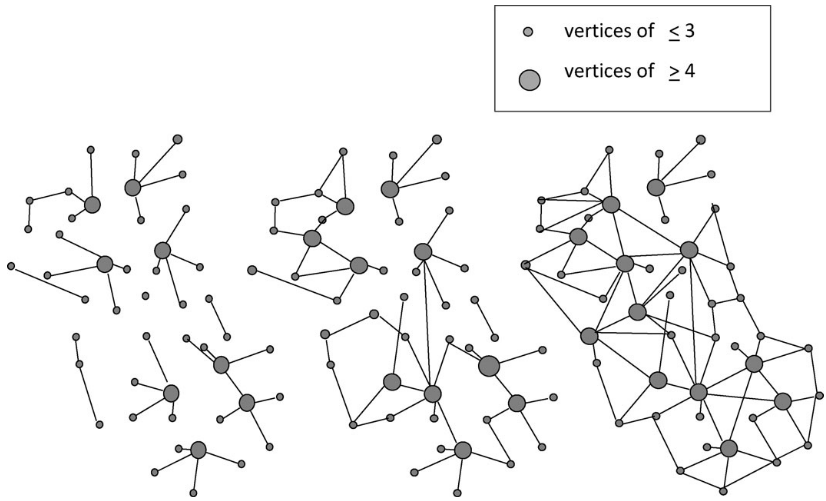

Figure 6. Phase transition of a network as it locks into a solidly linked giant component. Note the small isolated cluster remaining detached at upper right.

flowing past each other with minimal interaction, before, on the right, suddenly freezing into a solid community through only slightly further increased linkage. The maximum distance, today, between the most remote two astronomers who are members of this giant component is 14 of these links, or so-called "geodesic steps" across the network (Newman 2001b). For other scientific disciplines, Newman finds similar characteristics.

Second, the giant component links roughly 14,850 astronomers among a total of about 16,700 (Newman 2001b). Only about 10% of all astronomers have published work that has no cross-linkage to this giant component, or group. The maximum size of the co-author linkage within this second largest component numbers only 19 linked authors – a grouping nearly one thousand time smaller than the giant component. There are thus hundreds of publishing astronomers who work by themselves or in small groups, and whose work may be largely disconnected from the interests of, and perhaps totally ignored by, the vast majority of astronomers, most of whom learn about interesting results by word of mouth from trusted, closely-linked colleagues.

Newman's third finding is that a rapidly declining rate of joint-publications-rates places a very few highly published individuals as key intermediaries along the shortest path joining other members of the field, making them most closely connected, best informed and thus most influential members of the field. This is no small effect. Newman finds that the most highly linked individual in the field by virtue of co-authorship is substantially more highly linked than the second highest member who, in turn, is substantially more highly linked than the third most highly linked member, and so on (Newman 2001b). But it is not just the number of co-authors to which these individuals are linked that counts. Experimental high-energy physics collaborations often have many hundreds of collaborators, most of whom hardly know each other. Newman has established a criterion he calls the "collaboration strength", which ranks individuals highly if they publish many papers with relatively few co-authors. The strength of the link to each co-author is weighted in inverse proportion to the number of co-authors on a paper (Newman 2001c).

The status of highly linked intermediary has the potential of making an individual influential in sifting and transmitting new ideas. Newman suggests that these rare

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press

individuals are well-positioned to fashion opinions, decide what makes sense, and what does not, which ideas are to be accepted, and which are not, which areas of astronomy deserve further pursuit and funding – and which do not. Knowledge is power. At the other extreme, the subset of around 10% of the community that has no links to the giant component has virtually no influence. As everyone including Newman recognizes, joint publications are not the sole contacts that forge firm links between astronomers. Joint service on advisory panels, visiting committees, and planning boards, offer similar opportunities to fashion respect, trust, and consensus on directions that astronomy should be taking. Whether there is a close correlation between those who publish most and those who sit on these panels, boards, and committees has not yet been quantitatively researched, but it does not take much familiarity with the astronomical community to realize that there is a high correlation. Those who publish and co-author widely also find themselves asked to serve on influential committees.

Newman has studied the boards of Fortune 1000 companies, the thousand largest US corporations, and finds that directors who sit on only one of these boards are statistically likely to find themselves in the company of other directors who also sit only on one board, whereas directors who sit on many boards tend to have fellow directors who similarly sit on numerous boards. These are the most influential individuals. They spread their communal influence through the interlocking directorates on which they sit Newman, Strogatz & Watts (2001). Astronomical boards and committees are similarly constituted. Most of those conducting the 2010 Decadal Review of astronomy that has just started in the United States sit on many other advisory boards as well. Through these connections they influence decisions on new directions of research, on new facilities to be constructed, on the allocation of budgets and allotment of observing time, in short on how astronomy and astrophysics evolve.

3. External influences

Aside from influences on the course of astronomy from within the field, we also have seen external influences. The landscapes I had earlier drawn correspond to different realms of human activity, different scientific or technical fields, or funding structures. The influence exerted by workers from one field on developments in another, often occurs through the transmission of new tools. Scientist and engineers like Viktor Hess, who discovered cosmic rays, Karl Jansky, who first detected radio emission from the center of the Milky Way, or the Naval Research Laboratory scientists, who first measured X-rays from the Sun, made important contributions through the new tools they provided astronomers. They became members of the astronomical community, if at all, only after they made their contribution to the field, rather than before. To some extent the same holds true of the theoretical physicists who made fundamental contributions to astronomy and cosmology. People like Hans Bethe, Albert Einstein and J. Robert Oppenheimer would have thought of themselves purely as theoretical physicists bringing a useful new theoretical tool to bear on astronomical questions. The journals in which they chose to publish their findings all were issued by physical rather than astronomical societies. Interestingly, Einstein, whose work had a profound influence on early-twentieth-century astronomers, like Karl Schwarzschild, Arthur Stanley Eddington, and Willem de Sitter, was himself strongly influenced by the work of the 19th century mathematician Bernhard Riemann. All of these links stretched to join different scholarly disciplines.

4. Growth of the astrophysical community

Let me now look at the question from yet another perspective. In general, we expect the rate at which astrophysical understanding accumulates to correspond, in some fashion, to the number of active investigators. But does it? And, if so, what are the limits that determine how many scientists might or should devote themselves to astronomy. Young astronomers brimming with enthusiasm often cannot understand why nations do not spend far greater sums on astronomy. The answer is simple. Most citizens would prefer to feed their children, assure them of good health, send them to good schools, and provide them a secure, predictable future – rather than to be taxed to support the conduct of astronomy at the expense of their children. A primary, and readily understandable limit on the size of the community of astronomers and astrophysicists, then has to be funding that society can afford. But within this constraint other limits exist as well. The theoretical anthropologist Roland Fletcher has identified three such limits in his studies of the growth of human settlements, communities, villages, towns and cities (Fletcher 1995). Remarkably, the same limits seem to also apply to the growth of the astronomical community worldwide. The first of Fletcher's limits arises where the density of a community becomes so high that people interfere with one another's activities. When that happens, the community ceases to grow. Its members move elsewhere. Fletcher calls this limit the interference limit and designates it by the letter I. The mutual interference between astronomers is perhaps nowhere as apparent as in what the directors of major astronomical observatories somewhat euphemistically call their "oversubscription rates". A high oversubscription is considered a mark of an observatory's distinction and success. If four times as many astronomers are submitting applications to make use of the observatory than can actually be accommodated, the observatory must be offering a service that is highly valued. The flip side of this is that three out of every four astronomers who would like to make use of the observatory for their research are turned down.

Such oversubscription rates are not uncommon, either for observatories or for funding agencies. The result is that astronomers spend an inordinate amount of time writing proposals, knowing that the chances of having one that succeeds will often require the submission of another three that will be turned down. Since the entire system of graduate student education depends on raising enough money or obtaining observing time at an observatory, or other resources to support students' studies, most senior researchers involved in education cannot escape the necessities of competing for their share of support. Instead of devoting themselves to research, which is what they do best, they spend their time on entrepreneurial activities. This is where the I-limit most surely applies. When astronomers spend all of their time writing grant applications and none on research, we will have reached the limit where further growth is self-defeating. The field will be overcrowded.

Venturing into a sparsely populated new discipline, however, is not without its dangers either. If the field attracts little interest, nobody will care much about what you do. Your publications will not be read and the funding required for your research will be hard to attract. Fletcher then defines a threshold, designated T, below which a community cannot be expected to flourish. A flourishing new science requires interaction, discussion, debate, cross checking, refutation, and ultimate acceptance. Unless it succeeds in attracting more colleagues, the larger community will ignore its work; nobody is going to bother with it. Fletcher's third and final limit is the communication limit, designated C. Unless satisfactory lines of communication can be maintained across a discipline it will not flourish either. The field may then split into smaller disciplines that hardly communicate. This is already true of the larger well-established field of physics. Note the

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press

clumps in physics, mathematics, and astronomy in the impressionistic Figure 5 that are joined by only a single link. At one time the American Physical Society published The Physical Review, a journal for professional physicists. This has now split into Physical Review A, which publishes articles on atomic, molecular and optical physics; Physical Review B, which specializes in condensed-matter physics; Physical Review D, providing an outlet for "particles, fields, gravitation and cosmology" and so forth, through Physical Review E. These journals' fields seldom intersect, but in order not to lose total oversight, the Physical Society does publish Physical Review Letters, which accepts short research accounts on all sorts of topics that may be of interest to physicists working in areas quite different from those of an article's author.

Astronomy and astrophysics are now approaching a point where a lack of communication no longer permits most members of the field to maintain insight on work conducted in specialty areas other than their own. As Fletcher points out the I- and C-limits are not absolute. They can be overcome by taking suitable measures. In astronomy and astrophysics the tendency to avoid the I-limit is expressed in a steadily increasing joining of forces. Instead of competing against colleagues, you join them, often in the name of accomplishing more through joint rather than separate efforts. The joining of forces also translates into the increasing number of authors appearing on articles that, in earlier decades, might have been written by just one individual, or perhaps by a student and his professor. Hence the increasingly dense links between authors, and the emergence of the giant component of astronomers who publish jointly and think alike. Overcoming the communications limit will prove to be much harder. While communications links are strong within a specialized subfield, the larger community is losing touch with developments elsewhere. Splintering the field entirely is clearly undesirable. Something needs to hold astrophysics intact, otherwise we will miss the grander features of how the Universe evolved. The communications barrier is not the speed with which we can access information. Computerized archives already inundate us with anything we ask for. However, we may have to find ways to more quickly absorb information, either by improving techniques for entering it into our consciousness, or through means to extract key data from a mass of information in which they are embedded. Note how the limits to growth I have just described reflect the findings of the network theorists. The threshold limit corresponds to the portion of the network disconnected from the Giant Component. Community members that are part of the Giant Component remain ignorant of unlinked publications. The mutual interference limit which forces astronomers to work on ever larger collaborations, is traced by the appearance of ever more numerous linkages across the network, as people opt to collaborate instead of competing. A rapid escalation in the numbers of links to network nodes therefore heralds the approach of the interference limit. The communications limit makes itself partly apparent when the network starts to split into densely connected clusters with few links in between. The networks reflecting publication patterns, therefore, provide a way of tracing where astronomy and astrophysics are headed. An overly dense linkage in the field carries more than just a threat of mutual interference or of break-up of communication. It also heralds a potentially unhealthy congeniality of thought.

5. Pickering's assertions

It is these linkages, these large collaborations, this mutual acceptance of world models that Andrew Pickering's work was pointing out. This is what led to his concern that science is a social construct, rather than a gradual approach to some greater inherent truth about the structure of the Universe. So we return to Pickering's thesis and ask, "*Do our modern views about the Universe reflect its inherent properties, as is generally believed, or is the Universe a social construct?*" In brief, I am asking, "*Who actually runs the Universe?*" Is it some set of forces inherent in Nature? Is it the set of influential astronomers? Could it be the governments, which through the moneys they allocate determine the direction of research, or religious leaders who at some level influence thought? The answers to these questions are only partially clear: I think we can rule out the governments and religious leaders. They may have the motivation, but probably not the technical means. On the other hand, the most tightly linked astronomers in the networks revealed by Newman's studies do have not only the motivation, but also the opportunity and the means to fashion the Universe. The motivation may be a sincere wish to take astronomy into promising new directions. The opportunity and the means are provided by the boards on which these influential members of our community are invited to serve – boards asked to recommend which new observatories should be constructed, who will direct them, and how moneys should be distributed among the research projects they might carry out. But, just as in a court of law, motivation, opportunity, and means are merely circumstantial evidence. The question is, "*Do the most influential astronomers really run the Universe?*"

My impression is that in areas where we have a large accumulation of evidence, our astrophysical and cosmological theories do largely reflect a physical reality. Where evidence is scarce, however, the tightly knit community of leading astrophysicists is, in fact, engaged in constructing the Universe. And since we have already made all the easy discoveries, and those harder to make are becoming increasingly expensive, we may ultimately end up at a point where further research is no longer affordable. This wouldn't be all bad if, by then, we had ceased to uncover anything new. But with each instrumental advance we are still finding ever more tantalizing cosmic features. If this continues, we may ultimately be stuck with a model of the Universe that satisfactorily explains all the well-established observational features, but leaves rare phenomena, possibly involving the remote past history of the Cosmos, in the theorists' hands. If so, we will then have a Universe that, in some fundamental ways, will indeed be an astrophysicists' construct, whose verification will be unaffordable. This would be a terribly disappointing end to a journey on which Galileo embarked 400 years ago and which we have been pursuing ever since. We may have to learn to budget the cost of astronomy ever more prudently to keep this journey alive. But I know of no reason why we should not be able to continue for many more centuries to come, if only we can learn to live with each other and our planet. If we persist and, like Galileo, use ingenuity and affordable means, we may yet reach the goal of finally divining how the Universe began, how it evolved, and how it magically created life. Nothing could be more rewarding, when we reach that goal, than to establish that it is indeed the Universe that controls its own course and evolution, that the Cosmos is not a mere construct of human minds, and that our efforts at research have finally been rewarded with a recognition of how our world began, transformed itself over the eons, and gave rise to living matter, including us!

Acknowledgements

Research on this article was started while I was a Distinguished Fellow at the Institute of Advanced Study, Durham University, UK, in the fall of 2007. I am indebted to two of the other fellows visiting Durham at the time. Roland Fletcher's ideas on the growth of settlements greatly influenced my thinking; and David Stark first pointed out to me the work of Duncan Watts and the need for understanding social networks, and the quantitative insights they are able to yield. I take great pleasure also in thanking my hosts at the Institute, whose hospitality made my stay both enjoyable and fruitful.

References

Fleck, L. 1935, *Entstehung und Entwicklung einer wissenschaftlichen Tatsache* (Basel: Benno Schwabe), translated as *Genesis and Evolution of a Scientific Fact* (Chicago: University of Chicago Press)

Fletcher, R. 1995, *The Limits of Settlement Growth: A Theoretical Outline* (Cambridge: Cambridge University Press)

Harwit, M. 1981, *Cosmic Discovery The Search, Scope and Heritage of Astronomy* (New York: Basic Books)

Kuhn, T. 1962, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press)

Newman, M. J. E. 2001a, *Phys. Rev. E*, 64, 016131

Newman, M. J. E. 2001b, *Proceedings of the National Academy of Sciences*, 98, 404

Newman, M. J. E. 2001c, *Phys. Rev. E*, 64, 016132

Newman, M. J. E., Strogatz, S. H., & Watts, D. J. 2001, *Phys. Rev. E*, 64, 026118

Pickering, A. 1984, *Constructing Quarks: A Sociological History of Particle Physics* (Chicago: University of Chicago Press) , p. 413

https://doi.org/10.1017/S1743921311002109 Published online by Cambridge University Press