The frontier Universe: At the edge of the night

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The place we call our Universe is, for the most part, cold and dark and all but endless. It is the emptiest of empties. It is old, and yet young. It contains much that is dead, and yet much that is alive, forever re-inventing itself, and sometimes inventing something wholly new. It is permeated in a vacuum more than a billion, billion times the rarest air that ever wafts across the peak of Earth's Everest. This vacuum, though an insulator to sound and material communication (in part owing to its unimaginable expanse), is clearer by many orders of magnitude than the clearest Colorado sky, and so transmits across itself rich signals of light and gravity that reveal both its present-day and ancient workings.

Our Universe is larger than we humans can comprehend in any real sense, and it contains all we know. It is to our time what the Earth alone was to the ancients, but it is more, as well. For this magical place, this *all*, this *Universe* is also a source of inspiration, awe, and wonder that few humans can resist when they truly contemplate its meaning. So too it is the home of our home world, our home Solar System, our home Galaxy, and very likely all that we as a species and a civilization shall ever comprehend.

Within the depths of our Universe lie countless galaxies, and within each galaxy countless star systems and even more countless planets. Our Universe contains radiations that, while bathing it in light, poison many of its locales against anything we mortal shells of carbon and water could ever survive. And beyond the light and radiation, our Universe very likely contains inhabitants as bizarre and different from one another as black holes, quasars, roses, and the lurking hulks of faint, diffuse galaxies as ghostly as any Transilvanian fog. Perhaps the Universe also contains countless examples of life that are self-organizing and sometimes self-aware, counter to Nature's entropy. Perhaps not. We do not yet know.

In a scientific sense, we humans have only known that there even *is* a universe in the space beyond the Earth for a few handfuls of generations—far less than 1% of the time our species has walked this green Earth. And we, alone of Earth's creatures, perhaps (shudder the thought!) we alone of all creatures here and everywhere, have looked up beyond the sky, into the arms of this Universe, and asked the reporter's questions: "what and how, and when, and why?"

Those of us who ponder these questions, The Astronomers, wish to shed light on no less than *everything* in creation. It is a task so audacious that few of us, myself included, could sleep at night if we contemplated the challenge completely. (What ant in Manhattan wonders about, or is even aware of, the city that surrounds it?) We, of the cinder of stars, the debris of Solar System formation, and later of "slime mold" that rose a hundred thousand flights of biological stairs to become mammalia, and then further, *homo sapiens*, we dare to ask whence we came and what the Universe consists of? How does the "inside of the clock" work?

Nevertheless, we astronomers, practitioners of one of Earth's oldest professions, do dare to ask. And we do with increasing voracity seem to be progressing toward a real, if approximate, understanding of our Universe. It is more than any other species has achieved regarding its place on Earth, much less Earth's place in the all that the Universe is. It is something that sets humankind apart from whence we came.

In the collection of essays that follows, nine noted and accomplished extragalactic astronomers and cosmologists—some specialists in theory, some computational modelers, some observers—have written essays about their dearest subjects of study. In doing so, they have set forth watermark explanations of the state of knowledge regarding some of the hottest, most difficult, and most bizarre topics in all of far-away astrophysics. And so too, these nine experts have written about *why* their topics are of interest to them, why their careers, and even their lives, have been shaped by their particular cosmic quests.

In reading this collection of essays you will learn a good deal of the inner workings of modern astronomy, and its techniques and its state of knowledge. But you will also learn a good deal about the inner workings of a few of its most noted practitioners.

So come and follow along now, as a very special and talented nine people explain the latest explorations of no less than a Universe.

PART I

Revealing a Universe

1

Mapmaker, mapmaker make me a map

Probing the Universe's large-scale structure

JOHN HUCHRA, Harvard-Smithsonian Center for Astrophysics

John Huchra is one of the most naturally gifted extragalactic observers working today. He was educated in physics at MIT (Massachusetts Institute of Technology) and earned his PhD from Caltech (California Institute of Technology), but has spent most of his professional career at Harvard-Smithsonian. John's interests span cosmology, galaxy cluster dynamics, the large structure in the Universe, and star formation across the Universe. John is an avid outdoorsman, enjoying hiking, canoeing, and skiing. He and his wife Rebecca Henderson live in Lexington, Massachusetts, with their young son, Harry. John's specialty is doing large-scale projects in a field more often dominated by one- and two-person teams, something he tells us about here.

I love being on mountaintops. It's the next best thing to being in space. I guess I also love counting things, whether the things are 4,000 footers in New England, cards in games of chance, or galaxies on my observing list. Therein, of course, lies the tale.

It all started because I was a little kid much more interested in reading than in sports. I grew up in a moderately rough, poor neighborhood in northern New Jersey just outside New York City. I was lucky that both my parents were quite intelligent and always stressed the value of hard work and knowledge. That got me into reading, and science and science fiction were at the top of my list. By eleven I was trying to decipher *One, Two, Three Infinity* and *The Birth and Death of the Sun* by George Gamow and Fred Hoyle respectively. These books were amusing and described a beautiful and mind-stretching subject, so I knew quite early on that physics or mathematics was what I wanted to do. I took every opportunity I could to learn and experience more about science. In high school one summer I went to a camp to study ecology and conservation. The next summer I went to a wonderful National Science Foundation (NSF) summer program on chemistry at what was then the Newark College of Engineering. I learned how to program, studied the ''vapor pressure of organic borate esters,'' and baked brownies in the ovens in the chemistry laboratory. I even took Latin and drafting, figuring that a scientist ought to be able to name things and draw her or his experiments.

MIT came next. I had a slow start—it's interesting to walk into an auditorium and hear the famous lecture that starts ''look to your right, look to your left, one of you three won't be here in four years time,'' have the entering classes SATs (Scholastic Aptitude Tests) posted and realize you were in the bottom third of the class. Fortunately I managed to ignore that and keep on with the dream of being a scientist. I took a wonderful freshman seminar on cosmology with Philip Morrison (a course I now sometimes teach myself). Included in the usual undergraduate requisites was spending time as the social chairman for a dormitory of 550 guys. I eventually ended up playing with both modulation collimators for X-ray astronomy rocket experiments and stellar pulsation codes, that last as an undergraduate thesis topic with Icko Iben, now of the University of Illinois. I'm still not sure exactly why, but I found myself drifting slowly away from theoretical physics and into astronomy and astrophysics.

A few strokes of luck further firmed that career path. The first was flunking my draft physical—although that was a mixed blessing that I had to pay for a decade later with a cornea transplant—and the second was getting into Caltech. I went with the expectation of becoming a theorist, but that was just not to be. At every crossroad, I found myself moving more and more to the observational side. First, my fellowship paid \$200 per month, and the rent was \$125 per month. To solve that problem, I took a research assistantship helping to build a pressured scanned Fabry-Perot spectrometer for studies of planetary atmospheres. I chose a research project with George Preston on the measurement of magnetic fields in ''peculiar A stars.'' When that project was completed and the time came to pick a thesis advisor and topic, Wal Sargent took me under his wing. I started working on galaxies, little blue ones to be exact.

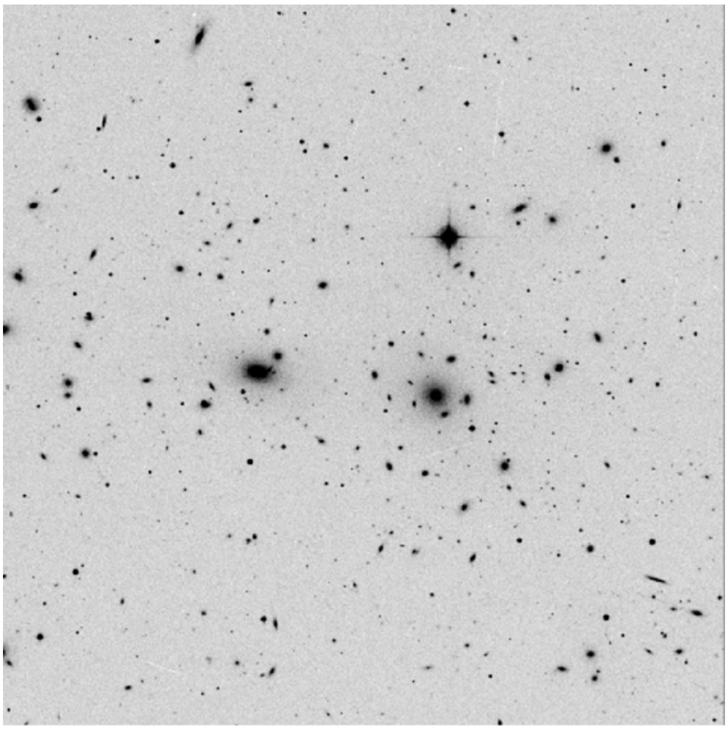

Figure 1.1

The Coma cluster of galaxies. (Image from the digitized Palomar Sky Survey, produced by the Space Telescope Science Institute, AURA Inc.)

Wal also offered me another great opportunity, to work on the Palomar Supernovae Search, which had been started by the noted Caltech astrophysicist Fritz Zwicky decades earlier. Although this was generally a hard and somewhat boring task, involving observing (with the 18-inch and sometimes the 48-inch diameter Schmidt telescopes) at Palomar for 5–7 nights a month, anyone doing it successfully quickly learned a lot about telescopes, photographic plates, the sky in general, galaxies and galaxy clusters in particular, and, most importantly, about patience. I enjoyed the solitude and the occasional thrill of discovery. I got into making improvements in the observing system. I was really enjoying doing something I was good at.

I was home. Between the supernova (SN) search and observing for my thesis project, I was observing ten or more nights a month. I found other excuses to go observing as well. I became the student in charge of checking out new visiting astronomers on all the small telescopes (the

200-inch was still the exclusive province of the senior staff, and students generally did not do independent work that required 200-inch time) and, whenever one of my fellow students needed an assistant, I was a willing volunteer. Observing at Palomar and Mt. Wilson was also a great way to meet people. Famous astronomers (and many who would later become famous) came as visitors, and the senior staff at Carnegie, people like Allan Sandage, Leonard Searle, Olin Wilson and George Preston, who rarely came down to Caltech, were lunch and dinner mates at the ‘‘Monasteries’’ (so-called because, up until the 1970s, women were not allowed to stay at them). It was still the case that the 200-inch or 100-inch observers sat at the heads of their respective tables, with fellow observers arrayed down the sides in order of telescope size. That generally kept us students in our place but, every once in a while, I got to be the 100-inch observer when a senior professor was on the 60-inch. Conversations were heady with the latest discoveries as well as the usual gossip and politics.

Through the supernovae search observations, I discovered a comet (1973h) and recovered one of the Mars-orbit-crossing asteroids that had been discovered three and a half decades earlier but then lost. Even that led to a job helping the geologists use the Schmidt telescopes for asteroid searches. Gene Shoemaker and Elinor Helin had developed a new and intense interest in finding Earth-orbit-crossing objects to bolster their theory that cratering on the Moon (and Earth!) was of asteroidal rather than volcanic origin. They needed to learn to use the Schmidt telescopes, and I was the man.

It’s hard to describe the beauty of observing in those days. I was lucky to be able to make use of the Hooker 100-inch telescope at Mt. Wilson for my thesis. Completed in 1917, the 100-inch had a glass mirror that had been superbly figured by G. Ritchey. You would observe galaxies from the optically fast Newtonian focus at the top of the telescope, standing on a platform 40 to 50 feet above the floor of the dome. In the late summer and fall, the city of Los Angeles would blaze in glory (ugh!) outside the dome. But, in the spring, Mt. Wilson could be one of the darkest sites I’ve ever observed at; the Pacific fog would cover the city so that you could often see the tops of the clouds illuminated from above by starlight. I was not only home, I was hooked.

On being an astronomer

Perhaps the hardest transition in science is moving from the life of a graduate student to that of an independent scientist. The object of the game is to go from working on *one* problem that has primarily been posed for you to being able to pose exciting and tractable problems yourself. One thing we all must learn if we are to succeed is that ideas are the coin of the realm. And really good ideas are not easy to come by. The following story illustrates the point.

Once upon a time in graduate school we had an astronomy department retreat for the faculty, postdocs, and students. It rained. Almost by definition, we ended up in a deep philosophical discussion concerning careers, and what made a successful scientist. We decided in the end that an individual's success in the game could be predicted by their characteristics in a seven-vector space. Each vector measured a critical personal characteristic or set of characteristics such as intelligence, taste and luck, and the ability to tell one's story (public relations). The vectors and their ''unit'' vectors, the people against which one was measured in astronomy in those days, were:

Raw Intelligence	S. Chandrasekhar
Knowledge	A. Sandage
Public Relations	C. Sagan
Creativity	J. Ostriker
Taste	W. Sargent
Effectiveness	J. Gunn
Competence	M. Schmidt

(Here, I've changed a few names to protect the innocent.)

Each unit vector represented someone who was without equal at the time (1974 or so), for example Chandrasekhar was the smartest person in astronomy any of us had come across, and similarly, Allan Sandage represented the unit vector of knowledge (which is *not* the same as intelligence, although he is a damn smart cookie!). Some vectors are worth more than others, for example taste and creativity are probably more important than knowledge. Looking back on this I've come to realize that being nearly a unit vector in any one of the important characteristics almost guarantees you a tenured job, two are good for membership in the National Academy, and three put you in contention for the Nobel Prize.[1]

So how do you go about developing some of these qualities? Again I was aided by a few flukes of fate. One was that I'd accepted a job in Australia, but, before I finished defending my thesis, there was a vote of no confidence for Australia's Prime Minister of that time and the government had to be reorganized. That froze all government jobs including mine. So, with my thesis 99% completed, I had no job.

Rather than turning my thesis in at that point, I stopped to think about the problem, something I hadn't been able to do while madly collecting data and writing it up. I also had the time to think about other, new projects, some related to my research, and some very interesting sidelines.

What to do after graduate school

My second fluke was falling into one of these new projects. At that time, a number of people at Caltech had come from Princeton where they'd been influenced by Jim Peebles, one of the great theoretical cosmologists of our time. Peebles had started trying to understand the clustering of galaxies, basically how the Universe got from a pretty smooth and uniform state at the time of the formation of the cosmic microwave background to the details of galaxy clustering we see today. His target was not just galaxy formation, a hard enough problem in itself, but the formation of large-scale structure. However, in trying to think about this, he had a simple problem, one even such as I could try to deal with. In the early 1970s many galaxy catalogs existed, based primarily on identifying galaxies by eye from the large photographic sky surveys of the 1950s and 1960s. Two examples were the Shane–Wirtanen catalog, which is not a set of actual galaxy identifications but a fine grid of galaxy counts of about 1,000,000 objects made from astrographic plates

[1] Many people would want to add "luck" to the list, but our learned conclusion was that luck is a product of at least three of the above vectors and not an attribute in and of itself.