Mapmaker, Mapmaker Make Me a Map

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I love being on mountaintops. Next best thing to being in space. I guess I also love counting things, whether the things are 4000 footers in New England, cards in games of chance, or galaxies on my observing list. There in, 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 NYC. I was lucky that both my parents were pretty 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.” George Gamow and Fred Hoyle were a hoot, so I knew pretty early on that physics or math 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, I went to a wonderful NSF summer program at what was then the Newark College of Engineering on chemistry. I learned how to program, studied the “vapor pressure of organic borate esters,” and baked brownies in the ovens in the chemistry lab. 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 — its 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,” have the entering classes SATs 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 dorm 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 moveing more and more to the observational side. First, my fellowship paid a whopping $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.

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 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 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 through 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 1970's, 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, amd I was the man.

Its hard to describe the beauty of observing in those days. I was lucky to be able to make use of the 100-inch Hooker 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 40-50 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 such 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), e.g. Chandrasekhar was the smartest person in astronomy any of us had come across, and ditto, 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 pretty much guarantee's you a tenured job, two are good for membership in the National Academy, and three put you in contention for the Nobel prize.[3]

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% in the can, I had no job.

Rather than turning it in at that point, I stopped to really 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 folks 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 1970's many galaxy catalogs existed, based primarily on identifying galaxies by eye from the large photographic sky surveys of the 1950's and 1960's. 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 from Lick Observatory, and the infamous Zwicky Catalogue (where "infamous" applies both to Zwicky and his catalog).[1] The Zwicky Catalogue is a list of more than 31,000 objects identified on the 14x14 inch glass plates of the Palomar Schmidt telescope. Peebles thus had lots of grist to study the galaxy distribution in two dimensions, but the structures were sure to be three dimensional and there was almost nothing known about the 3-D galaxy distribution. There were hints of filamentary structures in the maps Peebles and his coworkers made from both those catalogs, but what is filamentary on the sky could look quite different in 3-D. Projection effects also quite easily wash out the finer details of 3-D structures.

Although it had been known from Edwin Hubble's work in the late 1920's that there's a very good linear relation between the apparent radial velocity or redshift of a galaxy and its distance away from us (another long story for a different book!), measuring redshifts for large numbers of faint galaxies was quite a chore in the early 1970's. In fact, in 1972,

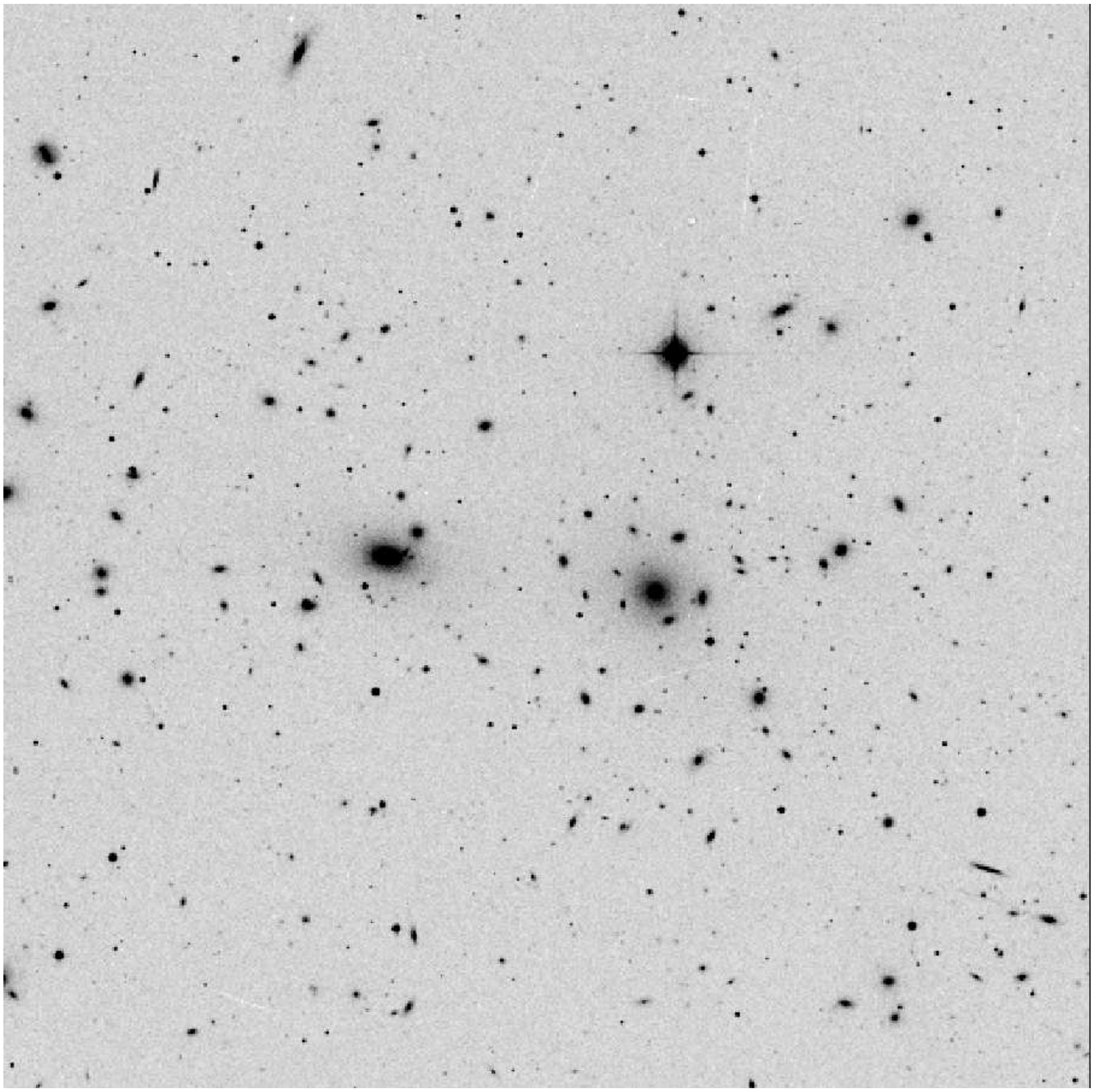


Figure 1: The Coma cluster of galaxies. (Image from the digitized Palomar Sky Survey, produced by the Space Telescope Science Institute, AURA Inc).

after more than 60 years of observing galaxy spectra by the likes of Vesto Sliper, Milton Humason, and Gerard deVaucouleurs, there were only a little over 1000 galaxy redshifts known, and many of these were for galaxies in clusters of galaxies. The largest complete, brightness limited redshift catalog contained less than 300 galaxies. Even though the method for creating a 3-D map of the galaxy distribution existed, the tools to apply this method were too primitive. Astronomers were just beginning to move away from photographic plates, which actually detect less than 1% of the light that falls on them, to much more efficient electronic detectors. Time on big telescopes was hard to come by (there were only the 200-inch Hale telescope at Palomar, the 120-inch at Lick, and the 107-inch at Mc Donald — the 4-meter telescopes at the national observatories hadn't been built yet), and small telescopes were generally not equipped with "modern" detectors. Nonetheless, Peebles began urging people to think about redshift surveys as a way of making real 3-D maps.

At that time (as today) the Princeton-Caltech axis was strong, with lots of trading of students and postdocs back and forth. J. Richard Gott, who had been a student at Princeton, came to work at Caltech as a postdoc. He and Ed Turner, a fellow student, took to analysing the clustering properties of the galaxies in Zwicky's catalog using whatever tools they could, including the small number of redshifts available. They produced a beautiful series of papers analysing the properties of a complete, brightness-limited sample of galaxies but with one flaw — the analysis was perforce only two dimensional. They still didn't have the tools to make a 3-D map.

Redshift Surveys

The break in the dam occured in the mid-1970's. First, electronic detectors (in the form of image intensifier tubes) became available commercially and cheaply enough that small telescopes could be equipped with them. Image tubes have 20 times the efficiency of the best astronomical photographic plate, and made a 1-meter telescope the equivalent of the 200-

inch! Second, centimeter wave radio receivers increased in sensitivity and the first efficient radio spectral correlators came into operation. This enabled rapid and accurate determination of the redshifts of galaxies with lots of neutral hydrogen gas, the most common element in the Universe and a major constituent of every spiral and irregular galaxy. In the space of just a few years, a redshift survey of 1000 or more galaxies went from being a daunting and near-impossible task to merely a very difficult one.

As both Ed and Richard prepared to go to Princeton, Ed to the Institute for Advanced Study, and Richard back to Princeton University, another collaboration was formed to attack this problem by obtaining redshifts for the Turner-Gott sample. The leaders were Wal Sargent, Gill Knapp and Trinh Thuan. Fortunately for me, they needed a little more horsepower, and I had both a little extra time on my hands and also a reasonablely high "competence" score, i.e. I could make telescopes sit up and take data. We started in the winter of 1975 to get redshifts for the spiral galaxies at Green Bank and Arecibo, two of the modern radio facilities, and at Palomar and later Kitt Peak for the gas-poor elliptical and lenticular galaxies. Our goal was to obtain redshifts (nee distances) and accurate brightness measurements for 1100 or so galaxies. We made a pretty good start of it, too, obtaining about 650 new redshifts in a year and a half before that collaboration broke up. All the players found themselves at different, widely scattered places, and e-mail hadn't been invented yet!

Meanwhile, I was aided by another bit of luck. On the job market once again, but this time with more publications and actually a much better idea of what I wanted to do next, I landed a postdoc at the newly formed Center for Astrophysics in Cambridge, Massachusetts. That was surprising because I'd hoped and expected to get a job at Kitt Peak National Observatory, the home to many a young observer, but that year KPNO chose a theorist instead. CfA, which had a reputation for hiring theorists, that year hired two observers!

At CfA, I met Marc Davis and Margaret Geller, two other Princeton trained theorists who had worked or were working with Jim Peebles. Marc was desperately trying to get his own redshift survey started, but he was having limited success. The existing instrument at CfA's observatory on Mt. Hopkins in Arizona had some real problems. Marc wanted to buy a very expensive camera from a commercial firm, but there was little money coming from either the CfA or the NSF to do so. Marc and Margaret and I started working on the best data set I could assemble, about 1200 redshifts for pretty bright galaxies (see Figure 2(a)), but the only progress being made on new observations was the observing at the Kitt Peak 0.9-m and the Green Bank 300-ft for the soon to wind down Caltech consortium.

Then came yet another fluke. I was at Palomar on a cloudy night, strolling the catwalk of the 200-inch in the fog with Steve Shectman and talking about spectra and redshifts. Steve, one of the real unsung heroes of redshift survey work, described a new instrument he was building, a photon-counting Reticon$^{@}$ detector for spectroscopy, which sounded a lot more robust than the commercial system and was 1/10th the cost. Steve offered to loan us the plans and even let us go to his lab and copy the instrument electronics. This sounded like a match made in heaven. I went back to Cambridge, convinced Marc (didn't take much!) that this was the way to go, and he and I proceeded to sell the higher ups on getting us some resources to make it so. Enter other heros: Herb Gursky, then the Associate Director at CfA, who came up with the internal support, including a few good computer programmers, and George Field, the CfA Director, who went to bat at the NSF to get Marc additional funds. Thus, in the early summer of 1977 the first CfA Redshift Survey was born.

Marc was in charge of duplicating the camera and electronics, and Tom Stevenson, the lead computer programmer, was in charge of data taking and analysis system. John Tonry (Marc's graduate student) wrote the data analysis software for our DG Nova computers (then state of the art). Dave Latham, an SAO scientist, took the lead in putting together the front of the detector package, a three-stage image-intensifier tube. Dave and I, with the Mt. Hopkins staff worked over the existing spectrograph, and found and corrected numerous optical problems including a missplaced collimator and mirrors that vignetted the field of view. I assembled the catalog of objects to be observed, all the galaxies brighter than a blue magnitude of 14.5 in Zwicky's catalog of galaxies and at high galactic latitude. Our own galaxy, the Milky Way, is a spiral galaxy that contains lots of gas and dust in its disk. The Solar System sits almost exactly in the plane of the Milky Way. As a consequence, when we astronomers look out at the universe, we get by far the clearest view when we look perpendicular to the plane of tha galaxy, at high galactic latitude.

We took our first real data in the spring of 1979 using the mighty(!) 24-inch at Mt. Hopkins. We pretty quickly switched to the 1.5-meter, and, because the 1.5-m was a really terrible telescope with a spherical mirror, we got to use it for spectroscopy a very large chunk of time. The Gary Larson cartoon showing a bunch of astronomers monopolizing the telescope all day (sic) long was not far from the truth. When the Moon was down, one of us, often me, was at the telescope. At the same time, I was also heavily involved with Marc Aaronson and Jeremy Mould on a new project to measure the Hubble constant with the infrared Tully-Fisher relation, a hot topic even today, for which we got gobs of time at the small telescopes at the National Observatories. I often spent 6 weeks at a time on mountaintops around Tucson, first measuring redshifts, then doing infrared photometry of galaxies and then going back to redshifts as the moon waxed and waned. In retrospect, it was also probably the only way to survive on a postdoc or junior staff salary — canned food in the mountain microwave usually covered by a too-small expense allowance. But it sure did improve my cooking skills!

I took the last redshift for that first survey of 2400 sources (2399 galaxies and 1 star) in June of 1981. We performed a number of statistical analyses of the data, getting perhaps the best galaxy luminosity function (the number of galaxies of a given luminosity per unit volume) and galaxy correlation function of the time. We measured the overdensity of the local supercluster of galaxies and saw very strong hints of larger scale structure, but even a survey of 2400 galaxies wasn't very deep. Figure 2(b) shows the state of the map at the end of the first CfA survey for the volume shown in Figure 2(a). Despite a significant improvement, the maps weren't really crisp and clear. As a result, none of the results around, including those from other surveys, really could convince either the theorists or observers that much was happening beyond Hubble's "sensibly uniform" universe.

The Second CfA Survey

About then, Marc Davis went off to Berkeley and Margaret Geller got back to CfA from an extended stay at the University of Cambridge. Margaret and I started working on what is called the Omega problem (determining the mean mass density of the Universe to see if its going to collapse back on itself or expand forever) by selecting groups of galaxies from the redshift survey and by measuring masses for groups and clusters of galaxies. We made some interesting discoveries about the dynamical state and relative youth of nearby galaxy clusters — we are living in the time of cluster formation — driven by Margaret's studies of cluster substructure and my work on the Virgo cluster. But in a few years we began to reach the end of what could profitably be observed in galaxy clusters with the 1.5-m telescope. Both Margaret and I had been dreaming of a wide-field redshift survey much deeper tha the first CfA survey, but both of us were wary of asking for so much telescope time.

Finally, in 1985, we took the plunge. The 1.5-m was an excellent spectroscopic telescope, it could easily reach a magnitude fainter than the first CfA survey, and Zwicky's catalog quite nicely went to that depth. Instead of a paltry 2400 galaxies, we decided to go after 15,000. The problem was that there was a great debate about the methodology of the next survey. There were essentially three plans floating around. Marc Davis suggested a knitting needle approach, namely sampling one-in-five or one-in-ten of the fainter galaxies to increase the volume surveyed very rapidly, but not so densely. Simon White, another player in the game, wanted dense sampling but in a smaller, contiguous, square or rectangular area of the sky. Margaret was convinced that long and relatively thin strips across the sky were the way to go.

You can think of the mapping problem this way. Suppose you want to study the topography of the surface of the Earth, and you have a steerable satellite but only a limited amount of film, say enough to take pictures of 1000 square miles. You could take random 1 square mile shots of the surface (the Marc Davis approach), you could carefully image a 33x33 mile square (the Simon White approach) or you could try to observe a strip, say 5000 miles by 1/5 of a mile (the Margaret Geller approach). The first approach would give you a pretty good idea of the fraction of the Earth's surface covered by ocean, desert, mountains, etc., but you wouldn't know anything about the sizes of such things. This type of sparse sampling was actually used for one of the earlier IRAS galaxy redshift surveys, the QDOT (Queen Mary/Durham/Oxford & Toronto) survey, and produces a deep but very low resolution map, ok for continents, but watch out for mountain ranges! The second approach would give you very detailed information about a specific place, but since you're likely to see only ocean or desert or mountain, you'd have a very distorted view of the Earth. The third approach, however, is a winner, since not only are you likely to cross a little bit of everything, but you can also estimate the sizes of the oceans, continents and mountain ranges you cross. Not a map, but surely a mapmaker's first crude topographical survey!

Better yet, from the point of view of a practiced observer, since the Earth rotates and the sky swings around overhead, if you observe in strips you can use the telescope in the most efficient manner — fewer slews, less time calibrating, all those good things. To me, that, plus Margaret's argument on sampling structure sizes, iced the deal.

I started observing for the second CfA Redshift Survey in the winter of 1984/85. Valerie deLapparent, a graduate student working with us on large scale structure and galaxy surveys, made some of the observations and also was given the task of plotting up the data from our first strip. I was so sure that we wouldn't find anything extraordinary (and also too tied up taking the data and too lazy to plot it as went went along!) that the plots of the galaxy distribution weren't made until all the data were in hand. When Valerie showed me the initial map in June of 1985, my first, very conservative reaction was "whoops! what did I do wrong?" But repeated checks showed that our map, Figure 2(c), was right. With this much deeper and denser map, we saw that the galaxy distribution was far from random. It was not the "meatball" topology of lumps (clusters) in an otherwise uniform soup (the field) that was the favorite view of theorists at the time. Galaxies lay on surfaces surrounding large empty regions, a.k.a. "voids." The first large void had actually been discovered 4 years earlier by Kirshner, Oemler, Schechter and Shectman, but had been dismissed as a fluke, a "one-of" that would not be seen again. But in one season's observing on the "mighty" 1.5-m, we shot that idea to pieces! The Universe was frothy. Most of the Universe was filled with voids. Margaret coined the analogy of the soap bubble universe, and it stuck.

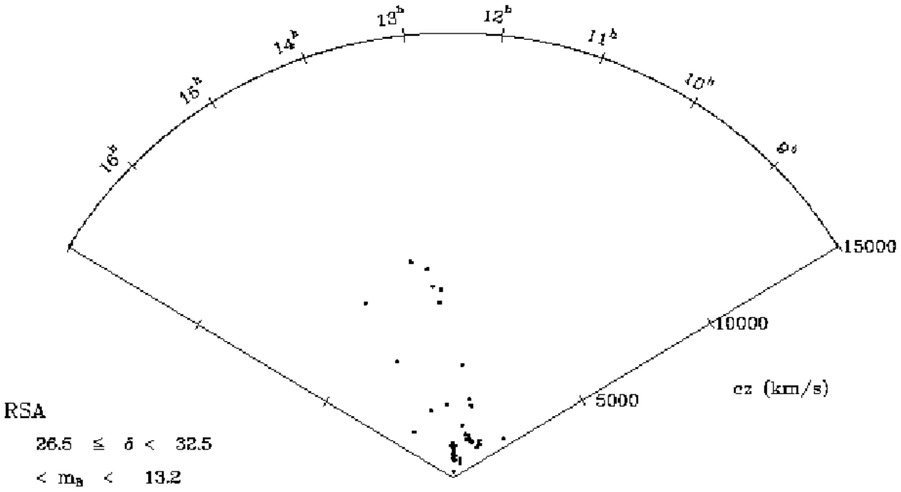
The CfA2 Redshift Survey is now complete. We have measured redshifts for over 18,000 bright galaxies in the northern celestial hemisphere. We have exquisite views of the nearby galaxy distribution over small volumes of space (Figures 2 and 3). And we know that the distribution of galaxies is exceedingly non-random. Galaxies are distributed on quilt-like surfaces, with lumps that are the large galaxy clusters at intersections of these surfaces. With 24 slices in hand, the basic results from our first slice still hold. We discovered the Great Wall of galaxies in 1989, and it remains one of the largest structures ever seen in the Universe. Theorists, using N-body simulations, are still trying to match the observed galaxy distribution with all the physics they can muster and with arcane mixes of normal baryons (the stuff you and I are made of), cold dark matter, neutrinos and even a Cosmological Constant, but they haven't been fully successful yet and there's still a lot of work to do.[2]

Figure 2. Wedge diagrams displaying two-dimensional projections of the 3-D distribution of galaxies. Each plot shows the distribution of galaxies in a wedge of sky six degrees thick by ~ 100 degrees wide. (a) Top. The view in 1978, before the start of the first CfA Survey. (b) Middle. The view in 1982 after the completion of the first CfA Survey by Davis, Huchra, Latham and Tonry. (c) Bottom. The view in 1985 after the completion of the first CfA2 Survey strip by de Lapparent, Geller and Huchra.

The Next Maps — More to Come

By definition, observationally we still have a long way to go. Existing redshift surveys have mapped only a few percent of the volume of the Universe and not very well at that. Most surveys are based on catalogs of galaxies assembled from photographic plates. These catalogs are non-uniform and not very accurate. Large chunks of the sky are invisible because they are obscured in visible light by the gas and dust of our own galaxy.

However, several new large surveys are underway. One, called the SDSS or Sloan Digital Sky Survey, aims to use a 2.5-m telescope in New Mexico to map about 1/5 of the sky, both photometrically, with new digital imaging detectors, and spectroscopically, with fiber optically fed spectrographs. They plan to measure 1,000,000 galaxy redshifts in the next 5-10 years. Their competition is the Two Degree Field Survey or 2DF, a survey of 250,000 galaxies, also over a small area of the sky, using the 3.9-m telescope in Australia, equiped with a special 2 degree field-of-view spectrograph. 2DF is underway and is madly trying to scoop SDSS. These surveys will provide excellent information about the statistics of galaxy clustering for matching to theories (and N-body simulations based on differing input physics) of structure and galaxy formation. However, they'll still explore much less than 1/4 of the sky.



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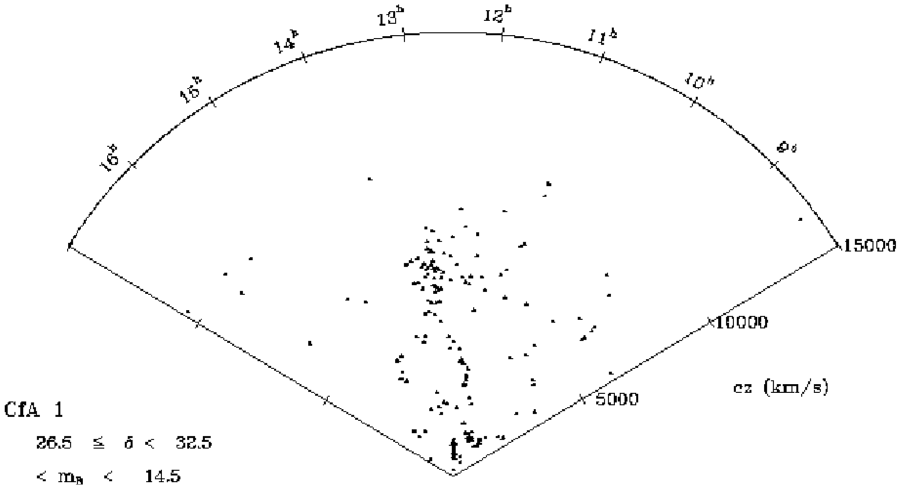

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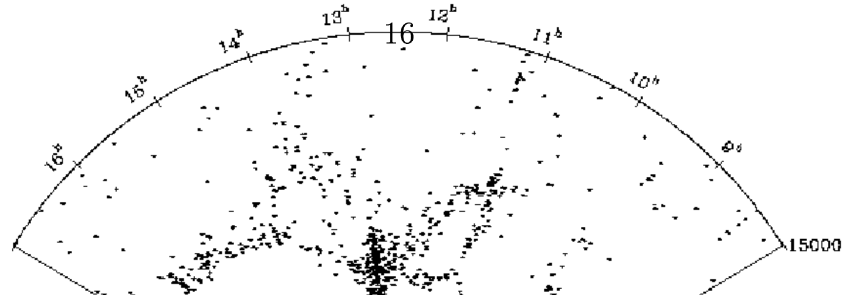

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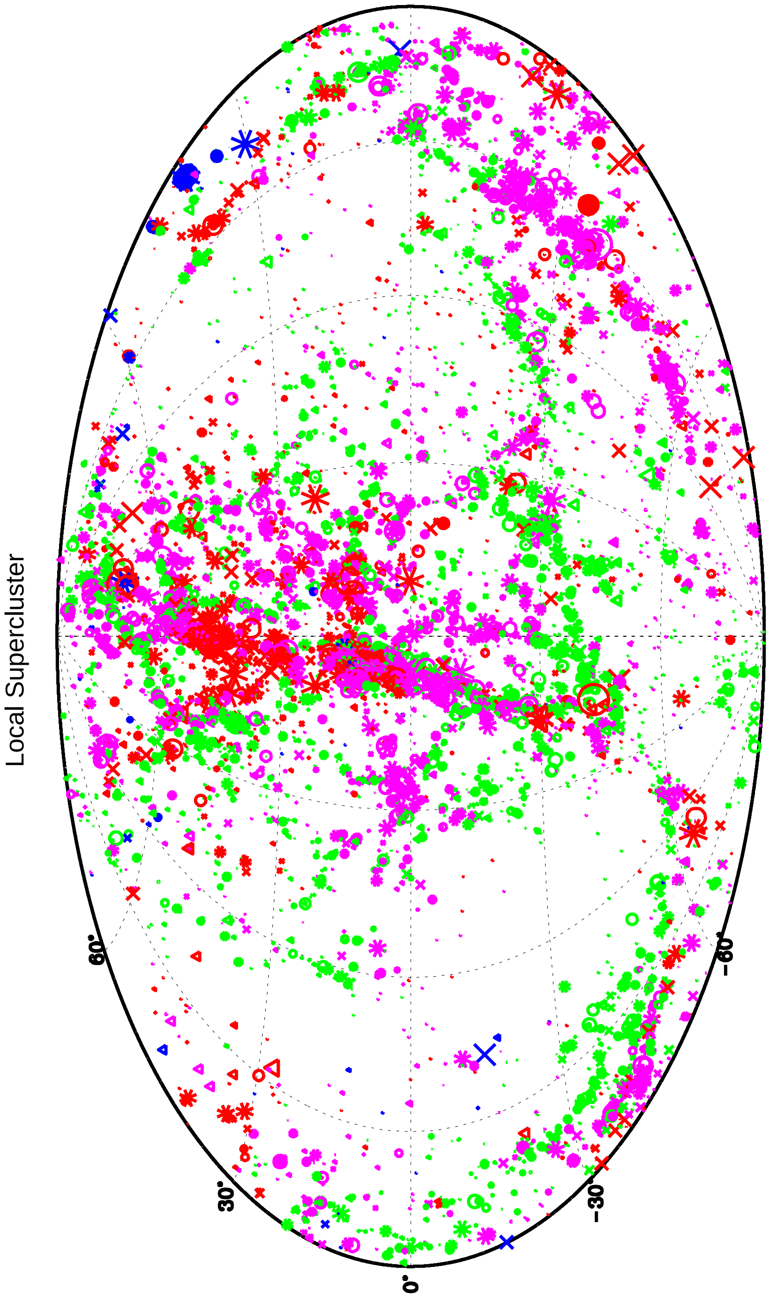

Figure 3: The current best map of the Local Supercluster of galaxies. This shows a projection on the sky of all the known galaxies with measured redshifts less than 3000 km/sec (i.e. galaxies nearer than about 130 million light-years. The Local Supercluster is the large band of galaxies running nearly vertical on this plot. The map is an equal area Aitoff projection of celestial coordinates. Our own galaxy, the Milky Way, lies at the edge of the "disk" of the

This figure available from the main website

Figure 4: Plot of the distribution on the sky of all known galaxy redshifts. The sampling isn't great, as in Figure 2, you can easily see the large areas of the sky obscured by our own galaxy, and you can also see where astronomers have probed especially hard. Galaxies marked in blue are closer than about 30 million light years, in red, between 30 and 200 million light years, in green, between 200 and 500 million light years and in cyan out beyond that. A few really deep strip surveys, primarily the Las Campanas redshift Survey, are seen as cyan strips.

Not being a real fan of maps with large areas marked “Here There Be Dragons,” my next project is an almost *whole sky* map of the *nearby* universe. Again the game is to attack the Omega problem. How much does the Universe weigh? — what is its mean mass density? We know that our galaxy is moving at 630 km/sec towards a point in the constellation of Hydra. Can we identify the mass concentrations causing that motion? Can we match gravity, as measured by the motions of galaxies relative to the general expansion of the Universe, to local lumps of stuff — galaxies or otherwise — whose gravitational pull might cause such motions? In doing so, can we learn how much dark matter there is in the Universe and where it is located?

The project is called 2MASS or the Two Micron All Sky Survey, and it aims to use the penetrating power of infrared light to map the nearby distribution of galaxies at wavelengths unaffected by gunk in the Milky Way. My colleagues and I, led by Mike Skruskie and Ray Stiening at the University of Massachussets, and including Steve Schneider, also at UMASS, and Tom Jarrett, Tom Chester, Roc Cutri and Chas Beichman at Caltech's IPAC, are using data from twin 1.3-m telescopes at Mt. Hopkins in Arizona and at Cerro Tololo in Chile. You need to observe with telescopes in both hemispheres to get the whole sky. So far (spring 1999), we have over 1,400,000 galaxies in our catalog with only about 50% of the scans completed. We'll start by getting redshifts for the brightest 150,000 galaxies. Telescope time allocation committees willing, we'll eventually do 1,000,000 over the whole sky. This will be the deepest and highest resolution map of the whole local Universe ever made, providing reliable charts out to about 10% of the speed of light.

Its a voyage of discovery to the Nearby Universe. My goal is to make the best map I can and leave no nearby areas uncovered. Come back in six to ten years and I'll show you the new geography of the local Universe!!

Footnotes:

[1] Fritz Zwicky was a professor of astrophysics at Caltech and one of the true giants of 20th century astronomy. He was responsible not only for producing one of the most important catalogs of galaxies, with $\sim$ 32,000 entries, but also, among many other things, for predicting the existence of neutron stars and gravitational lensing, for recognizing the importance of clustering in the Universe, especially galaxy clusters themselves, compact galaxies, wide field imaging, and supernovae, including organizing the first major supernova search at Palomar Observatory. He was the discoverer of "dark matter." He also served as a major foil for first Edwin Hubble, and later Hubble's protegé, Allan Sandage. The introduction to his "Red Volume" (*A Catalogue of Compact and Post Eruptive Galaxies*) is must reading for any student not destined to be one of the "high priests" or "sycophants" of American astronomy.

[2] More information on redshift surveys and maps of the local Universe can be found at John Huchra's website, http://cfa-www.harvard.edu/~huchra.

[3] 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.

Figure Captions:

Figure 1. The Coma cluster of galaxies. (Image from the digitized Palomar Sky Survey,

produced by the Space Telescope Science Institute, AURA Inc).

Figure 2. Wedge diagrams displaying two-dimensional projections of the 3-D distribution of galaxies. Each plot shows the distribution of galaxies in a wedge of sky six degrees thick by $\sim$ 100 degrees wide. (a) The view in 1978, before the start of the first CfA Survey. (b) The view in 1982 after the completion of the first CfA Survey by Davis, Huchra, Latham and Tonry. (c) The view in 1985 after the completion of the first CfA2 Survey strip by de Lapparent, Geller, and Huchra.

Figure 3. The current best map of the Local Supercluster of galaxies. This shows a projection on the sky of all the known galaxies with measured redshifts less than 3000 km/sec (i.e. galaxies nearer than about 130 million light-years. The Local Supercluster is the large band of galaxies running nearly vertical on this plot. The map is an equal area Aitoff projection of celestial coordinates. Our own galaxy, the Milky Way, lies at the edge of the "disk" of the Local Supercluster, much like the Sun lies near the edge of the disk of the Milky Way. The areas of the map that are only poorly covered are those parts of the sky essentially blanked out by dust in the Milky Way, through a glass, darkly.

Figure 4. Plot of the distribution on the sky of all known galaxy redshifts. The sampling isn't great, as in Figure 2, you can easily see the large areas of the sky obscured by our own galaxy, and you can also see where astronomers have probed especially hard.