The Evolution of Galaxies: Unsolved Problems and Future Prospects

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Abstract. We've had an extremely interesting conference covering the observational aspects of galaxy evolution near and far. We've come a very long way since the earliest papers int he 1960's by Tinsley and others first quantified the photometric evolution of galaxies. In this summary, I will first go over some of the things that we know, such as the background that is often not discussed but which is important to keep in mind while looking at new evidence. These include the great progress that has been made on the cosmological model and the identification of fluctuations in the Cosmic microwave background. I'll follow that with a description of what we have learned at this Granadian Euroconference and the questions that either have been newly raised or have remained to be solved in the future, many of which are not at all new and are decidedly non-trivial to attack. The article finishes with a description of some promises for the future plus some general caveats about the way we do research, including Tarzan's dilemma.

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1. Introduction – What We Know

In reviewing any subject, it is often useful to start by setting down what we know. The study of the evolution of galaxies began observationally only about 70 years ago with Hubble's (1936) work on morphology and Stebbins' and Whitford's (1937) work on spectral energy distributions. The first quantitative models of population evolution by Tinsley (1968) are only a little over 30 years old, and the concept of dynamical evolution is only slightly older than that (Spitzer & Baade 1951). One of the great astronomical tragedies of the 1970's was the realization that the uncertainties associated with galaxy evolution had derailed Hubble's program of using galaxies as standard candles to probe cosmology (Sandage 1961).

Since those times, and despite these uncertainties, we have made tremendous strides in understanding galaxy evolution. For one, we now have a very high degree of certainty about the cosmological model. Cosmic microwave background (CMB) observations, chemical abundance determinations, the linear expansion of the Universe point extremely strongly towards the hot big bang with Inflation. Uncertainties about cosmological parameters are becoming much smaller. The HST Key project on the Hubble Constant, for example, along with a lot of other

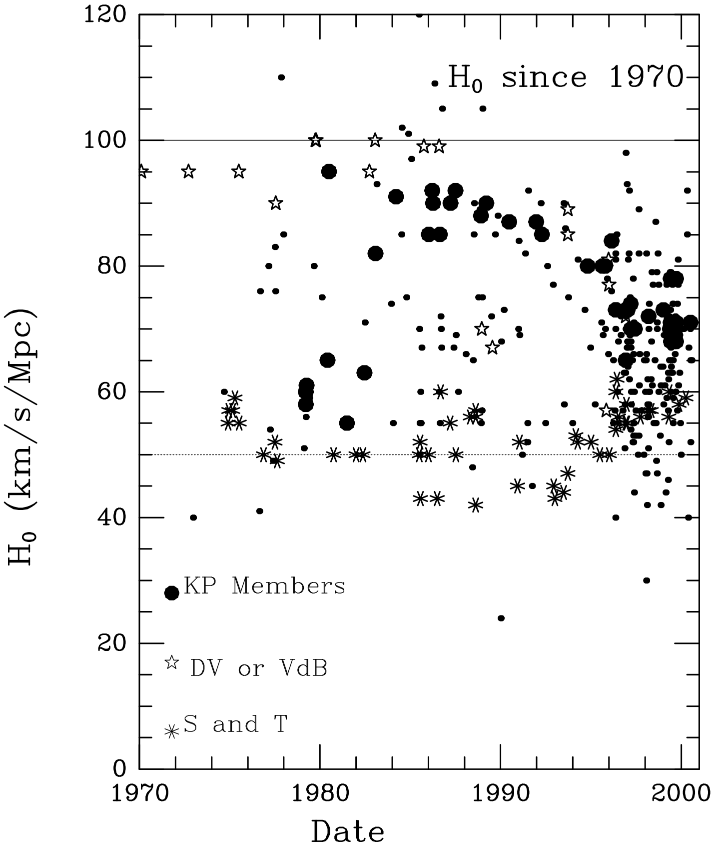

Figure 1. H_0 since 1970. (see http://cfa-www.harvard.edu/∼huchra for details.

work on the distance scale has now dropped the uncertainty in H_0 from almost a factor of two just a decade ago to something closer to +/-15% today (Mould et al. 2000; Freedman et al. 2001; Figure 1.)

Supernovae (Perlmutter et al. 1999; Garnavich et al. 1998) and CMB observations (Tegmark 1999; Lange et al. 2000), when combined with the wealth of data from galaxy clusters, weak lensing, and Large Scale Structure (Huchra 1999; Bahcall et al. 1999) have pretty much conclusively shown that we live in a Universe with Ω_{total}∼1.0 and

$\Omega_{Matter}\sim 0.3$, while the baryon content of the Universe is only $\sim 4\%$ of the closure density (c.f. Burles and Tytler 1998; Pagel, this conf.). The Hubble Constant appears to be around 70 km/s/Mpc (the KP value is now 73+/-7). And there is very likely a Cosmological Constant! Combining the numbers and the uncertainties, the age of the Universe is around 14 +/- 2 Gyr, and it looks as if the Universe will continue to expand forever. Thanks to Hipparcos, this expansion age is now also consistent with the ages of the oldest stars in globular clusters (Chaboyer et al. 1998). As Tyson and Turner (1999) have said, we are now entering the era of "precision" cosmology. That means we know the fundamental constants well enough to use the cosmological model to learn about galaxy evolution.

On just smaller scales, there is now an impressive array of data on Large Scale Structure. The fluctuations that are the probable progenitors of galaxies and LSS have been seen and measured in the CMB. We know that the Universe started out with bumps and wiggles of 1 part in 10^5 which have grown into the galaxies, clusters and superclusters we see today. LSS is not the simple field plus clusters of Hubble, but a rich tapestry of structures including superclusters, walls and voids on scales of hundreds of Mpc (Geller & Huchra 1989). With this has come a significant amount of information about the distribution and luminosity function of galaxies as a function or morphological type (Marzke et al. 1995, Figure 2). These are tremendous observational keys to the study of galaxy formation and evolution: we know that galaxies form differently in different environments (biased galaxy formation, Kaiser 1985) and that environment is linked to morphology and probably luminosity.

Work with the Hubble Space Telescope (HST) (Griffiths et al. 1994) combined with deep galaxy counts from a variety of sources (c.f. Gardner & Satyapal 2000), has also shown us that galaxies appear to have been assembled between redshifts of 3 and 1 from building blocks that formed earlier. This merger scenario needs to be more fully tested and parameterized, but it brings us one step closer to a full understanding of galaxy formation and evolution.

2. Lessons from Granada

The first lesson we learned here is that Granada is a beautiful city! That was quickly followed by Danielle Alloin's introduction to new and planned facilities (see below) and Francesca Matteucci's discussion of the match between models and data. We were exhorted to try to measure observables that are simply and directly linked to fundamental parameters of models — a lesson I will also exhort you to remember.

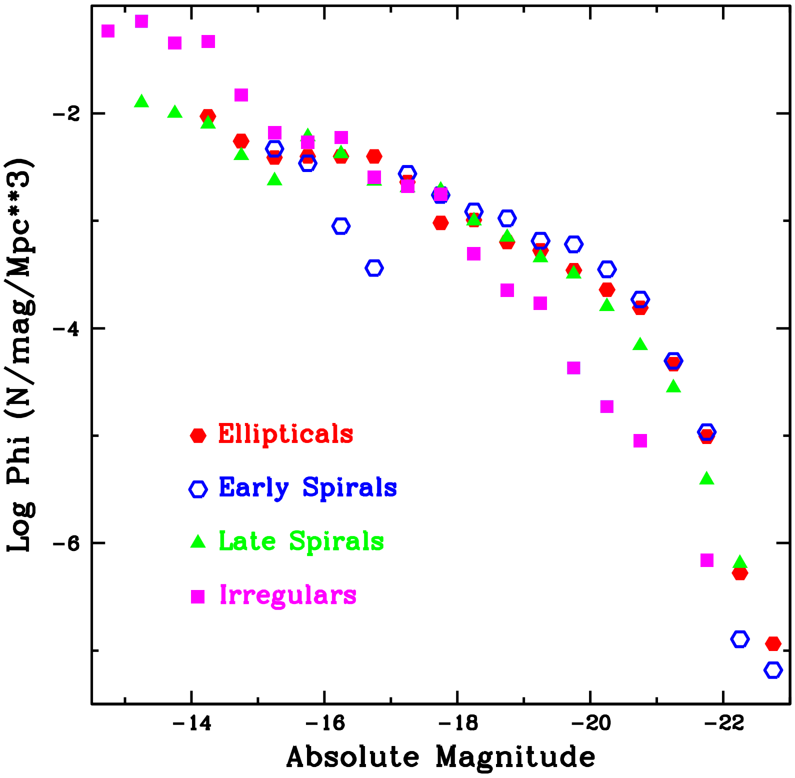

Figure 2. The galaxy luminosity function as a function of morphological type (adapted from Marzke et al. 1995). Note the steeply sloped LF for the very latest types. The normalization is uncertain.

We learned that size matters: surface effects are important in molecular clouds, little galaxies can have holes blown in their ISM by outflows but in high mass ones you don't. We were warned by José Franco that while isolated galaxies may be well fit by simple models, interacting galaxies are not. And Francoise Coombes and others presented beautiful ISO and other long wavelength images that clearly showed that for interacting galaxies like the Antennae, the most luminous new star clusters and associations are *not visible* in the optical/near-IR.

As the old saying goes in America, "better living through chemistry." Manuel Piembert, Max Pettini and others showed us that metals are everywhere. Based on QSO absorbers, they show up even in places in the IGM where you might naively expect little mixing to have occurred. To my mind, this highlights again the need for a higher dispersion spectrograph on NGST. A large number of people — not surprising at this conference — admonished "more data and less theory."

Eva Grebel and Carme Gallart once again showed some spectacular color-magnitude diagrams for Local Group dwarfs showing that these systems are indeed much more complex than previously thought, with bursty and gaspy star formation episodes throughout their histories. Gustavo Bruzual and others "quantified our ignorance" by showing the still rather large differences between predictions for parameters like the relative luminosities of the MS and post-MS stars if one uses either different IMFs or different parent tracks (Geneva vs Padova). Population models are not yet ready to reproduce all the data. In fact, Daniel Kunth noted that we still have problems of semantics in the definition of a "young galaxy," shades of my thesis (Huchra 1977) 25 years ago! Ostlin's latest IR CMD's for IZw18 show both young ($\sim 10^7$yr) and old (10^{10}yr) populations And Jorge Melnick and others once again reminded us that we're by no means sure that the IMF is universal.

Perhaps the biggest surprise to me was the beautiful work of Felix Mirabel, Elias Brinks and others on the Tidal Dwarf Galaxies (TDG's). These could be the real, local, young galaxies. As Guilliermo Tenorio-Tagle said, the histories of these objects might best be called "tidal tales."

The conference ended by moving outwards with results on faint galaxies, the evolution of galaxies in clusters, and the aforementioned QSO absorbers. Fasano, Moore and others reminded us of the problem really understanding the Butcher-Oemler effect. High S/N spectra of Coma galaxies show that there is a really strong correlation between [Fe/H] and σ,and that the age spread for the early type galaxies may be small, but much is still missing from our understanding. Deep surveys are beginning to come in from the VLT, Subaru, Keck and HST, but its too early to tell what they're indicating. Are the Lyman Break Galaxies (LBG's) good tracers of structure and/or populations?

3. Unsolved Problems

Almost by definition, what we saw mostly whetted our appetite for more data and theory; more problems have been discovered and highlighted than have been put to rest. My choices for the big problems in galaxy evolution that deserve attention are given below.

The first among these is the Dark Matter problem. It's hard to talk about galaxy formation and evolution only in the context of the $\sim$10% of the matter we see when we know that dynamical processes must be dominated on larger scales by the dark matter. We must find out where it is, what is is, and how much of it there is. This connects to the problem of Biased Galaxy Formation, or what is the difference in the distribution of the stuff we see radiating and the dark stuff. This must be solved soon or we will *not* have the complete picture.

Another long term favorite of mine is the semantics of young galaxies. What is a young galaxy? Try this: A young galaxy is a galaxy that has turned *more than* 50% of the mass it has *ever* turned into stars, into stars in the last 10^8 years. Or, if you prefer, in the last dynamical timescale, whatever that might be. TDG's might make it. LSB's and LBG's might make it. IZw18 probably won't make it. Semantics is important.

Another long term problem is how dynamics effects evolution. Its clear that the assembly of galaxies is a dynamical process and dynamics triggers star formation. Also important are stripping and mass loss. We need both better simulations and better observations. My favorite tool here would be integral field spectrographs in the near IR with high spatial resolution.

Perhaps the second most important problem (after DM) is the First Light/First Stars problem. When, where, what chemistry? Indications are that we may never see the first stars, they're just too darn faint. But ... And that leads us to chemistry. There appears to be an [Fe/H] floor as seen in the IGM by QSO absorbers. Why? How? Oxygen abundances and yields are still a problem. But Pagel & Edmunds both admonished "Be careful what you feed theorists." This appears to be too simple a problem; it might have a really complex answer. Some simulations of the first massive objects are beginning to appear, most notably from the NCSA and CfA groups (Abel et al.; Jang-Condell & Hernquist). They predict that the first objects are formed at $6 \leq z \leq 20$ and have masses between 100 and 1000 $M_{\odot}$.

Mergers and their role in galaxy assembly remain a puzzle. Tidal Dwarf Galaxies: to quote a famous old commercial, "are they real or are they memorex?" How much mass is contained in them? Do they last long enough to be interesting? That is to say, do they become a major fraction of the population of dwarf irregulars that dominate low luminosity galaxy counts? Do they take significant numbers of old stars with them? And, if mergers are important in galaxy evolution, what roles do the tidal dwarfs play?

Evolutionary codes. Enough said. We need to use real physics and both follow the chemistry and include the effects of gas and dust. We continue to need truth tests, matching data and stellar libraries against tracks. The new generation of large telescopes like the VLT should allow us to get real spectra of MS stars in the LMC and SMC with very different [Fe/H]'s from those in the Solar neighborhood. We need better tacks, better yields and we need to understand the role of binary stars. We extragalactic types also need to make better connections to the star formation community, especially in studies of the Milky Way.

Star formation histories: Are they Continuous, Gaspy, Bursty or all of the above? Can we beat the age metallicity degeneracy with better or different (e.g. UV or IR) observations? Studies of the faint, high redshift Universe will soon tell us more about the change of the properties of galaxies as a function of time, but there is still the problem of lamps and lamp posts. Lamps are good, e.g. using background QSO's to probe the IGM and lenses to probe the mass distribution or to magnify distant galaxies. Searching under lamp posts, however, is bad. You can only describe what you see — and we're back to the DM problem. M31 at a z of 4 would essentially be invisible with most current capabilities.

Last but not least, is it the Sun that's peculiar?

4. Promises for the Future

No talk of this kind would be complete without some discussion of where we are going to be going. Danielle Alloin began the discussion in her introductory talk. The last decade has seen an unprecedented growth in observing capabilities, many if not all extremely well suited towards the study of galaxy evolution. In just a few years, astronomers will have access to more than 15 eight meter class telescopes (Keck, Subaru and most of the VLT are already online) with nearly perfect detectors (low noise, quantum efficiencies approaching unity) in the optical and IR.

The range of instruments available, or about to become available, includes multiobject and integral field spectrographs (e.g. SAURON) in the optical, IR and even submillimeter (SCUBA), sky surveys like 2MASS, 2dF and Sloan (SDSS), and brand new x-ray imaging and spectroscopic satellites like AXAF-Chandra and XMM-Newton. In the near future there will also be SIRTF and MAP as well as significant upgrades to the Hubble Space Telescope instrumentation with the advanced camera, the Cosmic Origins Spectrograph and a camera including a replacement for NICMOS (WFPC3). Almost every one of those spacecraft and instruments will produce significant new data for the study of galaxy formation and evolution — for example, it is hoped that SIRTF will allow us to probe the "dark ages" between a redshift of 5 and 50 for the very first time.

Other major projects that will seriously impact the field in ways we can only begin to imagine include the planned centimeter and millime-

Table I. **Galaxy Evolution in the AASC Report**

Space-Based	Ground-Based
NGST	GSMT (30m)
Constellation X	LSST (8m)
GLAST	VLA Upgrade
SAFIR	LOFAR
TPF Development	CARMA
Long Duration Balloons	SKA Development
** National Virtual Observatory **	
** Theory Challenges **	

The table shows just some of the progams recommended in the AASC report relevant to galaxy formation evolution.

ter telescopes such as ALMA, the LMT, SMA, SKA and FIRST. We expect that longer wavelengths will probe the very earliest ages of star formation in the Universe, specially in dust filled regions. Even planned astrometric and interferometric missions like FAME, GAIA and SIM help us out by significantly improving the parameters (luminosities, sizes, masses and thus ages) of the basic stellar astrophysics that is the backbone of our theoretical models.

In fact, the US community has just released its decadal survey of astronomy and astrophysics (the AASC report by Taylor and McKee). A partial list of recommended missions and programs that are important for the study of galaxy evolution is given in Table 1.

This list includes missions and programs that will have spectacular capabilities to study the high redshift Universe. Chief among them NGST, if it's launched with proper instrumentation, the large cm an mm interferometers, the GSMT and its possible European follow-on, OWL (overwhelmingly large telescope), and the multiwavelength survey telescopes such as the LSST and the UK's VISTA now being planned. Spectroscopy with telescopes like the GSMT or OWL, when combined with multi-conjugate adaptive optics, offers us the ability to study both the chemistry of the very earliest objects in the universe and their kinematics. NGST may get there first provided it is equipped with spectrographs of sufficient combined spectral and spatial resolution — and its our job to make it so (Huchra et al. 1999). Frankly, with this array of capabilities, I'm hoping to retire in 15 years with all our major problems solved!

5. Cautions

Despite the progress that has been made, including some of the spectacular results presented here and incredible prospects for the future, I'd like to close with a few standard cautions to both the observers and theorists. Part of this is me getting old (!) and watching young astronomers make some of the same mistakes I made in my younger years. Part is just the feeling that it is necessary to state these concerns every few years, to reiterate these cautions and keep them in our collective thinking. How do we actually do science, especially and "observational" science like astronomy?

The first of these cautions goes back to Tommy Gold: Gold's Law is that:

Complex problems have simple, easy to understand, wrong solutions.

There are classic examples of this in the study of galaxy evolution. Twenty five years ago, the problem of the internal dynamics of elliptical galaxies was a solved problem. Then it was found that their internal kinematics didn't fit the models and suddenly we had to move from isothermal spheres with some angular momentum to triaxial systems with complex internal stellar motions. Even ten years ago, the Local group Dwarf spheroidals were thought to be dead old systems, but deep CMD's from HST and large ground-based telescopes have shown quite convincingly that these systems still have a whole lot of shakin' going on. Physics advances when old ways of looking at problems, often producing quite reasonable models of the phenomena, are replaced by new viewpoints that just do a better job of prediction and explanation, e.g. Einstein's General Relativity versus the much simpler, but incorrect, Newtonian Theory of Gravity.

The second is one of *my* favorite saws, having grown up in and around New York City. Yogi's caution (after the famed Yankee catcher and later NY Met manager) is that:

It ain't what you don't know, it's what you know that ain't so.

Astronomy, an observationally dominated science, tends to be filled with myths, biases and some "traditional wisdom." Often these myths and traditional wisdom, in the words of Yogi Berra, "just ain't so." For example, Hubble (1936) described the Universe beyond the scale of galaxy clusters as "sensibly uniform." Today we know that large scale structures exist on scales larger than superclusters, but that myth dominated cosmology for more than 50 years. We also have to confront what's often known as the lamp post problem, namely looking only at the things we can see. As new instruments and wavelengths are opened up to extragalactic astronomy, a new view of the world emerges. 2MASS, for example, gives us a chance to look at the universe as seen in the light of old stars, which proably traces the mass of baryons much better than the blue light photographic surveys of old. X-ray surveys do the same for hot gas. Both are changing our view of the Universe, and there's more yet to come!

Last is what I call "Tarzan's Dilemma:"

Don't miss the forest for the trees.

It is all too easy for researchers, especially young researchers, to get tied up in details or to work on such small pieces of the puzzle that we get disconnected from the larger problems. Its also all too easy to begin to ask questions or try to answer problems that may have only marginal relevance. So for all of us, I have three closing recommendations:

→ Keep the big picture in mind.
→ Ask clear questions.
→ Know why you asked them.

Trying to answer the right questions is the most important thing we can do as scientists. And making the questions clear, and relevant, is paramount. For example, the question of whether or not any of the nearby blue dwarf galaxies is "young" is a good one, but, as above, relies on both a good definition of what young means and the connection between that question and the general issues of galaxy and element formation.

In closing, it appears to me that we *are* getting closer to understanding the evolution of galaxies, and as we do so, the remaining questions get both harder *and* more interesting!

I would like to thank the organizers of this conference for the spectacular venue, for giving me the opportunity to come, learn, and express my views on the observational aspects of galaxy evolution and also for providing partial travel support. I would like to thank Ed Turner for recently reminding me of scientific "cautions" mentioned in this article, and I would also like to thank my many collaborators on the subjects of cosmology, galactic structure, galaxy evolution and stellar populations. This work has been supported by the Smithsonian Institution and Nasa.

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