Tracing the Ancestry of Galaxies (on the land of our ancestors)
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Conference Summary

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Abstract. This summary is from the perspective of a person who is interested in galaxy assembly and works from an observational low redshift perspective, using evidence from the components of our Galaxy: the thin and thick disks, the bulge and the halo.

1. Introduction

Huge N-body simulations have outlined the evolution of the dark matter in the universe, and they are critical to interpreting what we see at high redshift. But now we need to understand the processes of baryon acquisition in galaxy assembly, observationally and theoretically. That was the main theme of our meeting.

We are going into a very exciting time of opportunity, with many new telescopes and instruments on the ground and in space, covering almost the entire spectrum of interest for galaxy assembly.

I congratulate all of the speakers on the level of interest and excitement in their presentations. I would like to include them all in this summary, but that would take very long: this summary will concentrate on aspects of the meeting directly related to baryon assembly.

2. Baryon Acquisition

Ideas on the delivery of gas into galaxies have changed over the last few years. Cold flows are seen in simulations of virialising gas. Mergers remain significant for building high mass galaxies: mergers and star formation each doubles the stellar mass between $z = 3$ and $z = 1.5$. The role of mergers in building up disk galaxies now appears, however, less than previously believed.

The near-linear rise in star formation rate with stellar mass is roughly consistent with the accretion of gas in proportion to the accretion of dark matter.

Feedback from star formation and AGNs is important in regulating the star formation in both high mass and low mass systems, and in making star formation relatively inefficient as required by observations. Galaxy mass is the primary factor determining the assembly history of massive galaxies - again, this is probably related to feedback in these systems.

Galaxies lie in the two color families: blue star-forming systems and red galaxies in which star formation appears slow or has ceased. Depending on the accretion and quenching processes, galaxies appear able to make the transition in either direction between the color families, quenching from blue to red (e.g. galaxies being stripped in Virgo) and revitalising their star formation from red to blue. None of these processes is very well understood yet. New projects on mapping the gas in the cosmic filaments are exciting. Relating the gas flows to star formation remains an issue.

3. Evidence for Gold Gas Accretion

Cold flows may be difficult to detect directly, because their covering fraction is small. Observational evidence for cold gas accretion comes from deep HI observations which show kinematic and structural lopsidedness, warps, holes, and kinematic lags in gas halos. In some cases, high latitude gas is probably related to a galactic fountain which is likely to be entraining gas, maybe from the hot halo, and delivering it to the disk on return. In this way, star formation provides its own fuel via the fountain.

4. Downsizing

At redshifts $z < 0.5$, the massive red galaxies appear to have almost ceased their star formation, while the blue galaxies are burning on. This phenomenon is also evident at high z, with large galaxies being more advanced in their star formation history. Some appear to be already red and passive at high z, but they may in fact be dusty and star-forming.

5. The Cosmic Star Formation History

The star formation in the universe has the well-known rise and fall towards higher z, as measured by various star formation indicators: combining UV (with its dust extinction) and the mid/far-IR emission (with its dust emission) reduces the individual uncertainties in the estimates of the star formation rate.

By $z = 6$, estimates of the star formation rate in the universe are at an uncomfortably low level, so low that they may be inconsistent with reionization by galactic light.

Comparison of the observed stellar mass density $M_*(z)$ with the integrated star formation history remains potentially inconsistent. The problem may lie with the contribution from low mass galaxies, which may be underestimated if the galaxy mass function is steep. The new CANDELS HST Treasury survey will help to sort this out.

Deriving M_* and the star formation rates from spectral energy distributions requires good stellar population synthesis models including all significant stages of stellar evolution, and the estimates are sensitive to how the star formation history is modelled. For systems at $z \sim 2$, models with exponentially *increasing* star formation rates appear to give star formation rates that are consistent with those from UV data.

6. Cold Gas in Galaxies

New work on detecting massive cold gas fractions in nearby star forming galaxies like M33 and NGC 1705 indicates that the cold 6K component is much more massive than the warmer 21K component, and provides a reservoir for fueling the star formation.

The power of molecular observations in investigating the gas content of high-z galaxies is long established. Some of the systems at $z \sim 1$ are seen to be $30 - 40\%$ gas. A large population of gas rich galaxies is seen at $z \sim 2$. They show low excitation now but with much more CO emission than expected.

In the low-z early type galaxies, it was interesting to hear of systems with plenty of molecular gas but no star formation, with the ionized gas ionized presumably by post-AGB stars.

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7. 3D Optical Spectroscopy

3D optical spectroscopy (IFUs, and also Fabry-Perot and FTS systems) is powerful for measuring detailed velocity distributions and 2D metallicity distributions to guide theories of galaxy assembly. It provides an excellent way to determine if systems are supported by rotation or velocity dispersion.

Many major surveys are in progress for spirals and also for early-type systems. These early-type galaxies provide about half of the stellar mass in the universe, evenly split between elliptical and S0 galaxies (which are presumably former spiral systems that have lost their fuel).

They include a subset of about 10% slow rotators. However most of the S0s and the intrinsically flatter ellipticals have aligned photometry and kinematics, so are probably near-oblate: more than 85% are disk-like systems, showing us the great preponderance by number of galaxies which came out of the galaxy formation process as disks.

The formation of the central bulge structures is a key issue in understanding how different kinds of galaxies form and grow. The details of the bulge structures and their formation routes are critical, but the structures can be complex and it is often unclear what the central structures are and how they should be modelled to derive bulge-to-disk ratios.

Evaluating the formation, abundance gradients and lifetime of central bar structures is important goal for understanding bulge formation, including the secular processes.

A well controlled study of SDSS galaxies shows that bars are much more important than interactions in enhancing the central star formation rate in galaxies

8. 3D Radio spectroscopy

Large radio surveys are in progress on halo HI gas, with more to come from MeerKAT and ASKAP in the next few years.

HI observations of galaxies in voids show some very gas rich and extended galaxies, with some appearing to lie in common HI filaments and showing slightly enhanced star formation rates. Some of the nearby galaxies show kinematically and spatially displaced HI, which can be interpreted as direct evidence of cold mode accretion. In dense environments like Virgo, one sees direct evidence of local gas stripping (HI tails) enhanced by dynamic motions of the intra-cluster medium. This mechanism provides one route to quenching of star formation.

9. Galaxies at High Redshift

High-z surveys provide the basic data on number counts and the luminosity function, the luminosity and mass density functions as function of z, and the star formation history which constrains the theory of galaxy formation and evolution. They also show the different star formation histories of the massive early red galaxies with their rapid growth at high z, contrasting with the steady mass growth of the currently star forming galaxies.

The role of major mergers in growth of bright galaxies is very significant: galaxies brighter than L^* have typically acquired 25% of their mass since $z = 1$, mainly from major mergers.

Quenching of star formation is needed to give the observed form of the luminosity function and to generate the S0 galaxies in which the star formation in the disk has gone out. Note that all nearby galaxies, no matter what their type and current star formation rate, appear to have very old stars: star formation started at roughly the same time but proceeded at very different rates depending on the mass.

3D optical/NIR spectroscopic surveys, some with adaptive optics, provide potential diagnostics of the state of galaxies at high z. They show evidence of mergers and cold flows, irregular kinematics in some systems, and the presence of massive turbulent clumpy disks. For $z = 1$ to 3, comparable fractions are found of stable disks, dispersion-dominated systems and systems undergoing mergers.

Some rotationally supported galaxies show evidence for positive abundance gradients, possibly generated by interactions or cold flows of pristine material towards their centers. Systems that are strongly star forming show lower abundances for their luminosity: this may be due to inflow of pristine gas, which enhances the star formation rate and dilutes the metallicity. Interactions can also spatially redistribute metallicity.

Simulations show that SN-driven winds do not reduce the accretion of gas from filaments, and that SN feedback can enhance star formation because of enrichment and enhanced cooling. This is important for understanding the feedback in spheroidal systems, where both AGN and SN feedback may be needed.

10. Bulges and the Clump Cluster Galaxies

Many galaxies at high redshift show massive starbursting clumps, with masses $\sim 10^9$ $M_\odot$ and star formation rates ~ 20 $M_\odot$ yr^{-1} . The clumps are believed to form from a turbulent gas disk, fed by cold gas accretion. Although these massive clumps are believed to be relatively short lived, some authors have argued that they may spiral inwards under the effects of dynamical friction and merge to form a bulge (internal merger). They may also be important for forming thick disks. If they are short-lived, they are likely to be chemically homogeneous. If the early Milky Way was clumpy, we should be able to find the debris of these homogeneous dispersed clumps, from large high resolution spectroscopic surveys like the HERMES survey, using chemical tagging techniques.

Galaxies like the Milky Way, with small boxy bulges, are believed to build their bulges through a phase of disk instability (bar formation and buckling, sometimes called secular evolution) which lasted about 2 Gyr. Such galaxies are not rare, so this kind of instability would have been a common event soon after their formation. During this phase, these unstable galaxies would have high stellar and gas velocity dispersions. It would be useful to find ways to distinguish high redshift galaxies building bulges via disk instability from galaxies undergoing minor mergers.

Strong evolution of the disk to bulge ratio is observed from $z = 0.8$ to $z = 0$. The bulge fraction goes from 20% at $z = 0.8$ to 40% at $z = 0$. About 15% of local galaxies have small or negligible bulges. Somehow they have avoided the bulge formation processes, internal or external. These galaxies are still a problem for galaxy formation simulations in CDM.

11. Cosmological Simulations

The distribution of stellar mass in galaxies is concentrated in a relatively small interval of stellar mass between 10^{10} and 10^{11} $M_\odot$, while the dark matter has a much broader distribution. But the ratio of stellar masses to halo masses is only 3.5%, compared with global fraction of 17%: the efficiency of galaxy formation is low. Current simulations with baryons give much larger stellar fractions.

Simulations of structure development in dark matter are now well advanced. Until comprehensive baryonic simulations are available, the step from dark matter to the observable universe goes mainly via semi-analytic recipes. These work well for stellar mass functions of galaxies and the galaxy scaling relations (stellar mass, radius R, metallicity,

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rotational velocity V) and clustering of massive galaxies. They work also for number densities in clusters and the (stellar mass) - (halo mass) relation. They do not work so well for clustering of less massive galaxies, the cosmic star formation history, and the evolution of stellar mass function: the lower mass galaxies form too early in the models (this problem lies at the basis of the other misfits).

All of these assembly processes, involving baryons and dark matter, lead to the scaling laws for galaxies, like the V-L and L-R relations for disk galaxies and the fundamental plane for hot systems. These scaling laws are a manifestation of the underlying distributions and dynamics of the dark and baryonic components (stars and gas). The goal for the future is to interpret the scaling laws in terms of the stellar populations and the history of the star formation, and also the dynamics of the interactions between dark matter and the baryons as the galaxies were assembled. These are not yet well enough understood.

Two closing comments:

• high resolution hydrodynamic simulations are beginning to provide real insight into feedback and galaxy formation

• this was the first conference (for me) at which a review talk was presented remotely. While technically and scientifically very successful, this has ominous potential.

Many thanks to Claude for organising an exciting meeting in an exciting place. Our congratulations go to him on the great things that he is doing here in Burkina Faso.