Summary of the discussion from SKA Science Working Group 4,
Galaxy Formation
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Chris Carilli

LEVEL I science: Sensitive, wide field HI 21cm and radio continuum surveys.

[Level 1 science drivers are defined as fundamental to the science potential of the SKA and are used to set basic telescope parameters.]

The science case for WG4 as delineated in the 1999 SKA science case document focuses on sensitive, wide field HI 21cm line and radio continuum surveys. These programs will probe the evolution of neutral atomic gas, dark matter, and star formation, in galaxies out to z=4 and beyond. The WG4 discussions in both Berkeley and Bologna affirmed these programs as being the primary science drivers in the area of galaxy formation for a future large area cm-wave telescope. Some aspects of the science case are reviewed in the short document that follows, and the telescope specifications demanded by these programs are given in the table.

In Bologna WG4 identified a few areas that need to be explored further.

1. The HI 21cm science case could be dove-tailed with the CO case by pointing out that the SKA will detect 'normal' galaxies in HI 21cm emission out to about z = 4, and in CO 1-0 emission at higher redshifts, providing continuity in redshift. A potential danger here is the overlap with ALMA. It was pointed out that by studying the low order transitions, the SKA may give a better diagnostic of the total gas content. Also, the SKA will have dramatically better sensitivity than ALMA, even taking into consideration that the higher order transitions are stronger. [Responsible parties: Rawlings/Carilli]

2. We should emphasize that future radio/mm telescopes provide the only opportunity to probe beyond the epoch of reionization, i.e. z > 6, where optical telescopes get obscured by the neutral IGM. Models (e.g. Gnedin et al.) suggest that there will be a substantial period between the formation of the first ionizing sources (eg. galaxies and AGN at z = 7 to 15) and the 'epoch of reionization', i.e. when the individual ionization zones start to overlap at z = 6 to 7. This 'grey age' will be the exclusive realm of the radio telescopes. What kinds of sources are expected? How can the SKA contribute to their study? [Carilli/Gnedin?]

Note that this is a separate science driver from the study of the large-scale structure that may be seen in the redshifted 21cm line during the epoch of reionization, a topic covered in detail by WG3.

3. There is an apparent conflict between the telescope demands of the HI line surveys and the radio continuum surveys in terms of the array configuration. The HI surveys want resolutions on the

order of 1" for brightness temperature sensitivity (baselines <= 100 km). The radio continuum surveys want resolutions of 0.1" or better to avoid confusion, and preferably 0.01" to be able to differentiate AGN from starbursts. Can a compromise be reached? What fraction of the collecting area is required on baselines > 100 km in order to satisfy the continuum experiments? [Garrett/Muxlow]

Note that a partial solution to this problem comes from the fact that the most sensitive continuum observations will likely be done at a factor few higher frequency than the line observations (see point 6).

4. Condon et al. found a maximum brightness temperature for starburst galaxy radio continuum emission (3e4 K at 8 GHz). What demands does this brightness temperature limit set on required UV coverage? [Muxlow/Garrett]

5. It was first considered that the HI line and continuum surveys could 'piggy back', since the continuum comes for free during the line observations. However, WG4 noted that the continuum survey would probably best be done at somewhat higher frequency (1 to 4 GHz or so), rather than 0.3 to 1.4 GHz, in order to utilize a larger bandwidth, and lower the confusion/dynamic range problem. This increased sensitivity has to be balanced against 'typical' source spectral indices. Can we determine the optimum frequency for continuum surveys using simulations? [??]

Note that by moving to higher frequency for the continuum survey one also mitigates the problem of resolution, as outlined above.

6. The HI models in the 1999 science case do not include evolution in the HI mass function with redshift. New models should be generated which include reasonable assumptions concerning evolution. These will greatly improve the already strong science case. [van der Hulst]

7. The issue of natural confusion has to be considered for the continuum surveys. If the sources have a typical intrinsic size of X", what ultimate limit does that set to the sensitivity of continuum surveys? [Muxlow?/Garrett?]

8. What is the required imaging dynamic range for the continuum surveys? The current science case says 1e6, but Carilli and Muxlow separately estimated 1e7. [Muxlow?/Garrett?]

LEVEL II Science:

[Level II science is defined as important programs that should be high priority for the SKA, but are not absolutely fundamental if determined infeasible from a design/cost perspective.]

1. Low redshift 'Cosmic Web' in HI and Radio Continuum: studying the distribution of neutral atomic gas at low column densities and/or low masses in HI 21cm emission and absorption, and the radio continuum emission on super-cluster scales. This topic includes the environment of low z Ly alpha forest clouds, low surface brightness galaxies, high velocity clouds, the HI edges of galaxies

(UV background, dark matter at large radii), etc... Some of these topics are mentioned in the current science case, some not. WG4 felt that these issues might be consolidated into an interesting section in the revised science case. The surface brightness sensitivity (N(HI) <= 10^{17} cm^{-2}) requires fairly short baselines (<= 10 km). [Corbelli, Oosterloo, van der Hulst, Maloney?, Colgate?]

2. Redshifted thermal molecular emission: studying CO, HCN,... emission from high redshift galaxies. This topic may be one of the primary science drivers for pushing to frequencies higher than 22 GHz. Complementarity with ALMA should be emphasized (low vs. high order transitions), with the SKA providing a couple of advantages (wide FoV, better sensitivity). [Rawlings/Carilli]

3. OH megamasers: OH megamaser emission from intermediate and high redshift star forming galaxies may be a substantial contaminant to the HI surveys discussed above. But they are very interesting in their own right, being sign-posts to active star forming galaxies, and they may provide an estimate of the redshift evolution of the galaxy merger rate. The 1999 science case discusses OH megamasers as scientific curiosities. We should emphasize the potential of these systems for studying galaxy evolution in general, as per work by Briggs and Darling. [Darling/Briggs]

General Issues:

I. The science case document:

The science case document of 1999 was an excellent start. However, many interesting discoveries have been made in the interim, e.g. The 'epoch of reionization' via the Gunn-Peterson effect, the submm galaxy population and the possible (dominant) contribution of dust obscured galaxies to the star formation history of the universe, the black hole mass -- spheroidal stellar velocity dispersion relation suggesting a causal relationship between the formation of massive black holes and the spheroidal components of galaxies, etc... WG4 feels we need to revise the science case document in order to include these, and other, new discoveries.

Perhaps more importantly, WG4 feels that the document needs to be restructured. The current document presents the SKA capabilities, and then shows all the gee-whiz stuff that can be done. In order to better impress the general astronomical community, we should start by considering the important questions facing astrophysics today, and then show how the SKA will help to solve these questions. Part of the process will be to point out the complementarity of the SKA with other future instruments (NGST, ALMA,...), as well as to emphasize the unique science areas the SKA will explore.

We envision a science case document that is comprised of a few 'key programs'. Each WG should consider the key problems facing their field, and then delineate the key SKA observation that will address these problems.

It is clear to all that the SKA will make discoveries in many areas that we cannot currently envision. But that should not be used an excuse to abdicate responsibility for making the best science case for the instrument based on the questions that are paramount today.

II. Group membership:

The issue came up as to group membership. Thus far the membership has been completely ad hoc. In order to make further progress, a more targeted group membership may be required, extending outside the radio community. We need people who are knowledgeable about the capabilities of future instrumentation in other wavebands (e.g. NGST, SIRTF, ALMA) and how these will be used to address the issues of WG4. And perhaps more importantly, we need theoretical astrophysicists who work on galaxy formation to guide us on the most important outstanding questions. If such targeting is to occur before the Groningen meeting, then individuals have to be identified and approached soon.

Table 1. Telescope Specs from Working Group 4

	HI Surveys	CO	Continuum Surveys
A/T	Given	SKA/2	
Frequency Range (GHz)	0.1 – 1.8	10 – 20 (40?)	1 - 4?
FOV (deg^2)	1	0.003	1
Number of beams[a]	2	2	-
Angular Resolution (")	1	0.03	0.02
Maximum Baseline (km)	60	80	3000
Bandwidth GHz	0.7	4	1 - 2
Imaging Dynamic Range	-	-	10^7
Spectral Dynamic Range	10^5	-	-

[a] Two beams are needed for phase referencing calibration at high frequency due to tropospheric phase fluctuations, and at low frequency due to ionospheric phase fluctuations. True multi-beaming is not required, only paired-antenna calibration, i.e. using one element of a multi-element station to observe the calibrator continuously.