The Case for a James Webb Space Telescope Extragalactic Key Project

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This document summarizes and develops the results of a discussion session at the ”Exploring the Universe with JWST” meeting at ESA-ESTEC in October 2015.

The upcoming launch of the James Webb Space Telescope (JWST) in less than three years is certain to bring a revolution in our understanding of galaxy evolution. As the first proposals will be due in a little over two years, the time is ripe to take a holistic look at the science goals which the community would wish to accomplish with this observatory. Contrary to our experiences with the Hubble Space Telescope (HST), which has now operated successfully for over two decades due to several timely servicing missions, the lifetime of JWST is finite and relatively short with a lifetime requirement of five years, and a ten-year goal. In this document we highlight the (non-local) extragalactic science goals for JWST and describe how a concerted community effort will best address these, ensuring that the desired survey can be completed during the JWST mission.

One of the key extragalactic science goals for JWST is to discover the first galaxies to exist in the distant universe. Wavelength and aperture limitations restrict HST studies to $z < 10$, yet the relatively bright and massive galaxies we can now find out to such distances hint at a tantalizing plethora of sources to discover in the even more distant past. Deep imaging with JWST NIRCam out to $\lambda \simeq 3 - 5 \, \mu m$ will allow the discovery of star-forming galaxies out to possibly $z \sim 20$ (and certainly to $z \sim 15$). In addition to probing the physics of galaxy formation only $\sim 200$ Myr after the Big Bang, such studies will allow us to trace the evolution of the cosmic star-formation rate density to the earliest cosmic times, search for evidence of the first stars (via enrichment signatures, or possibly supernovae), and provide extremely tight constraints on the contribution of galaxies to reionization (both through tracking the evolving galaxy population back to earlier times, and also by probing deeper at the currently studied epoch corresponding to redshifts $6 < z < 10$). These topics are at the forefront of current astrophysical research, being prominently featured in the recent US decadal survey as well as NASAs Cosmic Origins goals. Most crucially, ”The End of the Dark Ages: First Light and Reionization” and ”The Assembly of Galaxies” are the first two of the four primary JWST Science Goals1.

Another key goal for JWST is to perform a comprehensive cosmic census of galaxies. A deep 1-10 $\mu m$ imaging survey would allow the selection of galaxies via stellar mass, rather than star-formation activity. By probing stellar emission over rest-frame near-infrared wavelengths, such a survey would be sensitive to all galaxies down to a specific stellar mass limit, regardless of the current level of star formation. This is in stark contrast to essentially all current studies at $z > 6$, which rely on rest-frame ultraviolet observations to select galaxies, and thus are not sensitive to galaxies more than 100 Myr after their most recent episode of star formation. Such a survey would allow detailed investigations into the evolution of 1http://www.stsci.edu/jwst/doc-archive/science-requirements.pdf
the total stellar mass density, the star-formation duty cycle, and a robust search into the progenitors of today’s massive galaxies at early times.

The science goals discussed above, which cover some of the key unanswered questions in galaxy evolution, can all be addressed with the same survey: a deep 1-10 \( \mu \)m imaging survey. Such a survey could be utilized by any science investigation at \( 0.5 < z < 15 \) that is not reliant on a specific region of the sky. This survey can also be optimized for supernovae (SNe) searches, allowing the discovery of SNe to \( z > 2 \), and mitigating the effect of dust on \( z < 2 \) SNe light curves. We now turn our attention to investigating the parameters for this potential survey. As we note below, such a survey requires both NIRCam and MIRI, and thus stands to benefit substantially by the ability to observe with both instruments in parallel. Likewise, performing some of the required imaging in parallel with prime NIRSpec surveys can also increase the efficiency of the proposed survey. Clearly spectroscopy would also be a desired component. However, this may be more difficult to implement in a key project simultaneously with imaging due to the necessity of target selection. However, one path to integrate spectroscopy with imaging in an efficient manner would be to include a grism component (with NIRSpec follow-up spectroscopy of interesting sources being pursued by the community), at the cost of increasing the program size.

One possible design would be to survey the CANDELS fields with a wedding-cake strategy. The choice of several fields distributed around the sky mitigates cosmic variance and eases the scheduling of such a program. In the era of JWST these particular fields may be less unique (though the in-place X-ray and infrared imaging will be useful) and other fields may be easier to schedule, thus other field options can certainly be considered. We base our straw-man survey design (which we stress is simply illustrative of the possible total time needed, and does not represent a thorough investigation into specific science requirements) on achieving the above science goals. The deep survey must be sensitive enough to detect rest-frame UV emission from a \( M_\star \sim 2 \times 10^7 \, M_\odot \) star-forming galaxy at \( z \sim 14 \) (\( m_{\text{UV}} \sim 30.5 \)), and rest-frame optical/near-infrared emission from a \( M_\star \sim 2 \times 10^9 \, M_\odot \) post-starburst galaxy at \( z = 7 \) (\( m_{\text{NIR}} \sim 27 \)). The wide portion must still be sensitive enough to detect sub-L* galaxies at \( z > 10 \) with NIRCam (\( m \sim 29 \)) and sub-L* galaxies at \( z \sim 6 \) with MIRI (\( m \sim 26 \)). Investigating several methods of tiling, we find that we can cover the majority of one CANDELS field with the configuration shown in Figure 1. This consists of a NIRCam survey with one deep pointing (\( m = 30.5 \), shown in red), four medium-deep pointings (\( m = 30 \), yellow), and eight wide pointings (\( m = 29 \), green), and a MIRI survey with three deep pointings (\( m = 27 \)), 12 medium-deep pointings (\( m = 26.5 \)), and 28 wide pointings (\( m = 26 \)).

We use the online JWST prototype exposure time calculator\(^3\) to estimate the exposure times for this straw-man survey. To reach 5\( \sigma \) limiting magnitudes of 30.5, 30 and 29 in seven NIRCam filters (Table 1) requires a total exposure time of 88, 35 and 6 hours, respectively (obtaining one short and one long channel filter simultaneously). To reach the same significance threshold with MIRI in the F560W and F770W filters at \( m = 27, 26.5, \) and 26 requires 18, 7.5 and 3 hours, respectively. Combining these exposure times with the number of pointings in the previous paragraph, we find total exposure times of 276 hours of integration with NIRCam and 160 hours with MIRI (assuming a conservative 30% savings on MIRI exposure time).

\(^2\)The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey; candels.ucolick.org

\(^3\)http://jwstetc.stsci.edu/etc/
time via coordinated parallels; the full exposure time needed is 228 hours). Therefore the total cost to survey one CANDELS field would be 436 hours. To perform such a survey over five such fields would therefore be 2180 hours (exclusive of overheads).

Although we only present one possible plan here, any survey which wishes to answer all of the outlined key science goals will likely require over 1000 hours. A 1000-2000 hour survey is clearly an enormous investment of telescope time, representing 20-40% of the available hours in one year, and 4-8% of the total number of hours over a five year mission duration (assuming 5000 hr/yr). A coordinated community survey is the best path forward to ensure this program maximizes a combination of science goals, and hence maximizes the science return for the JWST observatory. Large imaging surveys on HST (e.g., GOODS, CANDELS, COSMOS, the Hubble Frontier Fields) are supported by a large community which releases and exploits the data in a timely manner. Competition in doing similarly large surveys with JWST makes little sense as the parameter space is well-defined already and will be common to any proposing team (i.e., a wedding cake approach). If no such initiative is in place, then it is likely that such a program will be doomed to the benefit of smaller, less ambitious programs that will affect the overall science return for a broad community.

While such a survey is clearly essential for maximizing our use of JWST, it may not be prudent to set off on this path immediately. As a new observatory, there may be many aspects of how the telescope operates which are currently unknown, yet may influence the design of such a survey (including uncertainties on the expected sensitivities, whether the cameras integrate down as expected, etc.). These unknowns will be explored during the first cycle,
by commissioning, guaranteed time (GTO) and early release science (ERS) observations. Therefore, such a survey as we propose here may be more timely to begin in Cycle 2, when the Cycle 1 programs can provide direct input on the planning of this large endeavor. Additionally, GTO, ERS, and Cycle 1 programs will likely accomplish some of the required imaging, providing testbeds and seeds for larger surveys.

We propose two options. The first would be for the Space Telescope Science Institute to perform this survey as a key project, with the project time coming off the top of the entire mission time budget. This could be done in an institute-led, community-driven fashion, similar to the Hubble Frontier Fields (HFFs), with the construction of an advisory committee which seeks input from the community on the science goals and survey design. In contrast to the HFFs, a survey of such importance should have several levels of iteration and engagement with the community before a design is finalized. We prefer this option as it would result in a public survey maintaining the spirit of openness established through the existing legacy fields. Should such a program occur, we stress it is of the utmost importance to ensure that adequate funding is available through channels such as the archival program in the US, and national or EU (e.g. ESA or European Research Council) funding in Europe. It would also be advisable to organize science working groups to assist with the training and networking for junior scientists, which would occur naturally should this survey occur in a more traditional PI-led fashion. A second option would be for STScI to have a proposal call similar to HST’s highly successful Multi-Cycle Treasury program. If this call had adequate resources (several thousand hours to allocate over several years), it would provide a mechanism for a comprehensive galaxy survey to succeed in a competitive environment.

We thank the attendees of what proved to be a productive discussion session at the ESTEC JWST meeting, and acknowledge useful discussions with several colleagues over the past weeks which have produced further useful input and feedback.

Table 1: Strawman Survey Design

| Filter       | t(m5σ = 30.5) | t(m5σ = 30) | t(m5σ = 29) |
|--------------|--------------|-------------|-------------|
|              | (ksec)       | (ksec)      | (ksec)      |
| NIRCam F090W | 105          | 42          | 7           |
| NIRCam F115W | 85           | 34          | 6           |
| NIRCam F150W | 70           | 28          | 4.5         |
| NIRCam F200W | 50           | 20          | 3.5         |
| NIRCam F277W | 50           | 20          | 3.5         |
| NIRCam F356W | 70           | 30          | 5           |
| NIRCam F444W | 200          | 80          | 13          |
| Total NIRCam (hr) | 88          | 35          | 6           |

| Filter       | t(m5σ = 27) | t(m5σ = 26.5) | t(m5σ = 26) |
|--------------|------------|---------------|-------------|
| MIRI F560W   | 16         | 6.5           | 2.5         |
| MIRI F770W   | 50         | 21            | 8           |
| Total MIRI (hr) | 18         | 7.5           | 3           |

The total NIRCam time denotes the total in each NIRCam channel (short and long, split by the dashed line), which is approximately equal for this filter set.