

Student questions after Rogier Windhorst's colloquium: "The best of Hubble's Wide Field Camera 3, and what the James Webb Space Telescope will do after 2018"

Sept 18, 2013: School of Earth & Space Exploration (SESE), Marston Exploration Auditorium

The 42 ASU students who follow the SESE colloquia for course credit submitted an impressive list of excellent questions after my colloquium. Below I will answer every question to the best of my ability, and in a few cases I took the liberty to reword a question to clarify. Every student submitted two questions and there were a few similar questions. Hence, I renumbered all questions so that each student has a pair of questions (1a, 1b, etc.) with my answers correspondingly numbered (1a, 1b, etc.), so I can refer to previous answers where appropriate. First, I'll list several websites, papers and books that give more detailed answers to many of your questions, which I will refer to in my answers below where needed:

(0) Relevant Websites:

<http://www.asu.edu/clas/hst/www/jwst/>

My ASU talk is file: [jwsttalks/asuSESE13hstjwst.pdf](#)

These Q&A are file: [jwsttalks/asuSESE13hstjwst_QuestionsnAnswers.pdf](#)

AHaH Java tool shown: <http://www.asu.edu/clas/hst/www/ahah/>

JWST: <http://www.jwst.nasa.gov> and <http://jwst.gsfc.nasa.gov/index.html>

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(3) Kenyon, S. J., & Windhorst, R. A. 2001, *ApJL*, 547, 69 (astro-ph/0009162) "The Kuiper Belt and Olbers Paradox"

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ASU SESE Student’s Questions and Rogier Windhorst’s Answers:

Question 1a: How will the sky be significantly darker with the James Webb Space Telescope (JWST) than it was for Hubble?

Answer 1a: Three reasons: 1) JWST orbits L2 far away from the Sun, Earth and Moon so it doesn’t have 16 sunrises+sunsets per day like Hubble does. In fact. JWST will only see precisely one sunrise and sunset during its entire lifetime: a sunrise a few minutes after launch when the Ariane V launch fairing opens, and a permanent sunset a few days after launch when its sunshield deploys; 2) Its 5-layer sunshield will effectively block the light from Earth, Moon and Sun; and 3) the Zodiacal+thermal sky-background is substantially darker at 3–4 μ m than at 1–2 μ m wavelengths: in J- and H-bands in Low Earth Orbit (LEO) the sky is about $\sim 10^3 \times$ darker than what can be achieved from the ground (see paper 9), but in L2 in the L- and M-bands it is $\sim 10^4 \times$ darker from L2. That’s another huge gain over the ground, and even a significant gain over Hubble.

Question 1b: How do we know that the black hole discussed was present before the quasar?

Answer 1b: The quasar light very likely comes from material falling into a supermassive blackhole (SMBH), heating up its accretion disk so much — just before the matter falls permanently into the SMBH — that this region is literally visible to the edge of the universe, when seen under the right angle. For this to happen, the SMBH must be present, and it must swallow material that gives rise to the visible quasar, so the SMBH comes before the quasar. Repeated quasar activity does make SMBH’s grow over time (see papers 4, 8, 10).

Question 2a: Could the improved technology of the JWST be utilized to detect planets of similar atmospheres to Earth?

Answer 2a: Yes, JWST is exquisitely suited to measure the atmospheres of occulting Earth-like exoplanets. The actual detection of such planets can also be done with JWST, but is more likely done with other facilities first, such as Kepler or ground-based exoplanet searches (see paper 2).

Question 2b: If a protective screen was placed over the JWST to shield it from micrometeorites would it still generate photographs of equal resolution?

Answer 2b: No, this would blur the images, and the micrometeorites would likely go through the shield anyway. So best is to plan for only a very small chance of catastrophic impact over 10 years, and minimize the cross-section of JWST when it goes through a meteoroid storm, like Hubble has done so far successfully for 23 years every August 11 when the Perseids hit, and every November 16 when the Leonids hit (see also answer 17b).

Question 3a: Which instruments on JWST are the most promising for making new discoveries about the early universe?

Answer 3a: All 4 of JWST's instruments are designed for this in a complementary fashion, with some redundancy to reduce overall mission risk: NIRCam for 0.6–5 μm imaging, slitless spectroscopy, and coronagraphy; NIRSpec for 1–5 μm multi-object and integral-field spectroscopy, FGS/NIRISS for 0.6–5 μm imaging, slitless spectroscopy, and coronagraphy; and MIRI for 5–295 μm imaging, slitless spectroscopy, and coronagraphy. See also: <http://jwst.gsfc.nasa.gov/instruments.html>.

Question 3b: How pivotal was the role that supermassive black holes played in the evolution of the early universe?

Answer 3b: SMBH's played a critical role in the early universe. Not only are they a by-product of early star-formation and early galaxy formation, but they also affected — and moderated — the subsequent star-formation and galaxy formation through the significant outflows from their accretion disks. In extreme cases, their relativistic jets can also trigger star-formation, as I showed in the WFC3 images of the Cen A galaxy (see paper 1).

Question 4a: Is JWST also going to observe those groups of galaxies which were first cataloged by Astronomer Alton Harp, that appear to be connected by bridges of gas and dust, while showing very different redshift values?

Answer 4a: Yes, JWST likely will — I challenge you to write the best proposal in 2017 to do so. Although the main scientific reason for such a proposal should be something less controversial, hopefully such data will put any remaining redshift controversy permanently to bed, showing that high and low redshift objects are not physically connected.

Question 4b: You showed us a Hubble Space Telescope photograph of two galaxies colliding with each another. What's the percentage of galaxies that actually undergo violent collisions, as opposed to those for which such collisions are almost not happening, because of the low density of stars and other objects which characterizes most galaxies on a wide scale?

Answer 4b: The fraction of violent mergers in the universe today is no more than a few percent of all galaxies, but merging or significant infall happens in $\gtrsim 30\text{--}50\%$ of all galaxies at high redshifts ($z \gtrsim 2$; see paper 6 and other references in papers 7 and 8). It was a violent universe back then, and a pretty dormant one today!

Question 5a: You mentioned reflection in the infrared. I haven't thought about reflections in different wavelengths other than visible, how does reflection work in different wavelengths?

Answer 5a: As far as the telescope is concerned, a minute amount of gold is used (~ 2 grams in the entire spacecraft), because gold has much better reflectivity in the IR ($\sim 98\%$) than silver or Aluminum ($\sim 90\%$), thereby further optimizing JWST's throughput. The drawback is no performance below 0.6 nm (because gold looks "yellow"), so that we need to make sure that Hubble will have done all the important work in the UV-blue before JWST flies.

In interstellar space, scattering becomes efficient if the size of the dust grains is similar to the wavelength of the radiation. Reflection can occur when the size of the dust grains is similar or larger than the wavelength of the radiation. The probability of scattering and/or reflection as a function of direction may depend on the shape and dielectric properties (composition and structure) of the dust grains. Since sizes in the dust grain population tend to follow steep power laws (see paper 3 and answer 17b), relatively few dust grains are $\gtrsim 0.1\text{ mm}$ in size and their cross-section (geometric filling factor) for scattering and reflection becomes exceedingly small. Very long wavelength radiation such as far-IR, sub-mm and radio waves thus will not reflect, but simply go past the dust particles, while light at very short wavelengths (hard-UV, X-ray, gamma rays) can actually destroy dust particles, making reflection improbable there as well.

Question 5b: How does one bring to Congress the idea of an infrared sequel to the Hubble Telescope?

Answer 5b: By showing Congress for over 20 years that Hubble is one of the best performing scientific instruments ever built, that it will be nearing its end after 2018, and that the near-mid-IR ($2\text{--}29\mu\text{m}$) wavelength regime is needed to see First Light (+dusty galaxies & obscured quasars), which Hubble cannot see.

Question 6a: You mentioned in the beginning of the talk that there have been quasars observed without host galaxies. Could those be some of the 'primordial' black holes that formed during 'Cosmic Dawn' and are they these different than those theorized to begin the epoch of reionization?

Answer 6a: This is possible, although we think that the host galaxies are actually there, but not seen yet, since Hubble cannot go deep enough nor to long enough near-IR wavelengths (Hubble is limited to $\lambda \lesssim 1.7\mu\text{m}$). We believe, however, that JWST will easily see those quasar host galaxies at $\lambda \gtrsim 2\mu\text{m}$ — they are likely very dusty galaxies (see Fig. 4 of paper 4).

Question 6b: The sunshield below the primary mirror are expected to passively cool the JWST to 40 K. However, most infrared instruments are designed to operate at L-He temperatures of 4K. How will this temperature increase effect the performance of the telescope?

Answer 6b: JWST's sunshield indeed brings the temperature down to 40 K, which is sufficient to get the darkest possible thermal skies at wavelengths $\lesssim 4\text{--}5\mu\text{m}$. At $\lambda \gtrsim 5\mu\text{m}$, however, MIRI will be further cooled with a passive cryocooler to 6 K, that works like like Hubble's Near-IR Camera and Multi-Object Spectrograph ("NICMOS") cryocooler installed by the astronauts in 1999.

Question 7a: What forces the jets of material out from the center of these massive clusters of galaxies with a black hole at the center, and why doesn't the black hole eat all that material?

Answer 7a: Conservation of angular momentum is the answer to both questions: it helps create relativistic jets that emanate along the polar axes of the (assumed) rapidly rotating SMBH, and which also prevents all ambient material from falling into the SMBH. The matter that is unfortunate enough to fall into the SMBH also carries significant angular momentum, which is why the SMBH very likely spins rapidly. Think of a very large kitchen sink with a very powerful garbage disposal: throw in Avogadro's number worth of forks, and turn on garbage disposal ... (don't do this at home) ...

Question 7b: How exactly do you resolve the galaxy light from the light emitted by the quasar?

Answer 7b: The quasar light comes from a region in the inner accretion disk that is $\gtrsim 10^7$ – 10^8 K in temperature, and no bigger than 10–100 AU in size, and therefore *unresolved* to Hubble and JWST at cosmological distances. The galaxy star-light is *resolved* to Hubble and JWST at kpc scales (1 kpc = 206,265,000 AU), or a region 10^6 – 10^7 × bigger than the quasar accretion disk. “All” the observer has to do is to very carefully subtract the super-bright quasar light (see Mechtley et al. 2012), which is typically $\gtrsim 10^2$ × brighter than the entire galaxy (yes, this quasar accretion disk is equivalent to $\sim 10^{13}$ Suns inside Pluto's orbit — not a place from which an alien astronomer would like to do dark-sky astronomy, or install its own own JWST).

Question 8a: JWST is still 5 years from launch, so is it possibly in danger of being cut if congress makes more budget cuts?

Answer 8a: There is always some danger, it all depends whether Congress keep fully funding JWST's now viable plan to completion every fiscal year, which it has done since the JWST replan of 2010/2011. The best way to run over budget in future years is usually to cut your budgets unduly, or have unrealistic budgets in early years. This is precisely what we are explaining to Congress regularly.

Question 8b: How does JWST cool to 40K?

Answer 8b: Through its 5-layer kapton sun-shields, see paper 2 and answers 6b and 30a. The temperature of deep space, where JWST is pointing is 2.73 K (the Cosmic Microwave Background or CMB), and even when pointing in the Milky Way or the Ecliptic mid-plane outward from the Sun, it is usually less than a few 10s of K. Hence JWST can passively radiate away its heat to Deep Space and cool down to an equilibrium temperature of 35–40 K, as long as its 5-layer kapton sun-shields prevent Sunlight (and Earthshine plus Moonshine) to reach the telescope structure.

Question 9a: Are there any plans for a bigger/better telescope after JWST?

Answer 9a: The next highest priority mission formulated by the Astro 2010 Decadal Survey is WFIRST, the 2.4 m “Wide-Field Infra-Red Space Telescope”, which is designed to measure the cosmological parameters very accurately. After that, it all depends on you! Since space missions take typically 10-20 years from start to launch, you young folks will be designing the next generation space telescopes in the 2020's that come after WFIRST (planned for a ~ 2025 launch), and that hopefully will then be launched in the 2030's. I plan to be playing golf in those years, but will always be reachable by cell-phone for advise ... no Email's after retirement, please ...

Question 9b: The telescope is being assembled and tested in the US, but will be launched with an Ariane V

from Kourou (French Guiana), how will they move it so it doesn't get damaged?

Answer 9b: NASA has special containers to safely ship JWST: 36-wheelers that take two freeway lanes, C-5's cargo planes that can fly these containers to where needed, and/or barges to go from harbor to harbor. JWST will be well packaged during those trips, so it will not be contaminated.

Question 10a: What happens to planetary orbits when solar systems collide?

Answer 10a: This is a question for Prof. Jenny Patience, but I think there is a good chance that planetary orbits will be disturbed, and that some planets will be thrown out in the process, or that the two stars may “borrow” some planets from each other. Generally not a good solar system to raise your kids ...

Question 10b: Someone asked about the timing sequence of planning these missions, and if there is another mission being planned to follow JWST: How does the lapse between initial planning of a mission, and the fulfillment of a mission affect the development of the technology used?

Answer 10b: See also answer 9a. Each space mission takes typically 10–20 years to plan, so the NAS Decadal Surveys always plan for having a mission (or two) lined up for the next decade. A bottleneck can occur if one mission gets delayed (for a variety of reasons), and NASA or Congress then need to step in to address the issue, as they did for JWST in 2011. Regarding keeping up with the technology, NASA always tries to use the best technology available when the mission goes from Phase A/B (Design) to Phase C/D (Implementation), see also answer 21b.

Question 11a: Are there any plans for JWST after it outlives its operational period?

Answer 11a: JWST's lifetime requirement is 5 year, its goal is 10 years, and we have propellant on-board (for orbital station keeping and angular momentum management) for approximately 11.5 years. Hence, 11.5 years is the likely maximum performance for JWST. After that, you young folks have better planned for a new mission after JWST's launch in 2018 and after WFIRST's launch in 2025 to start in the next decade and launch in the 2030's.

Question 11b: Is there any possibility of unmanned servicing of JWST in case of an emergency situation where something goes wrong?

Answer 11b: JWST now does have a grapple hook, so in a true emergency, a robotic spacecraft can go out to L2 and grab it. However, unlike Hubble, JWST's hardware (instrument, gyros, batteries, reaction wheels) is not constructed to be serviceable or exchangeable in L2. Instead, the plan is to have enough redundancy in all these, so that the spacecraft will last for at least 5 years, and hopefully 10 years or a little longer, with a likely max of 11.5 years. So unlike Hubble, where the Shuttle Servicing was planned to be an essential part of the mission all along, JWST's grapple hook is not planned to be ever needed.

Question 12a: How will the two mirror segments with ~ 40 nm rms (out of 18) affect the JWST image data, and how will this be corrected for?

Answer 12a: First, the overall JWST mirror with its 18 mirror segments as finished fully meets its high-frequency design spec of ≤ 25 nm, since its actual performance is 23 nm rms. This is because — while these two mirror segments have ~ 40 nm rms — as many as 8 other mirror segments actually have an rms as good as 15–18 nm rms at high spatial frequencies. Remember that besides small-scale errors, mid- and large-scale

errors in the overall surface figure will also be present. To reach the required $2.0\mu\text{m}$ diffraction limit, the overall JWST error needs to be $\lesssim 150$ nm rms, which is achieved through active control of the overall mirror shape using actuators and hexapod control of all the mirrors to keep the whole telescope in focus. The mid- and low-frequency rms are allowed to be larger than the high-frequency rms, and are added in quadrature when the hexapods push JWST's overall mirror into its best possible focus to within $\lesssim 150$ nm rms. At that stage, you will never see the ~ 40 nm high-frequency rms from those two mirror segments. Second, these two mirror segments are placed below the spider-tripod that holds the secondary mirror, thereby further mitigating their effects in the JWST PSF. Third, these two mirror segments as fabricated do not produce more than a $\sim 1\%$ ripple in the overall point-spread function (PSF) wings, which will be well known, so even for the high redshift quasar PSF-subtraction work, they can be put to very excellent use. Fourth, while these mirror segments could be re-polished or replaced by their spares (which aren't finished yet), this would pose too much of a schedule risk, and so for the first three reasons, the JWST project has accepted them (I personally was the most skeptical on this in the JWST Science Working Group, but when I saw how little effect they actually would have on the overall JWST PSF, I too was convinced that the right decision was to use them as is). Once in orbit, I think you would be hard-pressed to ever see their imprints. This is a perfect example that in all space missions, the "perfect" is the enemy of the "good enough".

Question 12b: What do you expect to find when data from "the dark age" is returned?

Answer 12b: I expect to find many very faint, very high redshift objects in the deep JWST near-mid-IR images at redshifts $z \sim 10\text{--}20$. Many of these may be so faint that we may have to find them via gravitational lensing (see answer 36b and paper 11).

Question 13a: The photos about the groups of galaxies captured by the Hubble Space Telescope are really amazing and colorful. Is the galaxy's color (I saw yellow, white, green, blue, red in various shades) indicative of something like temperature, distance or are they some kind of a false color image?

Answer 13a: These are fairly true color images, if you accept the fact that the eye can only see $0.4\text{--}0.7\mu\text{m}$ wavelength, and the images rendered typically are taken with filters between $0.2\text{--}1.7\mu\text{m}$, so the actual color scale is compressed, so that the eye can see it. Color is an indicator of both galaxy redshift and of the typical age (or "temperature") and dust content of the stellar population at that redshift. So with enough filters, you can estimate both redshift, stellar population age, and also dust extinction (see paper 7, 8 and 9 plus references therein).

Question 13b: I was wondering what will happen to Hubble after launching JWST. Will it be decommissioned or service will continue until it wears out?

Answer 13b: Since Hubble is so complementary over its $0.1\text{--}2\mu\text{m}$ wavelength range to JWST ($0.6\text{--}29\mu\text{m}$), it will likely be used until we no longer can because of a major hardware failure. Hubble will no longer be serviced by the Shuttle, and the last Shuttle Servicing Mission SM4 was in May 2009, at which point all Hubble's gyros, batteries, and reaction wheels were replaced, and two new instruments were installed (WFC3 and COS). None of these have had any major failures in 4.5 years (knock on wood), and at the current rate of hardware failure and wear, Hubble could last to well after JWST's launch in Oct. 2018.

Question 14a: What technology allows the JWST to survey solar populations more successfully in dustier environments than the Hubble Telescope did?

Answer 14a: Hubble covers $0.1\text{--}1.7\mu\text{m}$, while JWST covers $0.6\text{--}29\mu\text{m}$, which is sufficiently far into the mid-IR that you can see through most of the dust, even at redshifts $z \gtrsim 10$.

Question 14b: What are the benefits of choosing the L2 gravitational landscape for JWST to take its data?

Answer 14b: L2 is far away from big bad bright things that result in strong gravitational perturbations, lots of straylight, and lots of heat, such as the Moon, Earth and Sun. See also answer 38b.

Question 15a: You mentioned that when further analysis of (most of) the ($z \simeq 6$) quasars was done, you could not see the host galaxies. Does the presence of a quasar indicate the presence of a black hole?

Answer 15a: Yes, it is generally believed (Occam’s razor) that the simplest explanation for everything we know about quasars that they are caused by SMBH’s in the center of galaxies. In many cases, the host galaxies are faint — $\sim 100\times$ fainter than the quasar itself — see answers 6a, 17b, and papers 4 and 8.

Question 15b: With the JWST besides being able to “see” further away with better quality, will its instrumentation help to better understand and explore exoplanets, other than merely locating possible ones?

Answer 15b: Yes, JWST is exquisitely suited to measure the chemical content (H_2O , CO , O_2) of the atmospheres of occulting Earth-like exoplanets. Since the Earth’s atmosphere has these same molecules, such near-IR spectroscopy is very hard to do from the ground — due to its intensely bright foreground as well as molecular absorption — but it is possible to do this work from L2 with JWST.

Question 16a: How does the spatial resolution vs. image depth of JWST compare to Hubble?

Answer 16a: Since JWST has a $2.5\times$ larger aperture than Hubble, it will have $2.5\times$ better resolution at the same wavelengths than Hubble (this applies to the $0.6\text{--}1.6\mu\text{m}$ wavelength range of overlap), and JWST will have the same resolution as Hubble at $2.5\times$ larger wavelengths. JWST’s $5\mu\text{m}$ images will thus be as sharp as Hubble’s $1.7\text{--}2\mu\text{m}$ images.

Question 16b: Are there any objects in the universe, other than stuff in our solar system, that are too bright for JWST to look at?

Answer 16b: Three of our planets (Mercury, Venus and Earth) are too close to the Sun for JWST to observe. However, Mars and Jupiter, and all other outer solar system planets, asteroids, and Kuiper Belt Objects (KBOs) can be observed, although in some cases only through short exposures or narrow-band filters. The same is true for bright stars (point source saturation occurs for AB-mag $\lesssim 9.5$ in 11 sec narrow-band exposures; see paper 2 & <http://www.stsci.edu/jwst/science/data-simulation-resources>).

Question 17a: What are you most excited to get from JWST?

Answer 17a: I’d like to see some First Light objects at redshifts $z \simeq 20$, when the universe was only 180 Myrs old, and just emerging from the Dark Ages (see paper 10).

Question 17b: How do you account for meteorite damage?

Answer 17b: The JWST instruments and hardware (gyros, batteries, reaction wheels, spacecraft electronics) are protected by a good bit of shielding, so they will likely cease operation due to some other cause after 5–10 years. Small micro-meteorites will impact the sunshield, and go straight through all 5 layers, so over 10 years, there will be a number of small holes in the sunshield. Because during the main meteoroid

storms JWST’s pointing will be set to minimize its cross-section to meteoroid hits (without exposing the mirror to the Sun; see answer 2b), most will hit under shallow angles, so that the Sun doesn’t hit the primary mirror directly through the resulting holes in the sunshield. Over 10 years, these holes will however increase straylight (leaked from the warmer sunshield layers below) onto the primary and secondary mirror somewhat. Some small micro-meteorites will also impact the primary mirror, and create small dents, as they did on the outside shields of WF/PC-1 and WFPC2 that have been in space for 3.5–16 years, respectively, as I pointed out during the talk. This will decrease the contrast of the image PSF somewhat over 10 years, but as I discussed in answer 12a, not to an extent that it would prevent your main science. Since these micro-meteorite particles (and also KBO’s) have a very steep power-law size-distribution of $r^{-\alpha}$ with $\alpha \simeq 3.5$ (see paper 3), there are $\sim 3000\times$ fewer 1-mm particles than 0.1-mm particles that hit, so large micro-meteorite hits are much more rare than the small ones. JWST Project engineers plan the mission such that JWST’s cross-section to micro-meteorites is not the main limiting life-time factor in 5–10 years.

Question 18a: If hydrogen had not been reionized by the early massive stars, what do models show the universe would be like?

Answer 18a: That Universe would be a pretty foggy place for a lot longer than the one we live in, and it would be harder to observe very distant objects in such a universe. I am glad that we are living in a universe today at a redshift of $z=0$ that has been reionized since redshifts $z \lesssim 6-7$, so we can see the high redshifts object better.

Question 18b: Will SESE have the ability to work using the data from the new telescope or just the Physics Department?

Answer 18b: The JWST facility will be open for proposals from all astronomers world-wide, and all data will go public after 1 year of proprietary time, and in many cases there will be no proprietary time (or perhaps only 6 months). In other words, you better stand by and be ready to look at the first JWST data in late 2018/early 2019. Proposals are due in 2017, less than four years from today!

Question 19a: How does one correct for dust while looking at the center of a galaxy when you don’t know how much dust there is?

Answer 19a: The small dust particles scatter and absorb the blue light a lot more than the red light. So as discussed in answer 13a, if you have enough filters (typically 7, and if possible 10), you can disentangle the effects from redshift, stellar population effective age (or “temperature”), and dust. For best results, this should include filters at the longer MIRI wavelengths ($\lambda \gtrsim 5\mu\text{m}$). Approximate or estimated corrections for dust might be possible with fewer filters, if these are judiciously selected.

Question 19b: What evidence is there for the case where a galaxy forms first and the central supermassive black hole forms later?

Answer 19b: I do not know of any case where the chicken (the galaxy) definitely fully formed before the egg (the SMBH). Many of the First Stars are believed to be massive ($M \simeq 100-200 M_{\odot}$) “Population III” stars at $z \gtrsim 20$, and likely left massive BH’s behind ($M \lesssim 50-100 M_{\odot}$). Eventually, these would grow and merge into more massive SMBHs (see paper 8), so it depends on how many stars you’d like to define as a galaxy. If a dwarf galaxy has a minimum of $\gtrsim 10^6 M_{\odot}$ in stars (a star-cluster or massive star-forming region is typically $\lesssim 10^6 M_{\odot}$ in stars), then it is likely that massive BH’s were already present ($\lesssim 10^3 M_{\odot}$), although massive

SMBH's ($\gtrsim 10^5 M_\odot$) were likely not present until later, when the galaxy contained at least $10^8 M_\odot$ or more in stars. Best way to state the issue is that SMBH-growth likely went hand-in-hand with the process of galaxy assembly, or in other words: the chickens were maturing while the eggs were growing.

Question 20a: When we create the models for piecing together the data we receive into usable images, are we doing so under the assumption that nothing anomalous occurred, and that the universe at this early stage in its life largely operated similar to how it does now, or is the model able to compensate for unexpected results?

Answer 20a: Yes, we assume that the universe is homogeneous and isotropic, and that the laws of physics apply on all scales and at all times (the basis for General Relativity). While there are exceptions to these rules in the very early universe on very small scales and at very high energies (the Planck time), we assume that the very distant universe that JWST will observe will be on average the same as our local environment would have been back then. There will be statistical variations on this statement, of course, due to local density fluctuations (called “cosmic variance”), but on average JWST will measure the typical universe as it was at redshifts $z \simeq 10\text{--}20$. To average over any cosmic variance, JWST will need to observe many survey areas well separated on the sky.

Question 20b: Are there plans to launch multiple JWST satellites, or is this seen as more if a stepping stone to higher accuracy instruments?

Answer 20b: No, there is only money for one JWST. However, nothing stops you to propose to NASA and industry during the next Astro Decadal survey in 2020 a much larger version of JWST, after JWST itself was successfully launched and deployed in Fall 2018. JWST weight 6500 kg, and the current/next generation of heavy-lifter launch vehicles can launch 25 metric tons into low-Earth orbit, and a little less to L2. Just make sure that you point out to Congress that other branches of government might also benefit from having such a sequel to JWST.

Question 21a: Were the Hubble spherical aberration issues known before its launch?

Answer 21a: There were some indications from one test that the Hubble mirror had an issue before launch. However, there were two *other* tests done, one was inconclusive, and the other test was done incorrectly, so NASA's management over-ruled the one test that showed that something was wrong with the Hubble mirror (see Robert Smith's book — item 5 in the bibliography). The Hubble mission was rescued, of course, by the ability to carry out the extremely successful Shuttle Servicing missions, which brought the Hubble — launched in April 1990 — to its full functionality after the first Servicing Mission (SM1) starting in December 1993. Because of this, JWST will undergo extensive tests that its primary mirror will *not* suffer from spherical aberration — or other serious issues — that cannot be corrected automatically with the hexapods in L2. As I pointed out during the talk, JWST mirrors appear to be nearly flawless (see answer 12a), and even if they did have some spherical or other aberrations — which they do *not!!* — its hexapods could still poke it out, unlike Hubble which only had very passive mirror control that was placed in the nulls for spherical aberration, and therefore it could only be corrected by the corrective optics installed by the Shuttle astronauts during Hubble's Servicing Missions.

Question 21b: How do you correct for damage done to mirrors/CCDs over time?

Answer 21b: For mirrors, see answers 12a and 17b — the PSF will slowly develop some more very subtle

features, that you can correct for in the stellar PSF-fitting, if needed. JWST does not have CCDs that suffer from Charge-Transfer Efficiency (CTE) degradation over time. Having said that, it's new IR detectors may have some mild degradation over time, but not something that will limit the JWST mission. With the Project replan of 2011, JWST near-IR detectors are being replaced with the best-longevity ones currently available in industry. As always for both CCD and IR-detector mosaics, you will need to take enough multiple independent exposures, so that you can *both* filter out all cosmic rays *and* “dither” over any detector defects. Should the number of defects increase significantly over time — which is not a given, unlike for CCDs! — then you may just have to take a few more independent exposures at each pointing later on during the mission.

Question 22a: Since some NIRSpec micro shutters already seem to be posing problems, is this a major worry for the future use of these shutters, once they are introduced to extreme cold and zero gravity?

Answer 22a: This is being investigated and will get further tested in the vacuum chambers. With the Project replan of 2011, JWST micro-shutter arrays are currently also being replaced with cosmetically better ones that meet the NIRSpec mission requirements. One can also “dither” the spectroscopic NIRSpec exposures to avoid the bad micro-shutters, and not lose a significant fraction of the objects in a deep spectroscopic survey.

Question 22b: Given the capabilities of JWST, will it be able to shed some light upon our positioning within the cosmos by detecting rates of Doppler shift, and a possible source from which everything is getting further away from?

Answer 22b: JWST's NIRSpec will measure accurate redshifts at spectral resolution of $R \simeq 2700$ for objects as faint as AB-mag $\lesssim 29$. Ground-based telescopes can do spectroscopy with higher resolution, but only for brighter objects (typically AB-mag $\lesssim 24$ – 25), and so get even more accurate redshifts (including finding exoplanets through radial velocities). None of the existing spectrographs is accurate enough to see the redshift of any one particular object change with time — thereby constraining cosmology very directly —, although this may be possible in the future (see our AST 422 H/W problems 5.2 and 5.3 from Ryden's Cosmology book). The cosmic expansion has no center in space, only in time (which is the Big Bang itself).

Question 23a: Are there any long term plans for maintenance on JWST?

Answer 23a: No, see answer 11b. Instead of servicing, all JWST components are spec-ed to live for at least 5 years without servicing, and with a goal of 10 years.

Question 23b: Are there any potential complications (whether mechanical or photographically) for the mirrors over 25 nm rms?

Answer 23b: See answer 12a. An overall high-frequency mirror rms of 23 nm is excellent, and quite sufficient for everything JWST needs to do.

Question 24a: When you mention the brightness of a firefly, are you talking about the beetle?

Answer 24a: Yes, the one that glows for a second every few seconds. The maximum brightness of that firefly — seen typically ~ 10 meters away from you in nature — is about 1 nJy or AB-mag $\simeq 31.5$, if it were seen from the distance of the Moon (mentally blocking out the Moonlight itself in this figure of speech), which is the detection limit in very long JWST integrations.

Question 24b: How far from Earth will the James Web orbit?

Answer 24b: 1.5 million km from Earth in the L2 Lagrange point. It will therefore have a sufficiently powerful high-gain antenna to upload instructions where to point from NASA STScI, and send all the data back to Earth twice a day.

Question 25a: Was the Hubble sequence developed purely from pictures or is there some sort of numerical model associated with it?

Answer 25a: Hubble (the astronomer) invented the qualitative Hubble sequence in the 1920's to permit to classify galaxies in some logical fashion. Hubble (the telescope) allowed us to measure more quantitative galaxy morphology starting in 1994 using various parameters that indicate galaxy compactness or concentration index, asymmetry, clumpiness, and bulge-to-disk ratio, etc. More recent Hubble surveys add longer wavelengths, and systematic ground-based spectroscopy has derived physical parameters of galaxies, such as mass, metallicity, age, and rotation properties, like the ratio of chaotic-to-systematic rotation, all of which correlate in some way with Hubble's original galaxy morphology (see papers 6–8 and references therein).

Question 25b: How negative of an affect do micro-meteorite impacts have on the mirrors/telescope?

Answer 25b: See answer 17b.

Question 26a: Would JWST have an active ToO program given its slow slew rate?

Answer 26a: Yes, absolutely, there will be JWST Target of Opportunity (ToO) program. If a target is deemed important enough by the Time Allocation Committee (TAC), it will be possible to interrupt a days-long, or even week's long, JWST observing sequence to observe your favorite Gamma Ray Burster at $z=20$, or your favorite Earth-like exoplanet that has shown an orbiting Moon. Just make sure that you have your ToO proposal submitted by 2017.

Question 26b: What would be the effects of radiation damage on the filter set?

Answer 26b: The near-IR filters suffer very little from radiation damage. Everything in the telescope — at the component or instrument level — is radiated pretty harshly with a radio-active source during ground-based testing, so we know how it responds to radiation damage, and where to shore up the more sensitive parts.

Question 27a: How close is JWST from being able to tell us for certain that there is water at other planets?

Answer 27a: See answer 15b, JWST is excellently suited to find H₂O, CO, or O₂ features in the atmospheres of Transiting Earth-like exoplanets.

Question 27b: What would you say is the best feature of the JWST?

Answer 27b: Literally, it's so *cool* (6-40 K:), and therefore the perfect faint-object infrared telescope.

Question 28a: You kept reiterating that you had to account for “this and that” correction or variable. With so much room for error, how do you fathom the amount of variables that need to be accounted for when putting this telescope into space?

Answer 28a: 1000's of NASA and industry engineers, machinists and instrument builders, managers, and

scientists are working together since 2001 to define, design, model, fabricate, integrate, test and re-test, and calibrate every aspect of JWST. Needless to say that the number of important variables in this project is large, one of the more complex missions that NASA and industry have ever built together. Engineers try to conceive of everything that could happen a priori, and managers and scientists will want to have everything tested, re-tested, calibrated, and verified a posteriori. To quote Donald Rumsfeld: “There are the *known* unknowns, and the *unknown* unknowns”. It is the latter we want to be especially vigilant for, so that a complex mission like JWST is not impacted by an unknown factor that we should or might have seen coming. This takes a lot of modeling, finite element analysis, risk analysis, and error analysis, plus a lot of out-of-the-box thinking. The combination of industry and government have quite well established ways to do this. At the same time, we need to be constantly vigilant to expect the unanticipated during the ground testing, and in retrospect, figure out why an issue happened in the test chamber, and why we didn’t see it coming, and what we’ll do during the next tests to make sure this doesn’t happen again.

Question 28b: During the 3D video model at the end, you mentioned that we can view these galaxies from any angle- the front, the side, the back- because of collected satellite and telescope data. Is this enough data to also create a 4D model, or are other aspects need (i.e. longer periods of time, or more variations in wavelength)?

Answer 28b: The Java webtool “AHaH” (<http://www.asu.edu/clas/Hubble/www/ahah/>; or “Appreciating Hubble In Hyperspace”) zooms into the 3D data base of Hubble UltraDeep Field (HUDF) and Early Release Science (ERS) field galaxies sorted as a function of redshift. It does so at an imaginary $\sim 10^{16} \times$ the speed of light, so that you fly from $z=0$ to $z \simeq 6-8$ about 13 Gyr back in time in less than a minute, rather than this journey taking 13 billions years. During the exercise, the observed galaxy colors do not change (the PNG files that fly by at hyperspeed are kept at the same color), since it would be too expensive in computing time to do otherwise. While you can zoom, pan and rotate through the data-base, you cannot actually turn the galaxies on their side or upside-down, since the structure of each galaxy itself is not known 3-dimensionally, only in 2D as a projected Hubble image.

Question 29a: When galaxies collide, what are the consequences?

Answer 29a: The interstellar and intergalactic gas gets shocked and compressed, causing new stars to form, and the combined gravity of the colliding system caused the older and new stars, as well as the gas, to significantly redistribute, typically transforming two spiral disk-dominated galaxies into a more bulge-dominated galaxy, plus copious amounts of dust. As I suggested during the talk:

In 5 Gyrs from today: Milky Way + Andromeda Galaxy \rightarrow = Cen A like-galaxy.

Question 29b: What material in the sun shield helps dissipate or reflect the heat of the sun?

Answer 29b: Kapton, typically reflecting most of the light and heat from behind, and so reducing the effective temperature for every next layer by a factor of 2.7 or more.

Question 30a: What are the consequences of the sun shades being misaligned on the JWST, resulting in the sun hitting the telescope itself, and would the damage be irreversible?

Answer 30a: Then a cool telescope would get partially hot, causing it to need to cool down again after proper re-alignment of the Sunshield, and in extreme cases also being able to impact or damage spacecraft hardware. JWST has 6 redundant gyros and Reaction-Wheel Assemblies (RWA’s) to make sure that this

never happens.

Question 30b: What do researchers hope to conclude about first light from study of the Dark Ages with the JWST?

Answer 30b: See answer 17a and 19b, we hope to see the first star-clusters containing Population III stars at redshifts $z \simeq 10\text{--}20$ with JWST.

Question 31a: How do small impacts on the equipment from meteorite pieces affect the images on the Hubble telescope?

Answer 31a: See answer 17b, small micro-meteorite hits will slowly affect the mirror rms surface accuracy and mirror micro-roughness over time, slowly increasing some structure in the wings of the PSF, which can largely be removed by careful PSF-modeling and PSF-subtraction (see paper 4).

Question 31b: Does the Hubble telescope pick up light from the big bang?

Answer 31b: No, you need an old TV set for that, and watch the “snow” after the evening’s regular program disappears. This is the CMB radiation signal. For a more accurate measurement of the CMB, you need microwave background satellites that orbit the Earth or L2 (e.g., COBE, WMAP, Planck), or complementary South Pole CMB experiments.

Question 32a: In which bands will JWST be able to collect data?

Answer 32a: JWST will have broad-band filters that range from 0.6–29 micron, with NIRCcam filters similar to RIJHK+LMN covering 0.6–5 μm , and a similar set in MIRI covering 5–29 μm .

Question 32b: What is the expected resolution in each band?

Answer 32b: The broad-band filters have a resolution of $R = \lambda / \Delta\lambda \simeq 4$. Medium and narrow-band filters are also available ($R \simeq 10\text{--}100$) for brown dwarf plus planetary atmosphere studies, and emission-line region studies, respectively.

Question 33a: What do the astronomers expect from JWST for CMB study?

Answer 33a: As stated before, JWST does not measure the CMB at $z \sim 1090 \pm 1$, but everything in the foreground at redshifts $z \lesssim 20\text{--}30$, whenever First Light started. WMAP and Planck CMB polarization studies are extremely useful to constrain the polarization optical depth parameter, which is currently estimated at $\tau \simeq 0.089 \pm 0.013$, corresponding to a reionization redshift of the main ionizing sources at $z_{\text{reion}} \simeq 11.1 \pm 1.1$ (see the 2013 Planck collaboration papers). That is, if reionization happened instantaneously, most reionizing dwarf galaxies would be seen at $z \simeq 11$. Hierarchical models suggest that in the real universe, this epoch likely stretched over a wide redshift range with First Light occurring at $z \gtrsim 20$ and with reionization finishing at $z \simeq 6\text{--}7$.

Question 33b: What was the most challenging part making JWST?

Answer 33b: I think it was making the mirrors to the required accuracy (which we now have done), plus making a well deploying sun-shield, which NASA and the main contractor Northrop Grumman are now doing. This all will get tested extensively from 2014–2016.

Question 34a: With JWST, how long would the integration time be in order to detect forming galaxies during the start of the epoch of reionization?

Answer 34a: To reach AB-mag \simeq 31.0 will take about 25 hrs (5- σ) for NIRCam’s 2–3 μ m filters (see papers 2 and 10 and <http://www.stsci.edu/jwst/science/data-simulation-resources>).

Question 34b: How does JWST remove stray light from zodiacal dust or light from the milky way?

Answer 34b: Through careful modeling of the response of the spacecraft as designed and fabricated to all possible sources of light in the sky. The Zodiacal sky is pretty featureless at small scales, and so just contributes as the main source of a flat featureless sky-brightness (see papers 3 and 9). The Galactic sky has more structure, and when it is *inside* JWST’s field-of-view, it will just be imaged and needs to be deblended with the targets of interest. When the Galactic sky is *behind* the telescope, it can sometimes scatter off the sun-shield and secondary mirror directly into the field-of-view, which by the way is very well baffled against such stray-light. Nonetheless, since the L2 sky is 10^3 – $10^4\times$ fainter than the ground-based sky at near-mid-IR wavelengths (one of the four advantages of going to space over ground-based observing that I discussed during the talk), a small fraction of the out-of-field Galactic light might make it onto the JWST detectors as “rogue-path straylight”. This stray-light has not gone through the entire optical path of JWST, and therefore does not carry the JWST PSF. It is a small additive error that we will need to carefully remove from those locations in the sky where it can enter the JWST field-of-view. If and when this occurs, the best way to correct for it is to take plenty of independent exposures or “sky-flats” — if needed during parallel calibration exposures — which the JWST schedulers will be planning for.

Question 35a: Is it thought at all that the formation of super-massive black holes is tied to the process of large galaxy mergers?

Answer 35a: SMBH’s can grow in two ways (see papers 8 and 10): 1) via SMBH mergers due to galaxy mergers, when the SMBH in each of the galaxy nucleus sink to the gravitational center of the end-product, and eventually merge because they lose their orbital angular momentum due to gravitational radiation; 2) via slower, more steady infall of gas onto the accretion disk around the SMBH. It is thought that the latter slower process is actually much more steady over cosmic time, and may lead to most of the SMBH growth, which is interspersed by the much more rare, but sudden swallowing of larger amounts of material, such as whole stars or other SMBH’s (see papers 8 and 10). The slow but steady feeding SMBH is thought to lead to lower-level Active Galactic Nucleus (AGN) activity, while the fast feeding may lead to the much rarer but super-bright quasar activity.

Question 35b: Is it mandated that JWST spend a certain percentage of its lifetime on cosmology projects, a certain percentage on exoplanet research, and a certain percentage on early galaxy formation, or is it possible that the majority of the observation time will be spent on only one topic?

Answer 35b: No, the JWST TAC will allocate the time broadly across disciplines, according where the hottest topics are in each discipline — which means paying close attention to the proposal pressure across disciplines — just like the Hubble TAC has done for Hubble in the last 24 years.

Question 36a: How did serviceability of JWST factor into the rationale for selecting the L2 point (i.e., does this location now preclude human service missions like those that were executed for Hubble, or were any plans made for human service missions using Orion to the L2 point)?

Answer 36a: See answer 11b, JWST is not serviceable in L2. Instead, all its parts are designed, fabricated and tested for at least 5 years with a goal of 10 years. See also answer 38b: L2 is the only dark and safe Lagrange point where JWST can go.

Question 36b: How might our position in the Universe bias what objects we can observe or inferences we make about the size and density of objects in the earliest universe with so many other objects that might be in the line-of-sight?

Answer 36b: Two answers: 1) ultradeep JWST images will be so crowded that we will experience the “forest-for-the-trees” effect, where objects will start overlapping, not due to the lack of instrumental resolution (called the “instrumental confusion” limit), but due to the finite galaxy sizes, where the galaxy wings start to overlap significantly (called the “natural confusion limit”); 2) with so many galaxies with massive halos in the foreground, it is possible that the most distant galaxies at $z \simeq 10$ –20 will enter the deep JWST images via the curved paths of gravitational lensing, rather than via straight lines-of-sight. I referred to this as the “gravitational confusion” limit or the “House-of-Mirrors” effect during the talk. Whether JWST will enter this regime depends on whether the galaxy luminosity function, which is so-called Schechter function that transits from its steep power-law function at the faint-end to its exponential part at the bright end, with the transition occurring around the characteristic break M^* ($= -2.5 \log L^*$). Hierarchical models are currently exploring if M^* declines quickly enough at high redshifts ($z \gtrsim 10$) for “gravitational confusion” by random foreground objects to be significant (see paper 7, 10 and 11 for a discussion).

Question 37a: What is a quasar with a large duty cycle, and how does it differ from a black hole?

Answer 37a: A quasar with a large (or long) duty cycle is one that takes forever to re-occur. A quasar with a short duty cycle is one that reoccurs repeatedly and very often. See answer 1b and 24a, plus paper 8, and think of the ratio of on/off-time of the firefly.

Question 37b: Is there a correlation between the age and the mass of the stars that Hubble has found?

Answer 37b: Yes, see any elementary textbook in astronomy. As I illustrated with the WFC3 optical–IR images of the 30 Doradus nebula in the Large Magellanic Cloud, high mass stars are like the cosmic fraternity members — they live fast and die young. Low mass stars are like the cosmic geezers — they live slowly but last a long time. JWST will see young stars at *all* redshifts $z \lesssim 1$ into the Epoch of First Light, and older stars at all redshifts $z \lesssim 6$, when the Universe was at least 1 Gyr old when the older stars first appeared. Hence, JWST can see stars of all relevant ages throughout most of the Universe.

Question 38a: What would it mean for the future of NASA if the JWST does not work?

Answer 38a: That would not be good. There would be Congressional investigations, and probably consequences for industry and NASA as a whole, like there were after Hubble’s spherical aberration was first discovered in June 1990, two months after Hubble’s launch.

Question 38b: If you could relocate JWST anywhere in the universe would you?

Answer 38b: No, L2 is the only option. Remember that L3 and L1 are too close to the Sun as seen from the Earth (i.e., JWST would get too hot in both L1 and L3, and could not communicate data to and from Earth if it were in L3 since it is behind the Sun). Also, L4 and L5 are the only stable Lagrange points that tend to have junk in them, like small asteroids and other rocks you don’t want to collide with. Unfortunately, Mr.

Lagrange found only 5 solutions to the gravitational rotating 3-body problem, only one of which is good enough for JWST: L2.

Question 39a: When a micrometeorite hits the telescope, is there any way to repair the damage besides taking the telescope back down to earth?

Answer 39a: No, see answer 11b, JWST cannot be easily hauled back to Earth (although it has a grapple hook), and it is not designed so that it needs to be refurbished in space in 5–10 years. See answer 17b for the likelihood of damage from larger micro-meteorites.

Question 39b: While the structure is unfolding in space, is it especially vulnerable during those days?

Answer 39b: Not really. If the sunshield deploys properly in 1-G on Earth, the drop to 0-G in space is very small given all the other forces involved in the mechanisms that perform the deployment. This will get tested a number of times on the ground. The JWST deployment is a very slow process that stretches out over many days. It is a little bit like watching grass grow. The difference between 1-G and 0-G on these mechanisms is very small, and where needed, their effects get modeled by computer to make sure they are not a show-stopper.

Question 40a: Is there any relationship between the spatial and temporal (age) organization of a galaxy to the frequency and degree of “train wreck-ness”/irregular-ness of galaxy structures?

Answer 40a: Galaxies do change morphology when they merge, and look temporarily like train wrecks when this happens. See paper 6, 7 and 8.

Question 40b: What other lessons and complications have scientists and engineers learned from the Hubble that are being applied to and improved upon with JWST?

Answer 40b: There is a long list, see Robert Smith’s book (reference 5). The main lessons are not to repeat spherical aberration, test everything a sufficient number of times, respond to the test properly if they show something dubious, and have a sufficient number of high-quality spare parts of all your essential spacecraft elements on-board.

Question 41a: How to use JWST to detect whether super-massive black-hole grew?

Answer 41a: See papers 4, 8, and 10, plus answers 1b and 15a: 1) We can either find the faint quasar or Seyfert-like nuclear point sources in the centers of galaxies, indicating weak AGN — JWST will be especially good to see these through the dust; or 2) We can see time-variability on timescales of days–weeks–months when matter falls via the accretion disk into the SMBH; and/or 3) We can use JWST NIRSpec to see the weak nuclear emission lines indicating AGN activity.

Question 41b: Who the data will be opened to? ASU?

Answer 41b: See answer 18b: The JWST data will be open to propose to all astronomers in the world, and will be available after a 0–12 month proprietary time. Our hope is that most of the data will be made public immediately. Just be ready with your compelling JWST proposals in 2017.