PLANETS, ASTEROIDS, COMETS, SATELLITES, AND KBO'S: HOW YOU CAN USE THE JWST. J.C. Mather, NASA GSFC Laboratory for Observational Cosmology, Mail Code 665, Greenbelt, MD 20771, john.c.mather@nasa.gov.

Introduction: The James Webb Space Telescope (JWST) is planned for launch in 2018 as the successor (not replacement) for the great Hubble Space Telescope. Its four instruments will provide cameras and spectrometers over the full range from 0.6 to 28.5 µm, with coronagraphs and capabilities to observe transiting exoplanets. For comparison, the Hubble has about 1/7 of the collecting area, and covers 0.11 to 1.7 µm. Under fine guidance control, JWST can observe targets moving at rates up to 0.030 arcsec/sec, which includes all the planets outside the orbit of Earth. JWST can respond to targets of opportunity within two days, limited by review and data link schedules. JWST can observe at angles from 85° to 135° from the Sun; the 50° field of regard is a fundamental limitation of the JWST sunshield that cools the telescope and instruments (see below). The required mission life is 5 years of scientific observations, and fuel is provided for 10 years.

Scientific Objectives: Observing time will be allocated through a proposal process at the Space Telescope Science Institute, comparable to the Hubble Space Telescope's, with the first solicitation due about a year before launch. The initial science case for JWST was outlined in the HST and Beyond report [1]. When the JWST was being formulated, a Design Reference Mission was established to guide the engineering requirements. The most challenging technical requirements came from cosmology and studies of the outer solar system, because important targets are extremely faint. The JWST is optimized for wavelengths longer than 1.7 µm, where HST is limited by thermal emission and ground-based telescopes are limited by atmospheric opacity. JWST's main requirements are unchanged since the prime contract with Northrop Grumman was signed in 2002 and the instruments were descoped in early 2003.

Observing Solar System Targets: The JWST will be a very useful tool for long-term monitoring of planetary and satellite weather and atmospheric constituents, for discovery and characterization of outer solar system objects, and for examination of individual asteroids and comets. The wavelength range of JWST includes strong molecular lines of many species, and includes the H_2 line at 28.3 µm. A new white paper is now available for Solar System observations with JWST [2], which includes a number of new science cases and the most current instrument performance measurements and/or expectations. This new paper updates the former online white papers by the JWST science team members about anticipated planetary science [3, 4]. A number of topics have been considered to date including: for KBO's and Dwarf planets, the composition of surface ices and volatiles in a wide range of bodies in the trans-Neptunian region. For comets, near and mid-infrared spectroscopy of cometary volatiles and organics, and spectroscopic studies of the new class of icy comets in the asteroid belt. For planets and moons, spectroscopy of the Martian atmosphere, imaging and spectral characterization of the atmospheres of the outer solar system, and monitoring of the Titan methane cycle beyond the end of the Cassini mission.

We are currently investigating unique opportunities with JWST in the solar system, including occultations of rings, atmospheres, and small bodies. Special studies are underway to explore unique modes of operation for observations of exceptionally bright targets. The latest findings will be presented at the 2014 DPS conference in Tucson, AZ. A compilation of white papers are expected to be available before launch.

Mission Design: A summary of the JWST mission and its scientific objectives is given by Gardner et al. [7]. The JWST will be launched from Kourou in French Guiana, by an Ariane 5 rocket provided by ESA, to an orbit around the Sun-Earth Lagrange point L2. The Ariane 5 now has 60 consecutive successful launches. In this orbit, a 5-layer sunshield protects the telescope from the heat of the Sun and the Earth, and allows it to cool radiatively to about 45 K. The JWST will avoid the L2 point, which is near the end of the Earth's umbra, but will spend time within the geotail plasma. Protons from cosmic rays and solar storms limit long exposure times but do not seriously degrade the scientific detectors. The JWST is designed without expectation of servicing or upgrades, but a robotic mission could attach itself to the interface ring used by the Ariane.

Observatory Design: The solar array is deployed in the first hour after launch, and the sunshield and telescope over the first week. The power, command, telemetry, orbit maintenance (fuel and jets) and attitude control systems (ACS) are all on the warm side of the sunshield, while the telescope and instruments are on the cold side. The instrument electronics are contained in a special compartment on the back of the telescope, arranged so that the heat is radiated away from the observatory. Pointing control is done by two nested control loops. Coarse guidance uses conventional star trackers and reaction wheels, with occasional firing of the small jets to keep reaction wheel speeds within the desired range. Fine guidance is controlled by the ACS, based on error signals from the Fine Guidance Sensor (a camera in the instrument package). The ACS keeps the guide star at its commanded position by rapidly adjusting the position of a Fine Steering Mirror (FSM) located at a pupil plane (image of the primary mirror).

Telescope Design: The telescope is a 6.6 m diameter three-mirror anastigmat with an f/20 beam at the instrument package and a small movable flat at the image of the primary. The primary mirror is nearly parabolic and is composed of 18 beryllium hexagons, arranged in 3 rings. The individual hexagons have surface errors of about 25 nm rms. Each segment is provided with 7 actuators, 6 for rigid-body motion and one for radius of curvature adjustment. The secondary mirror is also provided with 6-DoF (degree of freedom) actuation. All the mirrors will be deployed and adjusted to final position after launch, using a 10-step procedure proven on a 1/6-scale model. The fine adjustment uses images taken in and out of focus, with a least-squares fitting procedure developed for the Hubble repair. The performance is diffraction-limited at 2 µm, with a Strehl ratio of 0.8 and a wavefront error of 150 nm rms. The image will be sharper than HST's, even at 1 µm wavelength. The telescope mirrors are gold-coated for maximum IR reflectivity. The superior collecting area of JWST (7 times HST's) will facilitate observations of smaller solar system objects, enabling near-and mid-infrared spectroscopy of most outer irregular satellites for the first time.

Near IR Camera (NIRCam): The NIRCam is produced by the University of Arizona (M. Rieke, PI) with a contract to Lockheed Martin. It covers the wavelength range from 0.6 to 5 µm in two bands, split at 2.35 µm by a dichroic filter to allow simultaneous observations at two wavelengths. There are two modules for redundancy, which is essential because the NIRCam is also the wavefront sensor. Each module includes a dual filter wheel with a selection of fixed filters. The short wavelength channel is Nyquist sampled at 2 µm, with 0.032 arcsec pixels, and the long wavelength channel pixels are 0.065 arcsec. These provide two 2.2 x 2.2 arcmin adjacent fields. The detectors are Teledyne H2RG HgCdTe in 2048 x 2048 format, and are also used by the NIRSpec, FGS, and NIRISS instruments. The NIRCam detectors are built in two flavors, with cutoff wavelengths of 2.5 and 5 µm. They operate around 40 K, achieved by radiative cooling. The instrument sensitivity is limited by the background light, predominantly the zodiacal light with some contribution from scattered light from the telescope optics. The detectors are controlled and the signals are amplified and digitized by a custom Teledyne cryogenic ASIC operating inches away. The ASIC allows many variations of the operations, including rapid readouts of rectangular subarrays, which is essential for bright targets. A basic coronagraph is provided as well, with the ability to place a bright object behind a stop. A new proposed subarray mode would allow for observations of all the outer planets and provide some access to Mars. Figure 1 shows the maximum brightness observable with each NIRCam filter, in comparison with the brightness of the planets from Mars through Neptune.

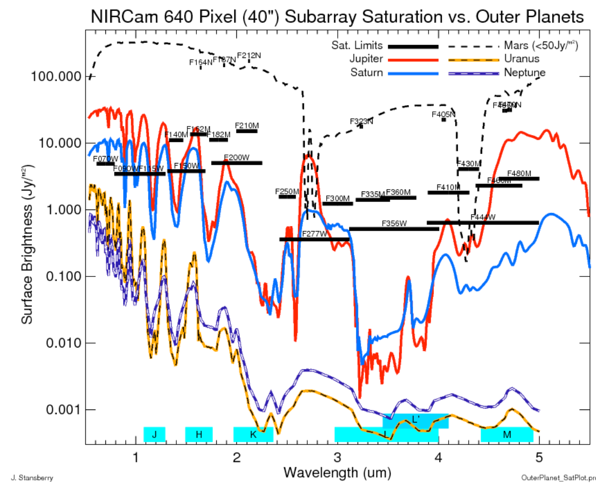

Figure 1. Estimated maximum brightness observable through NIRCam filters, vs. planet spectra.

Near IR Spectrometer (NIRSpec): The NIRSpec covers the wavelength range from 0.6 to 5 µm as well, with spectral resolutions of 100, 1000, and 2700. It is produced under the leadership of the ESA Project Scientist (P. Jakobsen, until his recent retirement, now P. Ferruit) with a contract to Astrium. NIRSpec offers fixed slits, a microshutter array, and an integral field spectrometer, and includes a grating wheel and a filter wheel. The microshutter array has 250,000 apertures that can be configured open or closed in any desired pattern; these are ideal for spectroscopy of up to 100 compact galaxies at a time. The field of view of the microshutter array is 3.1 x 3.4 arcmin. The integral field mode uses an image slicer to cover a 3 x 3 arcsec field with 0.1 arcsec resolution. It will be ideal for spectroscopy of resolved objects such as planets, satellites, and comets. NIRSpec IFU spectral imaging of Titan will build on the 2004-2017 Cassini mission survey, creating a potentially long (10 year +) baseline of spaceborne near-infrared observations of Titan's surface and atmosphere during a seasonal configuration. Additionally, the full range from 0.6-5 micron can be probed during nighttime of Mars. NIRSpec medium-resolution spectra in the 0.9-5 μm region will be used to search for organics, hydrated minerals, and water ice for a sample of ~100 small (D < 20 km) asteroids in the outer Main Belt (3.5-4 AU). The NIRSpec uses the same 5 μm HgCdTe detectors as the long wavelength channel of NIRCam. NIRSpec sensitivity is detector-limited for faint objects, but the detectors are astonishingly good, with dark currents measured in electrons per hour per pixel. Figure 2 illustrates the spatial resolution of the NIRSpec IFU compared with the size of Titan.

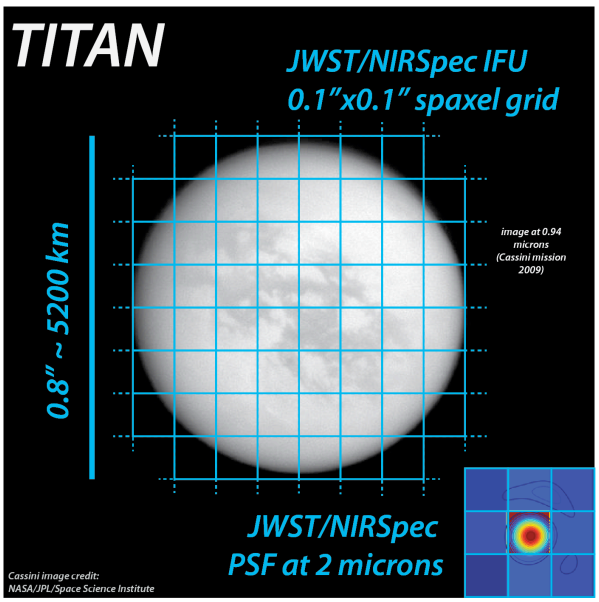

Figure 2. Spatial resolution of the integral field unit in the JWST NIRSpec, compared with Titan.

Mid IR Instrument (MIRI): The MIRI is produced by a European consortium of 14 institutions, in partnership with the Jet Propulsion Laboratory, led by G. Wright of the UKATC and G. Rieke of the University of Arizona. The MIRI covers the wavelength range from 5 μm to the detector cutoff around 28.8 μm, with imaging over a 1.4 x 1.9 arcmin field, integral field spectroscopy, and coronography. The spectral resolution ranges from 2250 to 3000, supported by filter wheels to select bands, and the image slicer is optimized for four bands to cover 3.7 x 3.7 up to 7.1 x 7.1 arcsec square fields of view. There are coronagraphic masks, optimized for the four different bands. In the mid-infrared, the thermal properties of icy satellites may be studied with MIRI observations with greater signal-to-noise than Spitzer. MIRI will additionally allow for the determination of albedos, diameters and thermal properties of a wide range of objects previously too faint to have such measurements, such as KBOs, asteroids, and distant comets. The detectors are Si:As photodetector arrays in 1024 x 1024 format from Raytheon, and operate below 7 K. The detectors are similar to those flown on the Spitzer Space Telescope but in larger arrays and with better sensitivity. The imaging sensitivity is limited by the background light, predominantly zodiacal light at $\lambda < 10$ μm, but with significant radiation from the ~45K telescope and sunshield at longer wavelengths. The MIRI is the only actively cooled instrument on JWST, and uses a Northrop Grumman pulse tube cooler with heat sinks at 6 K and 18 K. The cooler has no consumable materials and is expected to operate for the duration of the mission.

Near IR Imaging Slitless Spectrometer (NIRISS): This instrument is a reconfiguration of the planned Tunable Filter Imager, provided by the CSA with a contract to COMDEV, and led by R. Doyon of the U. de Montreal. The tunable Fabry-Perot interferometer is now replaced by three dispersive grisms, with almost no other changes to the optics. NIRISS also has a sparse aperture mask coronagraphic-type observations. The detector is the 5 μm HgCdTe type, the field of view is 2.2 x 2.2 arcmin, and the spectral resolution is 150 or 700. The NIRISS is ideal for wide field searches for strong spectral line emitters, such as Lyman-α galaxies or comets. The R~700 grism, specifically designed for bright point source spectroscopy, will also be a competitive tool for exoplanet transit spectroscopy.

Fine Guidance Sensor (FGS): This is a camera with two modules with 2.3 x 2.3 arcmin fields of view to enable the JWST to identify star fields and to lock onto a guide star for fixed and non-sidereal tracking, with a suitable uploaded ephemeris. It is produced by COMDEV as the other part of the CSA contribution. It uses unfiltered 5 μm HgCdTe detectors to monitor guide stars in the 17th magnitude range. There is at least a 95% chance that every proposed observing field has a good guide star. The camera uses a sub-array mode to read the guide star position 16 times per second.

Integration and Test Program: The flight instruments were delivered to GSFC fully tested and calibrated. They have now been integrated into the ISIM (Integrated Science Instrument Module) at GSFC and are being tested together in cold and vacuum for function, focus, and compatibility. Then, the telescope will be assembled and aligned at GSFC and combined with the ISIM, and shipped by air (on a C5 plane) to Johnson Spaceflight Center. At JSC the telescope will be cooled to flight temperature and focus will be demonstrated using the flight instruments and external autocollimating flats. In addition, the figure of the primary mirror will be tested using an interferometer at its center of curvature. After this test, the telescope and instruments will be flown to the Northrop Grumman facility in California and integrated with the spacecraft and sunshield, and tested. Finally, the entire observatory will be transported by ship to the launch site in French Guiana.

Project Status: The JWST project was reviewed in 2010 and replanned in 2011, and it has been fully funded ever since. JWST is now one of the top three priorities for NASA. Since the replan, the JWST has kept its planned schedule, meeting almost all planned milestones, and using only two months of the original 13 months of schedule reserve for the critical path. All of the instruments have been delivered to GSFC, and have just completed a full cryo-vacuum test with fully integrated ISIM (Oct. 2014). A few years ago, the near IR detectors were found to be degrading, but the fault has been identified and corrected. New detectors are now complete and ready to replace the faulty ones. All of the mirror segments have been polished, tested, and coated with gold, and are now at Goddard awaiting assembly in 2015. Progress over the past year has been excellent, but the purpose of the test program is to find faults with the equipment or procedures. The project schedule and budget include reserves for such events, so that the predicted probability of meeting budget is 80%, which is much higher than NASA standards for prior projects. Congress has determined that the allocated budget of $8.0 billion (pre-launch) is all that will be provided.

References: [1] Dressler, A. et al. *HST and Beyond* (lower right corner of page) (2006), AURA/STScI. [2] Norwood, J. et al. (2014), *Solar System Observations with JWST,* STScI web site [3] Lunine, J. et al. (2010), *JWST Planetary Observations within the Solar System*, STScI web site. [4] Sonneborn, G. et al. (2009), *JWST Study of Planetary Systems and Solar System Objects*, STScI web site. [5] Lunine, J., (2011), STScI web site, [6] JWST Exposure Time Calculator [7] Gardner, J., et al., (2006), The James Webb Space Telescope, *Space Science Reviews 123*, 485-606.