Science Enabled by Spitzer Observations Prior to JWST Launch
NASA COPAG Science Analysis Group # 9 (SAG9)
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Executive Summary: The SAG9 was tasked with identifying compelling science cases for JWST that would benefit from large blocks of observing time with the Spitzer Space Telescope prior to the JWST launch. In order to perform this task in an efficient manner, the SAG9 organized itself into sub-groups along main science areas (Galaxy Evolution and Cosmology, Nearby Galaxies, the Milky Way and Its Constituents, Extra-solar Planets, Solar System), and reached out to the community to solicit inputs using a variety of channels. As each area of investigation has its own unique needs, the science cases are presented by topical area and a summary of findings and recommendations is provided at the end of the report. For each science case, attention was given to the current holdings in the Spitzer Heritage Archive in order to avoid duplication. The main findings and recommendations of the SAG9 are:

1. The Zodiacal dust contribution to the Cosmic Infrared Background (CIB) is still poorly known, with a 30% uncertainty at 3.6 and 4.5 μm. Dedicated Spitzer observations, together with use of the IRAC shutter, could reduce the uncertainty of the CIB by a factor of a few. This will help both improve the stray light model for JWST and increase the accuracy in the knowledge of the CIB intensity. Both will carry a number of science benefits, as detailed in the Report.
2. Spitzer is still unique in its capability to produce priority lists of newly discovered extra-solar planets and solar system small bodies for JWST follow-up. Furthermore, although none of the science cases listed in this Report are new or unexplored, there are many areas of investigation that have been underexploited, such as wide area surveys, the outer disks and the satellites of our own and other galaxies, etc. A concern is that much of this science may not come to fruition with the current timeline for Spitzer operations. A future Senior Review should consider extending the Spitzer mission.
3. An ad-hoc or similar committee should evaluate whether the implementation of observationally- and resource-demanding (e.g., requiring multiple years of Spitzer time) programs is likely to provide a lasting Legacy for the community for future JWST science.

1. SAG9 Charter

The James Webb Space Telescope (JWST) is scheduled for launch in October 2018, with science operations commencing in mid 2019. The Spitzer Space Telescope is currently funded to continue operations through 2016 (and may continue to be operational out through 2018). Much of the science conducted with JWST will build off of existing Spitzer data and science results. Spitzer has now entered the 6th year of its Warm Mission, which enables imaging with the IRAC two shortest wavelengths, 3.6 and 4.5 μm, at ~1.9" resolution, over a 5' x 5' field of view. These capabilities still offer unique science opportunities, and it is expected that the astronomical community will have compelling ideas for Cosmic Origins investigations with JWST, that will require Spitzer precursor observations.

This Science Analysis Group (SAG9) will engage the astronomical community, the Spitzer User's Committee, and the JWST Science Working Group in identifying compelling science to be done with JWST, that is enabled by or that benefits from large blocks of Spitzer observing time prior to JWST launch. Science areas to explore include, but are not limited to:

1. extrasolar planets and planetary systems;
2. the properties and structure of the Milky Way and its components;
3. nearby galaxies; and
4. galaxy evolution and cosmology.

Within each of these science areas, the unique contributions that the Spitzer capabilities can offer will be considered, also in light of past and recent results.

2. Description of the Group's Process

The SAG9 Charter was approved in August 2014. The Group's membership was completed in early October 2014, with a goal of providing a report (the present document) in the Spring of 2015.

In order to capture as much as possible the diversity of the science areas listed above, the SAG9 members organized themselves into five subgroups:

1. *Galaxy Evolution and Cosmology*: Ranga-Ram Chary (Lead), Lee Armus, Pierre Ferruit, Adam Stanford, Massimo Stiavelli, Rogier Windhorst
2. *Nearby Galaxies*: Daniel Dale (Lead), Kathleen Kraemer, Massimo Stiavelli, Mike Werner
3. *The Milky Way and Its Constituents*: Kathleen Kraemer (Lead), Rachel Osten, John Stauffer, Mike Werner
4. *Extra-solar Planets*: Avi Mandell (Lead), Sean Carey, Drake Deming, Pierre Ferruit, Rachel Osten, John Stauffer
5. *Solar System*: Stefanie Milam (Lead), Sean Carey, Josh Emery

Each subgroup also included the SAG9 co-chairs, to ensure cross-fertilization. The five subgroups reviewed the available science holdings in the Spitzer Archive, and brainstormed on new science ideas/initiatives that could benefit future JWST science. SAG9 telecons were used to update the rest of the group on progress.

Community inputs were solicited via mail exploders (COPAG, Spitzer Users, DPS members, and the Planetary Exploration Newsletter) and presentations at the Winter 2015 meeting of the AAS in Seattle (January 4th, 2015), as well as the SBAG winter meeting (January 6th, 2015). A general email address, copag.sag9@gmail.com was set-up to facilitate inputs from the community, and community members could also contact individual SAG9 members.

A number of contributions were received from members of the community. Each was reviewed by the relevant sub-group and incorporated in their area-specific report (see section 3), as needed. Community members who provided inputs, sometimes on behalf of a larger group, include, in alphabetical order: Christine Chen (STScI), John Debes (STScI), Diana Dragomir (University of California, Santa Barbara), Jay Farihi (University College London), Boris Gänsicke (University of Warwick), Michael Gillon (Universite' de Liege), Nimish Hathi (Laboratoire d'Astrophysique de Marseille), Don Hoard (MPIA), Kathryn Johnston (Columbia University), Mark Lacy (National Radio Astronomical Observatory), Casey Lisse (Johns Hopkins University), Carl Melis (University of California, San Diego), Nicholas Ross (University of Edinburgh), Amaury Triaud (University of Toronto), Dan Weedman (Cornell University), and Mark Wyatt (University of Cambridge).

Suggestions for new or expanded science were vetted against the current Spitzer Heritage Archive (SHA) holdings, to evaluate whether the potentially new observations duplicated existing archival data. This committee recognizes that the SHA remains a fundamental reference for future JWST observations, including those observing modes (any data, both images and spectra, beyond 5 μm) that are no longer available with the Warm Spitzer. A "planet hunter", for example, may want to know the highest S/N that can be achieved for mid-infrared spectral features with the JWST MIRI instrument; for this, they may leverage existing spectra obtained with the IRS instrument. As yet unpublished large-area MIPS+IRAC surveys could also provide crucial targets for JWST; particular attention should be paid to those holdings whose impact would be amplified by many-folds with the addition of ancillary data from space (e.g., HST) and ground facilities.

The results of the investigation are first reported divided by science area, and a summary of the principal findings are given at the end of the report.

3. Findings by Science Area

3.1 Galaxy Evolution and Cosmology

The Spitzer Shutter: Impact on Zodiacal Dust Estimates, and the Extragalactic Background Light

Uncertainty associated with the contribution of zodiacal dust in our own solar system is the main reason the CIB (also known as the extragalactic background light) is poorly known at wavelengths ~ 3-4 μm, with a 30% uncertainty. Levenson & Wright (2008, ApJ, 683, 585) provide an estimate of 13.3+/-4.4 nW/m^2/sr at 3.6 μm, including systematic errors of 3.4 nW/m^2/sr and statistical errors of 2.8 nW/m^2/sr. A large portion of the systematic error originates from the differences in the Kensall et al. (1998, ApJ, 508, 44) and Wright & Reese (2000, ApJ, 545, 43) estimates of the zodiacal light. A better constrained CIB would enable more accurate calculation of the contribution of integrated starlight in galaxies, and better assessment of the contribution of different high redshift sources to the re-ionization of the Universe, which will discriminate among competing predictions.

Spitzer has unique characteristics that can be leveraged to constrain the zodiacal light contribution: (1) it is a closed, well-baffled telescope with low levels of stray light; (2) it is located about 1 AU away from the Earth in a heliocentric orbit and provides a unique vantage point on the zodiacal cloud, complementing the geocentric view from COBE/DIRBE; and (3) IRAC has a shutter which allows the level of dark current/bias on the detector to be measured. Because the shutter has never been operated on orbit, there is risk of mechanism failure, and these observations should be made toward the end of the telescope's useful life.

Spitzer can observe the zodiacal dust at 3.6 and 4.5 μm can over a wide range (82 to 132 degrees) in solar elongation angle and ecliptic latitude. Surface brightness measurements with accuracy of several % can be made by operating the IRAC shutter to remove the DC-level instrumental bias. The limiting photometric accuracy is due to the uncertainty in the fundamental mid-infrared calibration tied to Vega and Sirius. In principle, this uncertainty can be (and probably should be) removed by placing the IRAC calibration on the DIRBE calibration scale. With a dedicated calibration campaign using the IRAC shutter, Spitzer can be used to make precise surface brightness measurements.

These measurements of the zodiacal dust cloud would greatly improve the accuracy of our knowledge of the sky brightness at 3.6 and 4.5 μm, possibly by as much as a factor ~5 relative to current uncertainty. Coordinated ground-based monitoring of the solar Fraunhofer lines may further reduce the uncertainty.

Better knowledge of the zodiacal emission may lead to refinements of the JWST stray light model, which will enable improvements in the detection and characterization of background-limited JWST observations below ~10 μm.

Wide Fields: Strongly lensed galaxies, rare AGNs and proto-cluster overdensities

Wide fields of appropriate depth provide samples of rare and/or lensed sources that can be followed up with JWST. Examples include: (1) identification of hitherto unknown clusters at $z<2$ (there is 1 massive cluster per 10 deg^2); (2) identification of galaxy-galaxy lenses, which are expected to dominate over lensing by clusters (by at least

10x) for galaxies at $z>6$, and provide an opportunity to study candidate first light galaxies; (3) identification of $z>7$ QSO candidates, using the Lyman-break technique in conjunction with data from other surveys.

The sweet spot for a Spitzer Wide Field Survey is represented by a 1000 deg^2, 5 min depth ($5\sigma=22.4$ AB mag) or 500 deg^2 at 10 min depth ($5\sigma=22.8$ AB mag) areal coverage, which could be completed in about 2 years, and would be significantly deeper than the WISE all-sky survey. In combination with other survey data (e.g. the Dark Energy Survey with DECAM, LSST, etc.), such a Spitzer survey would provide full galaxy SEDs and robust photometric redshift calibration over a significant fraction of the survey area. It would also yield a robust measurement of cosmic variance at a range of redshifts, which may guide the largest surveys (up to 1 deg^2) that JWST will undertake. A Spitzer Wide Field Survey would be a pathfinder for the upcoming Euclid and WFIRST surveys, especially if it covers the same or similar sky regions, including yielding supporting data for the photo-z determinations in their deep field galaxy samples.

Deep Fields: Epoch of reionization galaxies

An unbiased survey of massive galaxy clusters at intermediate redshift would provide significant numbers of lensed, first-light galaxy candidates at $z>10$, which would be prime targets for spectroscopic JWST follow-up. There are ~100 known clusters at $0.5<z<1$ with $M_{500} > 5\text{x}10^{14}$ M_o from the Planck, WISE, SPT and ACT cluster searches, each requiring ~100 hrs of Spitzer time to be observed with adequate depth, and ancillary data from HST and other telescopes. A half-dozen clusters with the required characteristics are currently being observed by both Spitzer and HST as part of the 'Frontier Fields' initiative (http://www.stsci.edu/hst/campaigns/frontier-fields/). The presence of significant cosmic variance at $z>10$ suggests that one should target a larger (>10-20) sample of clusters at such depths.

3.2 Nearby Galaxies

IRAC Characterization of the Ultra-faint Dwarf Galaxy Population

SDSS has uncovered a previously unknown population of ultra-faint dwarf galaxies around the Milky Way (Willman et al. 2005, AJ, 129, 2692). These objects may help to alleviate the missing companion dilemma, wherein far fewer small Milky Way satellites are known compared to the number predicted by ΛCDM models of galaxy formation. The ultra-faint dwarfs tend to have old stellar populations, which may be best characterized in the near- and mid-infrared. These extreme galaxies have not yet been fully explored but may include some of the most metal-poor objects in the nearby Universe (Brown et al. 2014, ApJ, 796, 91; Jang & Lee 2014, ApJL, 796, 6), making them good surrogates for conditions in the early Universe as we explore how dust production and properties change as a function of decreasing metallicity. Large Spitzer/IRAC studies of brighter nearby dwarf galaxies such as the SPIRITS, LVL, and DUSTiNGS projects demonstrate the power of IRAC to find and characterize the dust-producing populations of AGB and massive stars in these galaxies.

JWST will be needed to examine in detail the spectroscopic properties of these objects, but first Spitzer should be used to identify the best targets within the population of local ultra-faint dwarfs.

Extended Stellar Emission in the Outskirts of Nearby Galaxies

In the hierarchical view of the Universe, galaxies are formed through mergers between galaxies and the accretion of satellite galaxies. Observations of nearby galaxies can provide significant insight into the dominant physical processes associated with the formation of structure on intermediate scales and the subsequent evolution of galaxies. For example, recent observations of the resolved stars in the extended distributions of the nearest galaxies (Ibata et al. 2007,ApJ, 671, 1591; McConnachie et al. 2010, ApJ, 723, 1038) and the diffuse light associated with nearby galaxies (Martinez-Delgado et al. 2008, ApJ, 689, 184) reveal faint remnants that are likely residuals of the minor merger accretion events predicted by ΛCDM models (Johnston et al. 2001, ApJ, 557, 137; Bullock & Johnston 2005, ApJ, 635, 931). These low mass accretion events are expected to yield numerous discrete stellar populations in the resultant system (Calura et al. 2012, MNRAS, 427, 1401; Pilkington et al. 2012, A&A, 540, A56) and interactions with low mass substructures can also induce a number of observable low surface brightness features, including flares, rings, thickened disk components, and anti-truncations (Abadi et al. 2006, MNRAS, 365, 747; Kazantzidis et al. 2008, ApJ, 688, 254; Younger et al. 2007, ApJ, 670, 269). Although the morphological signatures of these small mergers (m/M~1/20) are necessarily less dramatic than those of major mergers, these events are expected to be much more common.

The Extended Disk Galaxy Exploration Science (EDGES) survey is one Spitzer study that attempts to address these issues by deeply observing a limited sample of 92 mostly later-type galaxies over large fields-of-view. Other Spitzer nearby galaxy surveys (SINGS, LVL, S^4G) are typically much shallower and do not cover large enough areas to securely detect significant extended emission. Ground-based facilities cannot match the sensitivity to older stellar populations achievable with Spitzer/IRAC. Additional Spitzer work is needed to best leverage JWST's ability to probe the assembly history of galaxies, particularly in regions surrounding elliptical galaxies, where evidence for mergers may be enhanced.

Time Domain Astronomy in Nearby Galaxies

The exploration of the dynamic infrared sky has just begun. One such example is represented by a currently ongoing survey with a targeted time domain search of two hundred nearby galaxies with Spitzer (SPIRITS: SPitzer InfraRed Intensive Transients Survey). The Spitzer data are being supplemented by an intensive ground-based follow-up campaign. During Cycle 10 alone, over 40 infrared transients and over 1200 infrared variables were discovered, including explosive transients (ILRT, LRN, CNe, SNe), eruptive variables (LBV, RSG, YSG, AGB), and mysterious new infrared events devoid of optical counterparts. In the latter, we may be witnessing the possible births of massive star systems. Surveys like SPIRITS can ascertain the rate of new classes of infrared transients, quantify the contribution of classical novae to galactic chemical evolution, and uncover supernovae buried in starbursts.

However, the limited wavelength coverage afforded by the Warm Spitzer is sometimes inadequate for shedding light on the origin and physics of these emerging classes of infrared transients. Time-domain science may require partial overlap in Spitzer and JWST operations, to enable contemporaneous spectroscopy with JWST and imaging with Spitzer.

3.3 The Milky Way and Its Constituents

Externally Polluted White Dwarfs

White dwarfs (WDs) polluted with material from their remnant planetary systems offer the only opportunity to measure the bulk compositions of extra-solar minor planets. No other system allows us to probe the detailed mineralogy of the debris in situ or to obtain bulk, element-to-element ratios of the materials in the debris-polluted atmospheres. Because JWST will be much more sensitive than was the IRS and with access to more sources, it may be possible to distinguish the different kinds of rocky materials that are orbiting these stars. We will be able to study multiple assembly stages of terrestrial exoplanet formation, from atomic building blocks to mineral grains to planetesimals. Spitzer is critical to find more white dwarfs with dust disks, to ensure that a sufficiently large number of bright debris disks are known for JWST to carry out a systematic study of the mineralogy and bulk abundances of the planetary building blocks. New white dwarfs are being identified all the time, and many are known to be polluted. WISE detected hundreds of previously known, nearby WDs, including several dozen with infrared excess (Hoard et al. 2013, ApJ, 770, 21). However, many WDs are too faint for the WISE catalog to be useful, and even when WISE detected an excess, Spitzer follow-up is required to rule out source blending and background contamination in the larger WISE beam. Additionally, Spitzer can be used to help characterize which disks are time variable and probe the underlying physical process that drives any detected change, such as impact by a new object or disk instability.

The Cosmic Distance Ladder and Galactic Structure: IRAC Photometry for Gaia RR Lyr & Cepheid Variables

Gaia will identify a large number of RR Lyrae and Cepheids within 2 kpc and derive distances to each better than 2%. Those stars could be used as the cornerstones of a new version of the cosmic distance ladder, which would be filled out at large distances by JWST observations.

The flux observations for the ladder are best done in the IR, so getting accurate IRAC photometry of those stars, especially stars fainter than the WISE sensitivity limit or in crowded regions where WISE is confusion limited, would be highly desirable. Direct observations with JWST would come at a much higher cost. RR Lyrae stars, mostly beyond 2 kpc, are being discovered in large numbers by ground-based facilities, such as the Palomar Transient Factory, the Catalina Transient Survey, LINEAR, etc. Follow-up IRAC observations could yield 2% or better distances to these new RR Lyrae stars. In turn, these observations will provide well calibrated magnitude distributions in structures such as tidal streams in the Galactic halo and nearby dwarf galaxies, structures consisting of stellar populations that are quite different from traditional local samples. Better definition and characterization of these structures will impact our knowledge of the mass distribution of the Milky Way, and the assembly of galaxies in general, and in that way will improve the science landscape for both JWST and WFIRST.

Microlensing Fields in the Galactic Bulge: IRAC Photometry for the K2 Field 9

The 9th K2 field will be pointed towards the Milky Way bulge, in significant part for microlensing purposes. Spitzer will observe this area in 2015 for microlensing parallax studies with OGLE (Optical Gravitational Lensing Experiment), after a successful pilot experiment in 2014. WFIRST also plans to observe 10 individual bulge fields, each of order 30'x30' in size. Obtaining new and repeated IRAC images of all these fields would help characterize all the stars in the fields, and in particular the stars that are subsequently identified as lensing a background star. IRAC observations of these stars, possibly in combination with Gaia data, could potentially be used for additional galactic structure mapping projects. This effort would enhance JWST by improving both the exoplanet data to come from K2 and the Galactic structure data which might inform future JWST imaging of the halos of nearby galaxies.

The Outer Galaxy: Tracing the Disk Warp and Searching for Distant Star Forming Regions

Although the outer Galactic plane was partially mapped by Spitzer's GLIMPSE360 project, important structures have yet to be fully explored. For example, the warp of the Milky Way disk extends further in latitude than the survey boundaries, and the most distant star-forming regions in the outer Galaxy may therefore remain undiscovered. The WISE images can be leveraged to guide a project to trace the disk warp in the outer Galaxy. Revisits to selected fields from GLIMPSE360 may also yield clusters of variable stars, indicating their youth. JWST will be able to characterize the most distant star-forming regions, but finding them requires a facility with wide-field imaging capabilities in the IR at high sensitivity and angular resolution.

3.4 Extra-Solar Planets

Providing Critical Constraints on Thermal Profiles of New Exotic Hot Planets

We are now in the golden era of the discovery of close-in transiting planets around bright stars. The ground-based surveys are still discovering relatively bright new exoplanet host stars at a rapid rate, and the TESS and K2 missions will increase these yields by a factor of 2 – 3, leaving us with hundreds to thousands of hot Jupiters and Saturns that could be candidates for characterization with JWST. Even for the most optimal targets in this large sample, JWST will need to spend 5 – 10 hours just to acquire a single spectrum. Providing at least some constraint on the atmospheric temperature, composition and structure through transit and secondary eclipse measurements for as many hot planets as possible will give JWST proposers a much more solid foundation on which to base their proposal target selection.

K2 data for Field 0 has only recently become available. It is unlikely that data for K2 Field 5 and beyond will have been analyzed fully by the end of 2016. Spitzer operations would have to continue beyond 2016 to enable characterization of the complete set of currently targeted K2 exoplanets, and also of newly discovered exoplanets from ground surveys and the TESS mission, which will launch in 2017.

Pre-Characterization of Known Super-Earths for JWST

It is critical to continue warm Spitzer observations of as many high-value super-Earths and sub-Neptune-size planets as possible, in order to probe their transmission spectra toward the mid-IR. Super-Earths will be some of the most challenging and time-consuming targets for JWST to observe. Precursor observations with Warm Spitzer will provide important information on the magnitude and wavelength dependence of any high-altitude absorbers in the atmospheres of these planets.

Recent high-profile measurements of super-Earths using HST/WFC3 have shown a dispiriting trend: these planets appear to have significant cloud opacity across the near-infrared, with a number of planets showing no molecular absorption features at all in the spectral range of WFC3, or showing evidence of depressed amplitudes for these features (Knutson et al. 2014, ApJ, 794, 155; Fraine et al. 2014, DPS, 46.104.06). However, atmospheric models show that even if spectra may be flat in the near-IR due to high-altitude clouds or hazes, it may be possible to observe absorption features at longer wavelengths. This is because at longer wavelengths the cross-section for scattering by the cloud particles drops significantly, and the clouds become essentially transparent.

Observations with Warm Spitzer will be able to help determine which super-Earth systems should be prioritized for further observations with JWST and other observatories. Specifically, if these planets show flat transmission spectra all the way through 4.6 μm, then they might not be the best first candidates for JWST NIRSPEC and MIRI. However, if their spectra suggest the presence of molecular features in the Warm Spitzer channels, then there is a high probability that they would benefit from more sensitive observations in the same wavelength regime.

Locating Potentially Habitable Transiting Earth-Sized Planets For JWST Follow-Up

JWST will have the capacity to find biological activity on terrestrial planets around other stars, but only if provided with a sufficient number of suitable targets, i.e. Earth-mass planets and super-Earths transiting stars that are both very nearby and smaller than the Sun (e.g. Kaltenegger & Traub 2009, ApJ, 698, 519; Belu et al. 2011, A&A, 525, A83; Seager & Deming 2010, ARAA, 48, 631).

Wide-field surveys such as TESS and K2 will find a number of new super-Earths around M-stars, but the yields from these surveys could be augmented by following up targets detected by high-precision Doppler surveys (HARPS, HARPS-North, Keck, etc.) and searching for accompanying transits. Spitzer has the unique capacity to monitor the stellar flux of nearby G- and K-dwarfs with ultra-high photometric precision, as demonstrated by the detection by Spitzer of the transit of the super-Earth 55 Cnc e and the subsequent measurement of its 4.5 μm thermal emission (Demory et al. 2011, A&A, 533, A114; 2012, ApJ, 751, L28). This ability to monitor specific targets at specific times makes it the optimal facility to search for the putative transits of the small planets detected by high-precision RV measurements.

Secondly, Spitzer is the optimal facility to perform a transit search for targets that are too cool and too red for existing or future transit surveys: ultra-cool stellar and brown dwarfs (spectral type later than M7), which represent a real terra incognita for exoplanets.

This work is nearly impossible from the ground due to brown dwarfs' intrinsic faintness in the optical, making Spitzer one of the few telescopes with the necessary wavelength coverage and stability. Orbits in the Habitable Zone around brown dwarfs are of the order of a couple of days (Bolmont et al. 2011, A&A, 535, A94). In addition, the flux ratio between an Earth-sized, Earth-temperature planet and a brown dwarf has the same order of magnitude as that of a hot Jupiter to a G dwarf. For instance, monitoring 120 brown dwarfs for 48 hours each may yield two planetary systems (5 planets) if extrapolations from Kepler are correct. Finding just one such rocky planet would provide the community with one of the most accessible terrestrial planets ever for atmospheric characterization, and an ideal target for JWST follow-up.

3.5 Solar System

Detailed studies of small bodies in the Solar System may benefit from synergistic observations with Spitzer and JWST. Preliminary, large surveys of these targets using Spitzer will enable complementary and follow-up studies of a refined list with JWST to determine accurate thermal profiles, the composition, and the nature of the physical body. Key science will be thermal studies of airless bodies and molecular characterization studies of icy bodies. A number of Spitzer surveys have been performed or are currently underway (e.g. Trilling et al., 2010, AJ, 140, 770; Emery et al., 2014, Icarus, 234, 17; Thomas et al., 2014, Icarus, 228, 217). However, more are needed to provide statistically significant samples drawn from many classes of objects. Such surveys could complete wavelength coverage for targets where that is lacking, provide monitoring of active targets throughout perihelion/aphelion, and push the limits of sensitivity to characterize smaller and/or more distant targets that are ideal for further studies with JWST.

Photometry of Small Bodies

Thermal infrared photometry of Near Earth Objects (NEOs), asteroids, and nearby comets, measured with the Spitzer IRAC, provides a means of estimating the first-order physical parameters of size and albedo. Additionally, the thermal inertia and surface roughness can be determined from thermal-infrared measurements at multiple epochs, covering a full rotational period, and/or at multiple wavelengths. From the thermal inertia, in turn, physical properties of the surface, such as regolith grain size, packing state, and, with proper supporting data, cohesive strength, can be inferred. Thermal inertia and surface roughness control the Yarkovsky and YORP effects, which alter the orbits and rotation states of asteroids (particularly small asteroids). The wavelength range of JWST will be ideal for thermal-infrared observations of objects out to about the orbit of Saturn (and, though not ideal, will be useful to even greater distances).

The combination of wavelength range and sensitivity of JWST will provide excellent characterization of the NEOs, asteroids, and comet nuclei observed. The two currently available IRAC channels are not ideal for detailed thermal characterization, but IRAC surveys of small bodies prior to the launch of JWST will lay the groundwork for prioritization of targets and optimization of thermal IR observations with JWST.

Characterization of Icy Bodies

Primitive bodies from the outer Solar System are likely relics of the material that formed the planets beyond the frost line. Comets, comprised nearly equally of volatile ices and refractory solids, become active when major icy constituents (H_2O, CO_2, and CO) reach sublimation temperatures, driving material from the solid body, forming a gas/dust coma, tail and trail. These species are all activated at various heliocentric distances, and as major atmospheric species, are difficult to observe from the ground. While activity driven by H_2O sublimation is fairly well characterized for many comets and comet apparitions, the contribution of the more volatile species CO_2 and CO to cometary activity is not. By imaging these targets with the IRAC 3.6 and 4.5 μm filters the gas/dust production, distribution, and abundance can be determined (e.g. Reach et al., 2013, Icarus, 226, 777). The broad bandpasses of the IRAC filters make it impossible to distinguish between CO and CO_2 gas, both of which have strong features in the 4.5 μm band. JWST imaging and spectroscopic capabilities will make it possible to determine the relative importance of CO_2 and CO activity for many comets, and out to quite large heliocentric distances, where their activity is expected to strongly dominate over that of water ice. This is essential to study in all families of comets in order to probe the radial properties of the early solar nebula, and to explore the thermo-physical character of a large sample of comet nuclei.

Although significant strides have been made in compositional characterization of Kuiper Belt objects from ground-based observations, many questions remain. Typically, only the dominant ice composition (e.g., H_2O, CH_4) can be detected, but the secondary ices remain undetected or, at best, tentatively detected. It is generally inferred that KBO surfaces contain a significant fraction of complex organic material, but firm detections and characterization of the specific organic composition remains elusive. From the ground, spectra can only be obtained at wavelengths < 2.5 μm, due to the faintness (large distances) of KBOs. However, the relevant ices and organics have strong, diagnostic absorptions in the 2.5 to 8.0 μm spectral range. JWST will obtain spectra of KBOs in this wavelength range for the first time. This will undoubtedly lead to a leap in understanding of KBO surfaces and evolution. Photometric observations of KBOs with the Spitzer IRAC channels at 3.6 and 4.5 μm can be used to place some constraints on composition. Such photometric observations for a large number of KBOs will provide important data for selecting high-priority targets for JWST spectral observations. Many KBOs have been observed with Spitzer/IRAC over the past several years. Nevertheless, some targets remain unobserved and several others could benefit from follow-up observations (e.g., dwarf planets, KBOs with indications of rotational heterogeneities).

4. Summary of Findings and Recommendations

The diversity of science cases presented in section 3 demonstrates that Spitzer has potential to make a variety of precursor observations that can enhance the science return of JWST. Different areas of research have unique needs, as will be summarized below.

An important option is to use Spitzer to accurately measure the absolute brightness of the IR sky along different lines of sight, and at a variety of solar elongation angles. This information can be used to better characterize the interplanetary dust cloud, reduce uncertainty in the cosmic infrared background brightness, and, importantly, improve the JWST stray light model. To make these measurements, the IRAC shutter would have to be used for the first time since Spitzer was launched. Because the procedure is risky, it should be attempted toward the end of the telescope's useful life.

In the field of Galaxy Evolution and Cosmology, the main identified needs are: a wide-area IRAC survey to collect significant samples of rare sources and first-light galaxy candidates; and deep imaging of intermediate-redshift galaxy clusters to secure lensed first-light galaxy candidates.

In the field of Nearby Galaxies, we note Spitzer's utility to measure the outer disks of galaxies and observe local ultra-faint dwarf galaxies, enabling optimal commitment of JWST observing time.

In the Milky Way, Spitzer observations of RR Lyrae and Cepheids can be used to improve the cosmic distance ladder and better understand the mass distribution of our Galaxy. Our knowledge of the structure of the Galaxy can also be improved with more extended observations of its outer regions, including the Warp and distant star forming regions, and the Kepler-2 fields. Spitzer could be used to identify a large sample of polluted White Dwarfs for JWST follow-up.

In the area of Extra-Solar Planet science, the principal need is to prioritize the large numbers of targets provided by Kepler and (in the near future) TESS, for JWST spectroscopic follow-up. These include hot planets, super-Earths, and Earth-size candidates. Spitzer is uniquely capable of monitoring transiting planets around low-mass dwarfs, and of searching ultra-cool stellar and brown dwarfs (spectral type later than M7) via transit events.

In the Solar System area, key science goals are thermal studies of airless bodies and molecular characterization studies of icy bodies, for which large, statistically-significant samples drawn from many classes of objects will be needed. These samples need to be larger than those currently available, and should include monitoring, in order to prioritize candidates for JWST follow-up.

None of the identified science projects is completely new or unexplored, and, with possibly one exception, they can likely be accommodated within the current Spitzer proposal selection process. The exception is programs that require a year or more of observing time; this report identifies one such program, the wide-area IRAC survey, and others may be proposed by the community. Such resource-intensive observing programs may be best evaluated by an ad-hoc committee, rather than through the current proposal selection process.

Finally, this SAG recognizes that the current timescale for Spitzer operations (one more, smaller [1,000 hours], cycle of observations in addition to the current one) may be too limited to acquire the large statistical samples needed to prioritize target lists for JWST in many science areas. A more extended Spitzer mission would also be needed to observe TESS targets of interest and optimally select exo-planets for JWST spectroscopic follow-up.

Based on the SAG9 analysis, we conclude with the three main recommendations:

(1) Consider using the IRAC shutter toward the end of the Spitzer operational life to perform absolute brightness measurements of the IR sky, if doing so will greatly (factor of a few) reduce uncertainty in the cosmic infrared background and yield a better JWST stray light model.
(2) Evaluate the past proposal pressure and consider an extension of the timescale over which Spitzer will be offered to the community, in order to enable execution and/or completion of the precursor JWST science described in this report.
(3) Evaluate the possibility of implementing, through competitive selection, one or two multi-year observing programs, designed to extend the observed parameter space (e.g., area, depth, number of targets, etc.) by at least an order of magnitude to provide a firmer foundation on which JWST can build.