Added JWST Science Cases for the Timeframe 2012-2015

A SAR Study

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Introduction

The SAR has been tasked by the JWST Mission Office to investigate what science cases will be of relevance for the general community in the timeframe 2012-2015, uniquely exploiting the JWST capabilities. These science cases are in addition to, and not a repetition of, the science drivers developed in the JWST Science Requirements Document (SRD). They do not necessarily represent `drivers', but are a representative sample of science that the `community' considers important to pursue with JWST in the indicated timeframe, and in addition to the fundamental science described in the SRD.

This study is provided to the JWST Science Assessment Team (SAT), led by Peter Stockman and Matt Mountain, as an aid in their efforts to prioritize the JWST science capabilities.

For this study, only the STScI Science Staff was probed, and not the community at large; thus, the science cases contained in this document should be considered somewhat representative, but not exempt from biases. No effort was spent in trying to reach completeness in one or more specific areas, as the intent was to probe the genuine interests, rather than some specific subject.

The only two guidelines provided to the STScI Science Staff were:

- No science case should require added capabilities.
- No repetition, or criticism, of the JWST SRD.

This work was developed between May 26th and June 10th, 2005. A brainstorming meeting for the Science Staff was held on June 2nd, 2005, after which Science Cases were collected until June 8th. The science cases submitted by the staff are attached to this Introduction, with a running number (1 through XX). The cases are roughly ordered as a function of redshift, from the distant to the nearby Universe. A summary table of these cases, and their mapping into JWST capabilities, is provided in the next Section.

Mapping of the Science Cases onto JWST Capabilities

A summary of the JWST capabilities required by each science case presented in this study is given in the table below, whose format has been borrowed from the SRD as a mean to provide easy comparison.

Title	Case #	JWST Capability					
		NIRCam	MIRI	NIRSpec	Sensitivity	PSF	FOV
Tools for Dark Energy	1	X			X	resol	X
Stellar Clusters for Reionization	2	X			X	resol	X
Gravitational Lensing	3	X			X	resol, stab	X
Hubble Constant	4	X			X	resol	X
Resolved Populations	5	X(0.6 μm)			X	resol, stab	X
Embedded Clusters in External Galaxies	6	X	X(S)		X	resol	X
Black Holes & AGN	7		X		X	resol, stab	
Hot Jupiters in LMC	8	X			X	resol, stab	X
Microlensing	9	X(0.8 μm)			X	resol	
Age of the Galaxy	10	X			X	resol, stab	
Star Formation in the Galaxy	11	X	X	X		resol, stab	X
IMF in Young Clusters	12	X			X	resol, stab	X
Extrasolar Planets	13,14,15	X(C)	X(S)(C)	X	X	resol, stab	
Astrobiology	16	X(C)	X(C)	X	X	resol, stab	

Legends:
Title: title of the science case.
Case #: running number for the science case, given in the order the contribution appears in the text.
NIRCam: (0.6 μm) or (0.8 μm)=blue wavelength cut-off down to 0.6 (0.8) micron required; (C)=coronograph
MIRI: (S)=spectroscopic mode required; (C)=coronograph
PSF: resol=high angular resolution required; stab=PSF stability required.

Science Case # 1
Title: JWST and Fundamental Cosmology: A Crucial Tool for Determining the Nature of Dark Energy

Authors: Adam Riess and Mario Livio

Science Case:
One of the very biggest challenges facing cosmology and physics is to determine the nature of the apparent dark energy which is presently accelerating the expansion of the Universe and dominating its mass-energy budget. At the time JWST was first designed, the existence of the dark energy was not even known. However, in the intervening years, techniques have been developed to measure dark energy, and JWST is likely to play a crucial role in their application.

Observations of the brightness of type Ia supernovae provided the first empirical indication for dark energy and they remain one of the best tools for determining its nature.

An important step when using Type Ia supernovae to constrain the nature of dark energy, is to characterize and calibrate out any evolutionary drift in their intrinsic properties. One such type of evolution that would be exceedingly difficult to characterize is the dependence of supernova properties on the metallicity of the progenitor. (Note, that because of the delay of type Ia supernovae from the time of formation of the progenitor system the relevant metallicity would be that prevailing when the progenitor formed, possibly billions of years before the supernova explodes.) A powerful method to calibrate this effect is to study Type Ia supernovae at $z>2$, i.e. at redshifts where the effects of dark energy are very modest, and where the changes in cosmic chemical abundances are enhanced and thus their impact may be cleanly measured (Riess and Livio in preparation). The evolutionary effects affecting supernovae at $z=1-1.5$, where dark energy is important, could then be interpolated out from the local and $z>2$ observations.

Why JWST?
For reasonable assumptions on the delay (based on the sample obtained with HST), JWST will be able to detect about 1.5 Type Ia SNe down to a flux limit of 10 nJY in the K band (achievable in 10,000s), for each NIRCam field. The uncertainty is probably about 50%. These supernovae would then need to be followed to determine their light curves. Approximately half of them would be at $z<2$, and could be used to aid in constraining the dark energy equation of state. Half would be at $z>2$, and should provide powerful leverage on evolutionary effects. As an added bonus, the rates of the observed Type Ia SNe would further constrain specific supernova models. Such a study would be carried out through repeated observations of a few fields with intervals of ~ 100 days. This could in fact be the method used to build up deep fields. Clearly this study benefits from the NIRCam sensitivity and field of view.

Science Case # 2
Title: Were Super Star Clusters (a.k.a. Young Globular Clusters) Responsible for Reionizing the Universe?

Author: Brad Whitmore

Science Case:
There are two schools of thought concerning what caused the reionization of the universe. One possibility is that QSOs and AGNs are responsible while the other contender is star formation (i.e., starbursting galaxies and ULIRGs). The present contribution focuses on the possibility that star formation is the primary cause.

One of the primary discoveries during the past decade is that most of the star formation in starbursting galaxies and ULIRGS is in the form of young massive star clusters, often referred to as super star clusters (e.g, in the Antennae Galaxies; Whitmore et al. 1999). These clusters have magnitudes as bright as Mv = -17. JWST will be able to detect the brightest of these objects out to a redshift of ~20 (based on JWST SRD), and at redshifts of ~10 and ~5, would be able to go down ~ 1 - 2 magnitudes into the distribution function respectively in 10 hour exposures. Hence, we should be able to directly image the youngest galaxies and determine whether these super star clusters are responsible for reionizing the universe (e.g., Santos 2003).

During the past decade, super star clusters (hereafter SSCs) have gained the attention of many astronomers since they have all the attributes to be "young globular clusters" (i.e., luminosity, color, mass, size, ...; Whitmore 2003). Hence, we can use the existing population of metal-poor old globular clusters (i.e., with ages ~13 Gyr) to extrapolate back into the past to estimate the number of super star clusters that formed early in the history of the universe.

Only about 0.1 % of the stars in a galaxy are found in globular clusters. However, there is growing consensus that most of the stars in the universe were originally formed in star clusters, and that the vast majority of these clusters then dissolve to form the population of field stars (e.g., Lada & Lada 2003, Fall 2004, Whitmore 2004). These field stars outnumber the stars currently found in clusters by a factor of ~1000. Surprisingly, the probability of cluster destruction appears to be roughly independent of mass (Fall 2005). Hence, for a galaxy like the Milky Way, with roughly 100 old, metal-poor globular clusters, roughly 100,000 super star clusters may have originally been formed, most of them in the first 1 or 2 billion years. This prodigious burst of star formation may have been sufficient to reionize the universe (Santos, 2003).

JWST will allow us to see this process in detail. Does a typical galaxy undergo a single "monolithic collapse", with tens of thousands of SSS all going off at once? Does it instead grow from the assemblage of thousands of small fragments, each with perhaps a single "globular clusters" at its nucleus (e.g., Meylan 2001)? Or more likely, is the truth somewhere between these two extremes. With JWST we will be able to directly image the youngest galaxies and make this determination.

Mapping onto JWST Capabilites

A wide range of filters would be used in order to age date the clusters. At the short wavelength end, the U-band has been found to be very important for age-dating the clusters. This corresponds to ~ 1.6, 3.3, and 6.6 microns at Z = 5, 10, and 20 respectively. At the long wavelength end, the rest-band I, J, and H are useful for penetrating the dust surrounding the youngest clusters. This corresponds to wavelengths in the range 5 - 40 microns, depending on redshift.

Hence, the primary instrument for most clusters would be NIRCAM, but MIRI would be important for studying the youngest (i.e., < 5 Myr) clusters.

Spatial resolution is important in two regard; 1) maximal sensitivity against the bright background of the galaxy, since the clusters will be essentially point sources, and 2) separating individual clusters in complex fields (NOTE: the importance of complex fields will depend on whether the monolithic collapse or many sub-fragments model is more typical). In either case, there will be a strong premium on optimal spatial resolution, hence the lower wavelengths, at least for the detection of the sources.

Any deep field is likely to have hundreds or thousands of good candidates (i.e., star forming galaxies with Z in the range 5 - 20), hence the field of view is not critical.

References

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Science Case # 3
Title: Dark Energy and Dark Matter from Gravitational Lensing

Authors: H. Ferguson and S. Casertano

Science Case:

Gravitational lensing offers several extremely promising avenues toward constraining the fundamental constituents of the universe. Many will be pursued vigorously from the ground, from HST, and from a wide-field optical space telescope (JDEM), should such a mission be approved. Nevertheless, JWST can make important --- indeed vital contributions if JDEM is delayed or de-scoped.

Gravitational lensing encompasses a wide range of measurements: (1) Strong lensing (arcs and multiple images) by individual galaxies or clusters of galaxies, (2) weak lensing due to the statistical effect of such mass concentrations --- measured via tangential shear of background source images around known foreground sources --- and (3) weak lensing due to large scale structure --- measured via the statistics of shear and magnification.

JWST uniqueness in this field derives from (a) high spatial resolution, (b) excellent sensitivity, and (c) PSF stability. However, its relatively small field of view relative limits its competitiveness in some areas.
The following are among the most compelling topics for JWST.

(1) Strong lensing measurements of galaxy clusters.

Over the past five years, major efforts have been initiated to discover clusters via the Sunyaev-Zeldovich (S-Z) decrement in the microwave background. Such surveys will yield large samples of clusters out to high redshift. The Planck satellite is expected to detect roughly one cluster per square degree via the S-Z effect. Combining this relatively unbiased selection with redshift measurements from the ground and JWST and lensing measurements from JWST will provide powerful cosmological constraints. Dalal et al. (2005) show that a sample of 50 clusters can constrain the equation of state parameter w to 30% with only information from lensing. Constraints will no doubt be substantially improved with independent estimates of the cluster mass profile from kinematics, X-rays, and the S-Z effect itself.

CDM models predict a universal dark-matter density profile, and predict a specific scaling law (and scatter about that scaling law) with between halo mass and concentration index. The scatter is related to second parameters such as velocity anisotropy, which can in principle be measured via radial velocity surveys. Combining strong-lensing measurements with weak lensing, velocities, S-Z constraints, and x-rays for a sample of ~30 clusters could well be a decisive test of non-interacting CDM as the source of dark matter --- it would be the subject of a good PhD thesis to determine how strong such constraints could be. Strong lensing measurements are crucial, because they provide the estimate of the central concentration of mass.

Galaxy clusters also act as giant telescopes, brightening distant objects that fall within the critical radius. Surveys and study of high-redshift candidates along the critical radii of clusters of galaxies will be an important aspect of the JWST mission to find and characterize the first objects --- as it has been already for studies with HST, large ground-based telescopes, and sub-mm observatories.

(2) Galaxy-galaxy lensing

When the gravitational lens is a massive foreground galaxy and the background source is a distant galaxy or quasar, further constraints on the nature of dark matter are possible. Measurements of so-called flux anomalies -- departures in the relative brightness of lensed images from the predictions of models involving smooth dark-matter halos -- offer a vital clue to the nature of dark matter by probing substructure on the subgalactic scale. This has emerged as a hot topic only within the past three years (Dalal & Kochanek 2002).

Existing constraints from ~10 lens systems are highly controversial -- showing either as much substructure as predicted by CDM, or considerably more than expected. These measurements probe the power spectrum of dark matter on smaller scales than the above-described measurements of strong-lensing by clusters.

In the strong lensing regime, at the current rate of discovery there will be at least 400 known strong galaxy-galaxy lens systems by the time JWST flies. Deep, high-resolution data from JWST will provide the best constraints on flux anomalies.

Weak galaxy-galaxy lensing traces statistically the distribution of matter in massive halos around luminous galaxies. CDM models predict how massive haloes grow in density and size with cosmic time (Bullock et al 2001); semianalytic models predict how luminous galaxies form and grow within these structures (Benson et al 2003, Berlind et al 2003). Ground-based observations have measured the mass distribution of haloes in the local universe ($z<0.1$, Sheldon et al 2004); HST observations already reach $z\sim0.5$, and farther in redshift will be reached with WFC3, to yield a clear picture of how both luminous galaxies and their dark matter envelopes grow from $z\sim1.5$ to the present.

The practical limit for HST (and current incarnations of JDEM) is the ability to detect and measure the shape of background galaxies at $z\sim4$, which requires the high sensitivity and PSF quality at 2.5 micron of JWST.

(3) Cosmic shear

JWST will cover much smaller fields of view than ground-based surveys or SNAP/JDEM. However, JWST will detect higher surface density of galaxies than other facilities and those galaxies will have a significantly higher mean redshift than those detected via optical surveys. While JWST cannot carry out the purely geometric tests envisioned for nearly all-sky surveys (e.g. Bernstein & Jain 2004), it will provide model-dependent constraints on the dark-matter power spectrum and angular-diameter at relatively high redshift . The importance of this is difficult to gauge, since the field is in

its infancy. Today, the model dependence -- primarily the dependence on the power-spectrum in the non-linear regime -- is considered a negative feature of weak lensing surveys that probe primarily small scales.
However, a decade hence this model sensitivity may be its greatest strength. With constraints on cosmic geometry from other techniques, cosmological weak lensing will constrain the dark-matter power spectrum and its growth on small scales, JWST may provide the best leverage for detecting any departures from theory.

Mapping onto JWST Capabilities

The S/N for lensing measurements depends field of view, sensitivity, resolution, and PSF stability.

- Field of View (FOV)
For measurements where the density of "interesting" sources is nearly uniform, the S/N increases linearly with the area of the FOV, until one hits a systematic floor imposed by PSF stability.

- Resolution (PSF FWHM)
To make the best use of distant galaxies for weak lensing measurements, itis important to resolve (at least marginally) most galaxies down to the sensitivity limit. A typical half-light radius for galaxies at z~4 is r~0.25 arcsec, thus resolution of better than 0.1 arcsec is desirable.

- Sensitivity
The S/N of lensing measurements varies slowly with sensitivity. Two terms are involved: the S/N of ellipticity measurements of individual galaxies, and the number of galaxies for which a measurement is possible in a fixed FOV and exposure time. Both are slow functions of sensitivity.

- PSF Stability
The JWST FOV is not large enough to encompass a few dozen good PSF stars. Therefore the PSF will need to be stable enough so that PSF calibration can be done at different times on fields with a higher density of stars. PSF uncertainties probably dominate the error budget. Thus, for lensing, it is sensible to trade PSF stability for sensitivity and resolution.

References

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Science Case # 4
Title: JWST and Fundamental Cosmology: Bringing the Hubble Constant into the Age of Precision Cosmology

Authors: Adam Riess and Mario Livio

Science Case:
One of the basic purposes for which HST was built was to provide a precise measurement of the fundamental scale of the Universe, the Hubble constant. While this goal has been greatly advanced, the circuitous route to calibrating the Hubble constant (i.e., the rickety distance ladder) propagates uncertainty which limits the calibration to a precision of ~10-15%. In the new "Age of Precision Cosmology", the Hubble Constant remains one of the worst calibrated of the fundamental constants of the Universe. Worse, a calibration of the Hubble Constant to a few percent precision remains one of the "tall poles" for extracting dark energy information from the CMB via WMAP (Hu et al. 2004).

Why JWST?
JWST will be crucial in removing one of the uncertain rungs in the distance ladder. JWST/Nircam is expected to have the resolution and light collecting power to directly calibrate Cepheids in the Hubble flow (cz~10,000 km/sec, m_J~28.0-30.0 mag). This will allow a direct calibration of the Hubble Constant, free from the additional uncertainty in the secondary calibration of usual long-distance indicators (e.g., Tully-Fisher, PNLF, SNe, SBF, and the fundamental-plane). In addition, JWST's ability to extend measurements of Cepheids into the near-infrared will greatly remove extinction uncertainties from the error budget. Though not widely appreciated, JWST can be expected to help improve the fundamental calibration of the scale of the Universe to an unprecedented few percent precision with resulting benefits to all fields of cosmology.

Science Case # 5
Title: Galaxy Formation: Studies of Resolved Stellar Populations in the Nearby Universe

Authors: Michael Fall, Roelof de Jong, & Harry Ferguson

Science Case:
JWST will revolutionize our understanding of galaxy formation and evolution. Its core mission is to observe the development of the population of very distant galaxies through cosmic time. Observations of this type, however, will tell us only part of the story; they will *not*, for example, tell us the assembly histories (merger trees) of galaxies, even in a statistical sense. A complete understanding of galaxy formation requires *both* high-redshift observations *and* comprehensive studies of the present-day structure and kinematics of galaxies, especially those features that provide fossil records of the events and processes involved in their formation. JWST will be a superb facility for studying the fossil record of galaxy evolution, through observations of resolved stellar populations both in the Milky Way and in nearby galaxies. Within the context of the current NASA roadmap, during its mission, JWST is likely to be the only facility capable of accurate stellar photometry at magnitudes fainter than I_AB = 28-28.5. Experience with HST indicates that groundbreaking studies of resolved stellar populations are likely to demand a substantial fraction of JWST observing time. Such studies stress resolution, collecting area, and the short-wavelength response of the observatory.
The following are among the **most compelling scientific objectives for JWST** in this area of astrophysics.

(1) Red-giant stars in the outer regions of galaxies.
This field has become a "hot topic" only within the past five years. Extensive surveys of the halos of the Milky Way and M31 have revealed rich substructure in both the phase-space distribution of stars an their ages and chemical compositions. Such studies provide important insight into the collapse process in galaxy formation and are the subject of major theoretical as well as observational advances. Measurements of substructure address a major problem for the standard ΛCDM model: a Milky-Way sized galaxy is expected to have ~100 satellite dark matter halos, but only ~10 satellite galaxies are observed. The distribution of distant stars contains information about tidal interactions and mergers among galaxies, and the influence of reionization on galaxy formation. The luminosity and size of stellar halos around massive galaxies, the amount of substructure in halos, and the scale-height and flaring of old stellar disks all depend sensitively on the slope of the primordial power spectrum and the extent to which star formation in low-mass halos is suppressed by reionization.

The outer parts of galaxies are also of great interest in connection with studies of the cosmic (large-scale average) luminosity and star formation densities and their evolution with redshift. There are indications from measurements with HST and the DIRBE instrument on COBE that the extra-galactic background light (EBL) at optical and near-IR wavelengths may be several times higher than accounted for by the parts of galaxies detectable in deep images taken with HST (from galaxy counts in the HDF and UDF; Hauser et al 1998, Bernstein et al 2002). In other words, it is possible that most of the sources of optical and near-IR light in the universe have not yet been accounted for in terms of the readily visible parts of known galaxies. Given the uncertainties in the EBL, this result is currently indicative rather than conclusive. Much, if not most, of the EBL may instead have been emitted by stars in the low-surface brightness outer parts of galaxies, in intergalactic space, or extremely faint galaxies. Finding these stars should be a major goal of astronomy, one that could be achieved by very deep optical/near-IR images with JWST in the outer parts of, and between, galaxies. This problem is so important that even non-detections would be extremely valuable. Resolving individual stars in the outskirts of relatively nearby galaxies allows us to probe regions many times lower in surface brightness than is possible from integrated photometry.

(2) Horizontal branch stars.

The blue horizontal branch (BHB) is a secure indicator of old age, appearing in low-metallicity stellar populations older than 10 Gyr. JWST would make possible a census of BHB stars in nearby galaxies, out to distances of at least 10 Mpc (the current HST record is ~3 Mpc -- NGC5128). This will provide an important local constraint on the volume density of low-metallicity stars that formed at $z > 2$. Such a global constraint is not possible from HST because of the small volume that can be probed with observations of practical duration. Detection of BHB stars in the nearest extremely metal-poor blue compact dwarfs (BCD) such as I Zw 18 may be possible with JWST and would provide a definitive test for whether they are truly young galaxies or instead began forming stars in the early universe. This measurement is not possible with HST because there are no BCD galaxies close enough for the measurement.

(3) The main-sequence turnoff (MSTO).

This is the gold-standard age indicator for stellar populations. HST measurements of the MSTO in M31 have revealed a surprisingly complex star-forming history, with nearly half the stellar population of the halo having formed within the past 8 Gyr. Ongoing HST observations will yield MSTO observations for more fields in M31, M33, and dwarf galaxies in the local group. JWST, if it is more sensitive than HST for point sources at wavelengths < 0.9 microns, will extend the use of MSTO beyond the bounds of the local group. The Sculptor group, at a distance of 1.5-3 Mpc, is particularly interesting in that it provides a diverse sample of galaxies of various morphological types.

(4) Globular clusters.

The age distribution of Milky-Way and M31 globular clusters provides a vital diagnostic of the early phases of galaxy evolution. Distance and reddening uncertainties currently dominate the errors on the *relative ages* of Galactic Globular clusters. This will change with SIM and with proper-motion studies from HST and JWST. Furthermore, it is likely that theoretical advances, coupled with astroseismology measurements over the next half decade, will improve our calibration of *absolute* ages of star clusters (reducing major uncertainties in helium diffusion and semi-convection). Both sets of advances open the opportunity to use globular clusters color-magnitude diagrams to probe the time-sequence of star formation in the early galaxy, addressing such questions as whether the globular clusters formed before or after reionization, whether early cluster formation in the Milky Way and other galaxies were synchronized, how metals were built up and distributed within the early galaxy, and how and whether globular clusters were captured during galaxy mergers. JWST observations would involve measurements of the MSTO and horizontal branch in both the Milky Way and M31, as well as measurements of the end of the white-dwarf cooling sequence in Milky-Way globular clusters to test the absolute age estimates.

Mapping onto JWST Capabilities

- Mirror Diameter (D)

For background-limited photometry of optimally-sampled point sources, the distance to which one can observe a source scales as D, the flux one can measure in fixed time scales as D^{-2}, and the exposure-time needed to detect a source of fixed flux scales as D^{-4}. This is provided that the resolution scales as D.

- Spectral Coverage

Having short wavelength coverage is essential to distinguish different stellar populations with color-magnitude diagrams. Once we are too much in the Rayleigh-Jeans part of the spectrum most stars have similar colors, with only good metallicity sensitivity due to line blanketing, but little age sensitivity. The wavelength coverage should reach down to at least 0.9 μm, preferably 0.6-0.7 μm, with at least 3 broadband filters providing coverage to 2 micron.

- Spatial Resolution (e.g., PSF FWHM)

Spatial resolution is critical, and is not likely to be provided over large fields by 30-m groundbased telescopes shortward of 1 μm. Dekaney, Nelson & Bauman (2001) list 10% Strehl in a 40" FOV over 30% of the sky as a goal for CELT with MCAO at 0.9 μm. The I-band dark-sky background from Mauna Kea is a factor of 9 higher than from JWST. An accurate measurement of the PSF encircled energy is extremely important for accurate photometry; either the field must contain enough bright stars to measure the PSF, which imposes strict requirements on where one can do the observations, or the PSF must be stable enough to allow observations of comparison stars. This is likely to be the major limitation for groundbased AO.

For JWST, with a stable PSF, there are two motivations for high spatial resolution: (1) to improve sensitivity and (2) to allow photometry in crowded fields. For an isolated source, the total sky background within an optimal photometric aperture increases as the square of the aperture radius. Hence for a fixed mirror diameter, the S/N for sky-limited point-source increases as $FWHM^{-1}$ (for the same PSF shape). Crowding results in higher and more variable sky background and a loss of area due to confusion. To maintain the same level of crowding (e.g.,100 beams per source) the allowable star density varies as the square of the PSF width. Hence for measurements requiring a fixed number of stars, the S/N varies in a fixed FOV increases as $FWHM^{-1}$. Also the maximum distance a galaxy can be observed at at a limiting crowding/surface brightness limit scales as $FWHM^{-1}$.

For stellar color-magnitude diagrams in the outskirts of galaxies, the two factors are both in play. A better PSF allows observations to be done faster, in fields that are more crowded. Hence the scaling with resolution is close to $FWHM^{-2}$.

A spatial resolution of at least 0.15 arcsec over the full field of view is needed for a viable galaxy archaeology program. The PSF can be a factor of 2-3 undersampled provided the detector intrapixel sensitivity is well characterized.

- Field of View (FOV)

For most measurements the S/N of the ultimate statistical measurement depends as the square root of the number of stars measured, and thus S/N increases as FOV**1.

Figures of Merit

Several features are of interest:

	M_I(AB)	M_K(AB)
Main-sequence turnoff (MSTO) at >10 Gyr	+4.0	+4.5
Blue Horizontal branch (HB)	+1.4	+2.9
RGB Tip (TRGB)	-3.6	-5.5
Bottom of White dwarf cooling sequence	15.4	?

These translate into the following limiting magnitudes (breakpoints) for JWST. All of these already stretch the limits of the current design.

	I_AB	K_AB
Reach the MSTO in NGC300 (2 Mpc)	30.5	31.0
Reach the HB at 10 Mpc (e.g. Leo Group)	31.3	32.9
Reach TRGB+1.0 in the Coma cluster (90 Mpc)	32.1	30.2
Reach end of white-dwarf sequence in M92 (9 kpc)	30.4	?

Distance to encompass 10 L>0.5L* edge-on spirals	25 Mpc	(M-m = 32)
Distance to encompass 10 L>0.5L* ellipticals	16 Mpc	(M-m = 31)

To study halo substructure and chemistry, and quantify disk flaring, nearly edge-on galaxies are required. To estimate the volume that should be probed for a statistical study of at least ten galaxies with L>0.5L*, we adopt a number density phi* = 7 e^{-4} Mpc^{-3}, alpha= -1 for spiral galaxies, we assume 17% have inclinations greater than 85 degrees, and half of those have Galactic latitudes greater than 30 degrees. This implies a minimum distance of 25 Mpc, or distance modules 32.6. Such studies are therefore possible with JWST, even significantly degraded, using RGB stars, but not HB stars. However, while the optical disk diameters of galaxies at these distances are typically 5 arcmin, their halos are predicted to have diameters of 15-20 arcmin, and the observing time needed to cover a halo directly scales with sensitivity and FOV.

A similar calculation yields 16 Mpc for the distance to encompass 10 elliptical galaxies with L>0.5 L* and galactic latitude > 30 degrees. Studies of the RGB are achievable at

16 Mpc, studies of the HB are probably infeasible with the current JWST. The nearest normal giant elliptical galaxy is NGC3379 at 10 Mpc. The HB is already out of reach. JWST will be able to reach the HB in nearer, generally lower-luminosity galaxies, but for normal giant ellipticals will be focusing on the RGB.

Science Case # 6
Title: The Earliest Stages of Star Formation in External Galaxies: the Foundation We Don't Yet Understand.

Authors: D. Calzetti, R. Chandar, D. Figer, N. Walborn

Science Case:
Star formation requires large reservoirs of gas, which in the local Universe is always accompanied by the presence of large quantities of dust. Thus, the earliest phases of star formation are completely obscured at UV, optical, and even near-IR wavelengths. Even in galaxies that have small total dust masses, and low metallicities (e.g., SBS0335-052, with Z~1/40 Z_sun) highly obscured star formation is present.
High extinctions currently prevent the investigation of the very young, thus crucial, phase of star formation not only in our own Galaxy (this part is already covered in the SRD), but also in nearby galaxies. Clearly, efforts to understand star formation in the high and intermediate redshift Universe cannot dispense from knowing the modes in which the earliest stages of star formation evolve in the Local Universe.

The main product of star formation is stellar clusters. More than 80%, and possibly as much as 100% of stars are produced in some form of clustered or associated group (e.g. Meurer et al. 1995). Embedded stellar clusters, at a stage when stars have formed inside the molecular cloud, but before they have had time to radically alter their local environment, are, therefore, a goldmine for investigating how star formation evolves and for addressing the open issues:

1. What are the scales of star formation (sizes of the produced clusters/associations)? What are the parameters (star formation rate density, host galaxy environment and mass, concentration of the star formation, metallicity, etc.) that determine whether compact clusters, like those in the starburst of NGC1569, or loose associations, like those in IZw18, will be formed?

2. What is the timescale for the separation of a cluster from its natal cloud, and how does this timescale depend on environmental properties (metallicity, gas/dust concentration/density, dynamical conditions, etc.)?

3. What physical properties influence the "infant mortality" of stellar clusters? Number counts of star cluster systems as a function of age require that approximately 90% of clusters are destroyed within their first 10 Myr of life. While there are hints that this phenomenon occurs in many, and possibly all, local star-forming environments, there is currently little empirical evidence for the physics behind this.

4. How effective is each generation of stars at producing/triggering a second generation?

JWST will build onto the Spitzer's legacy, by resolving the individual components of star formation, and separating the clusters from the surrounding environment, thus enabling their investigation in the Mid-IR wavelength region.

Studies of our own Galaxy can only answer part of the questions above. External galaxies offer a much broader range of metallicities (down to ~1/40-1/50 solar, e.g. SBS0335-052), higher star formation intensities (e.g., starbursts like the one in the center of NGC5253, about 1000 times more intense per unit area than Orion), and a larger variety of dynamical environments, including interacting/merging galaxies.
Progress in this area requires at the same time high angular resolution, field size, and MIR access, which only JWST can offer simultaneously. For instance, the Carina Nebula and 30 Doradus, which are key paradigms to understand more distant objects, are replete with microstructures such as jets and pillars containing triggered second generations, the understanding of which is resolution limited. ALMA will provide complementary information by probing star formation at an even earlier stage than embedded cluster, when the gas in the parent molecular cloud is compressing and is forming starless cores and protostars.

Mapping onto JWST Capabilities

Addressing the 4 open fundamental questions above will require at the same time access to high-angular resolution, large FOVs, near-IR imaging and mid-IR spectroscopy and imaging.

- Angular Resolution

Stellar clusters will have to be resolved against the crowded background of their parent galaxy, to measure sizes (issue # 1). As a fiducial point, we discuss the case of the nearby galaxy M51a, at a distance of 9 Mpc. Compact stellar clusters have sizes around 3 pc, while scaled OB associations are in the range 10-15 pc. At the distance of M51a, this translates into an angular scale of 0.05"-0.1" for the compact clusters. This requires more than one order of magnitude higher resolution than what Spitzer can achieve.

- Field-of-View

Obtaining statistically meaningful samples of embedded clusters in a galaxy, and tracing cloud fragmentation as a function of local environment, will require imaging of large portions of the galaxy itself, thus requiring large FOVs, of order 1-2 arcmin at least (M51a has a major-axis diameter of 11 arcmin), with stable and reproducible PSFs. This requirement is much beyond what can be achieved even with future 30-m telescopes with AO.

- Near-IR (3-5 micron) capability
Embedded clusters will typically be heavily extincted even in the K band. Thus imaging at the longest wavelength where photospheric emission from stars can still be detected without excessive contamination from hot dust emission will be required, i.e. ~3-5 micron region. Such luminosities will be employed to measure masses. The least massive clusters that will be measured have masses around 10^1-10^2 M_sun, which, for ages younger than 5 Myr and at the distance of M51a, correspond to L_AB~18-20. These brightnesses will not push the sensitivity limit of JWST, but the combination of angular resolution and FOV are required for the science goals. However, detecting and characterizing triggered/second generation star formation (issue # 4) will fall into the category of embedded single stars, thus requiring higher sensitivities than described above.

- Mid-IR capability/sensitivity
Ages and extinction are derived from the Mid-IR spectroscopy (MIRI). This will allow us to access important diagnostic nebular lines (i.e. [NeIII]15.5 micron, [NeII]12.8 micron, [SIV]10.5 micron, [SIII]18.7 micron, [NeV]14.3 micron, [SIV]10.5 micron, and [OIV]25.9 micron), which provide information on the hardness of the ionizing radiation field and the effective temperature of the ionizing stars. By comparing the resulting radiation field with population synthesis models (e.g., an expansion of the STARBURST99 code), ages for the embedded clusters can be derived, as well as temperatures, densities, and extinctions. With the ages, masses can be derived from broad--band near-IR (3 micron and longward) imaging, and from the [NeII](12.8 micron) line that provides a measure of the total ionization rate of the cluster. Pure rotational emission lines from H_2 at 12.28 micron and 17.04 micron will reveal the presence of warm molecular gas. Ages and masses, in addition to the other physical properties, will address issues # 2 and 3.
As an example, the expected luminosity of [OIV](25.9 micron) in a 10^3 M_sun cluster in M51a is about 3-5 10^{-20} erg/s/cm^2, implying that S/N=10 can be achieved for this line with MIRI, at R=1000, in 100,000 seconds.
Spectroscopy with MIRI of embedded clusters in nearby galaxies (closer than ~10 Mpc) will therefore push the JWST capabilities to their limit.

Science Case # 7
Title: Physical Processes Related to Black Holes and Active Galactic Nuclei

Authors: Anton Koekemoer, Marco Chiaberge, Duccio Macchetto, andJerry Kriss

Science case:
The nature of active galactic nuclei and the supermassive black holes that power them concerns several other key questions in the early universe, including the heating of the ICM and the interplay between black hole and galaxy formation and evolution. the combination of sensitivity, wavelength coverage and resolution of JWST is uniquely suited to address the following questions related to AGN physics:

- identification of extremely obscured AGN
- the energetics of synchrotron-emitting plasma
- the physics of very low-luminosity AGN

Extremely obscured AGN have recently become a crucial consideration in the total census of black holes in the universe, since recent results from Spitzer indicate that there may be many more of them than previously thought, particularly at increasing redshift. However, they are difficult to detect at X-ray wavelengths (being Compton thick), they do not display optical evidence of activity, and most are radio-quiet. So the near/mid-IR offers the only window to study them directly. Specifically, their bolometric luminosity can only be determined by measuring the total energy output from the warm obscuring dust that is heated by the AGN, and the 5 - 28 micron regime probed by JWST/MIRI is ideally matched to this, providing resolution and sensitity improvements by 1 - 2 orders of magnitude over what Spitzer can currently achieve. It will therefore be possible to measure directly the luminosity function of all active galactic nuclei down to luminosities that are sufficiently faint to start becoming representative of a large fraction of galaxies. In addition, the effects of AGN heating on dust and molecular gas and the possible implications for star formation near the centers of their hosts will be directly observable in such heavily obscured sources, and will expand our current knowledge of the effect of AGN on star formation.

Another area where progress is currently restricted by observational limitations is in the physics of synchrotron-emitting plasma in radio jets. We still do not fully understand how radio jets are formed, and how this may relate to the properties of the black hole or the galaxy environment, and part of the problem has been the lack of understanding of the detailed energetics of the synchrotron plasma. The principal observational constraints have come from the radio, followed by X-ray or optical synchrotron studies of specific regions of particle acceleration in jets. However, the synchrotron emission in the bulk of radio plasma turns over at longer wavelengths than optical, starting in the near/mid-IR. Thus, in order to understand the energetics of most radio sources, we need the wavelength coverage as well as as resolution and sensitivity to match those of the radio observations (typically being on scales of a few tenths of an arcsecond or less). Here, JWST will play a crucial role since it provides orders of magnitude more sensitivity and resolution than any other facility in this unique wavelength regime. Being able to fully constrain the energetics of the synchrotron plasma in the majority of radio sources will play a crucial role in understanding the physics of radio jets and how they are energized.

Finally, low luminosity AGN (LLAGN) are a particularly important class of objects to understand better, because they represent a large fraction (>30%) of nearly all galaxies. At the lowest level of activity, even our own Galaxy is an AGN. Thus, they constitute a link between powerful quasars and "normal" galaxies, and a comprehensive understanding of the properties of these objects can shed light on some of the most important questions on the physics of accretion onto supermassive black holes and the launching of jets. In particular, the observational properties of accretion at very low rates (in the form of e.g. ADAF, CDAF or ADIOS), which most likely takes place in AGN at the end of their life cycle, is still totally unknown. Although the level of activity is low, these objects are capable to produce powerful relativistic jets, such as those seen in nearby radio galaxies. The lack of knowledge is mainly due to the observational difficulty in detecting such a faint radiation located at the center of bright galaxies, in order to constrain the models.

The fact that LL AGN are nearby ($z \ll 0.1$) is a great advantage: the radiation from their faint active nucleus can be disentangled from the underlying emission of the host galaxy, when data with high resolution (and stable PSF) combined with high sensitivity are obtained. Faint nuclei with angular size below 0.1" have been indeed discovered in the optical and near-IR band with the HST in LLAGN (i.e. Seyferts, LINERs and low luminosity radio galaxies).
Those features have been proven to be directly related to the active nucleus, as they are interpreted as radiation from either the accretion process or from the base of the jet. The IR band offers a unique opportunity to obtain a significant spectral coverage of their SED in a crucial part of the spectrum, which is necessary to constrain the emission models. But while the stellar emission from the host galaxy decreases for wavelengths larger than optical, a significant contribution from dust emission is present in the IR. Therefore, even though the contrast between the host galaxy and the nuclear emission is enhanced in the IR, neither ISO or Spitzer are suitable instruments for this kind of studies. High angular resolution (< 0.1") and PSF stability over a wide spectral band are mandatory requirements.

Science Case # 8
Title: Transiting Hot Jupiters in another Galaxy, the LMC

Authors: P. McCullough, J. Valenti, and R. Gilliland

Science Case:
This investigation proposes to observe the LMC for a period on 12 days continuously with NIRCam in multiple filters to detect transiting hot Jupiters. The comparison with Transiting Hot Jupiters (THJs) in our own Milky Way will provide the first step in assessing whether planet frequencies in our own Galaxy are similar or different in other galaxies. Because the LMC's metallicity is lower than that of the MW, and lower than that of the MW's bulge and because the frequency of THJs increases with metallicity (Valenti & Fischer 2005), we expect fewer stars with THJs in the LMC than in the bulge of the MW (Sahu et al 2005). However, that hypothesis should be verified observationally. It could be that in the separate galaxy of the LMC, other factors, such as star formation rate, stellar and molecular cloud density, could affect star and planet formation.

Why JWST?
Difference Image Analysis with HST ACS data has proven photometric performance limited primarily by the number of photons from the stars themselves. We assume that JWST NIRCam MULTIACCUM data will achieve similar Poisson-limited performance for this sort of observations also. Although formally the performance required for these observations exceed the 5% photometric *accuracy* requirement for NIRCam by a factor of ~10, we do not expect any changes are required of the JWST or NIRCam to achieve the *precision* required for these observations in this particular case. The rationale is that these observations will be self calibrated by virtue of having thousands of observations of the same field of view and only requiring differential photometry, i.e. we require repeatability/precision not accuracy.
At the distance of the LMC, a solar type star has K=21.8 mag, or 1.3 microJy. In a 1000 sec exposure through F200W, such a star yields 8500 e/pixel at the peak of its PSF, or 34000 e total, resulting in a S/N = 180. (Zodi contribution is negligible at 0.1 e/s/pixel).
A typical transit is 2 hours long and occurs every 3 days, so in a 12-day continuous observing period, we could expect at least three transit intervals and seven 1000 sec observations in each interval.
The number density of solar type stars per square degree is sufficient, but marginally so, for this project. Elson et al (1997) find 15800 stars in a WFPC2 FOV, 4.56 sq arcmin; ~5000 of those would be suitable spectral type for this investigation. Two NIRCam modules, each of 4.75 sq arcmin, can monitor ~10000 stars of solar type in the LMC at once. This would result in 10 THJs based upon Marcy estimate (2005, May Symposium, 1% of solar type stars has a hot Jupiter, and 10% of those will transit). (Presumably picking a richer field for observation might increase the number density by a factor of 2 (?).) That we estimate only 10 THJs with solar type stars (not accounting for the metallicity effect that might reduce the number) suggests the number density of stars is marginal for the nominal NIRCam FOV, so halving that FOV would have a direct impact on this sort of observation and might possibly disable it. Halving the aperture and

the FOV would really make it hard to do in a reasonable amount of time because the fewer photons per transit duration will also be spread over a larger (diffraction-limited) PSF, increasing blending problems, but those presumably aren't bad for 5000 stars per FOV.

While SNAP will have much larger field of view than JWST NIRCam, its 2-m diameter will be marginal for detecting 1%-deep planet transits in the LMC.

We base that assessment on HST observations that have demonstrated shot-noise-limited photometry, $\sigma \sim 2\%$ at V=23, i.e. the Sun at 50 kpc, in ~5 minute exposures (Gilliland p.c.).

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Science Case # 9
Title: Microlensing Parallax Measurements with JWST

Author: Kailash Sahu

Science Case:
JWST will be in an orbit approximately 1.5 million km away from the Earth. The characteristics of microlensing events, particularly those observed towards the Galactic bulge and the Magellanic Clouds, will therefore be different as seen from the satellite and the Earth. JWST observations can be used to take advantage of this property to solve some important astronomical problems; 2 such problems are described below.

1. Location of the Lenses towards the Magellanic Clouds and Contribution of MACHOS to Dark Matter:
Over a dozen candidate microlensing events have been discovered toward the Large Magellanic Cloud (LMC) (Alcock et al. 1997). If the lenses are in the Galactic halo, they would appear to make up about half the dark matter and have typical masses of 0.5 solar masses (Alcock et al. 1997). Several lines of reasoning suggest that this interpretation is implausible, and it has been suggested that the lenses could be within the Magellanic Clouds (e.g. Sahu, 1994), or the local disk (Gates et al. 1996). However, to date there is no clear consensus on the location of the lenses. The different possible lens populations have radically different kinematics, and one could therefore distinguish among them if kinematic parameters could be measured. This is not possible for most events, because the one measured quantity, the timescale, is a combination of the mass, distance, and the transverse velocity of the lens.
However, the microlensing event would appear differently from JWST than from the Earth. In particular, the difference in the photometric signal at any given time, which depends on the location of the lens, is measurable. The difference in the time of the peak amplification, which is determined taking all the observed points in the light curve into account, is even easier to measure. From these observed differences, one could in effect measure the length of time it takes for the projected position of the lens to travel from the Earth to the satellite. Since the distance between the Earth and the satellite is known, one could thereby determine the transverse velocity projected onto the plane of the observer. Since the transverse velocity is about 50 km/s for disk lenses, about 250 km/s for halo lenses, and about 1000 km/s for LMC lenses, measurement of this quantity should distinguish well among the different components. Combining the ground-based photometric observations with the JWST photometry, one can thus determine the location, and hence the nature, of the lenses. This will lead to a direct estimate of the contribution of MACHOs to dark matter.

2. Mass Determination Planetary-Mass Objects through Microlensing:
Microlensing is the only currently known technique capable of detecting planets down to Earth mass planets at distances up to about 6 AU from the parent star. The presence of the planet is most easily inferred from the light curve when the planet causes "caustics" in the lensing geometry, giving rise to high-amplification as the source crosses the caustics.

Indeed, the 2 planetary-mass objects detected so far through microlensing have been through such observations of caustic crossings (Bond et al.2004; Gould et al. 2005). However, the microlensing observations only provide the mass ratio between the primary lens star and the planet; they do not provide information on the absolute mass. Since the lens star is generally not seen directly, and since there is a degeneracy between the mass and the distance, the mass of the lens is generally unknown. Consequently, the mass of the planet is also unknown. The degeneracy between the mass and the distance can be broken by a second set of observations with JWST.
For a typical caustic crossing event observed towards the Galactic bulge, the time difference between the onset of caustic crossing at Earth and at the JWST is about 20 minutes which is clearly measurable. The time difference can be used to determine the distance to the lens, and hence its mass. This will directly lead to an accurate determination of the mass of the planetary object.

Mapping onto JWST Capabilities.

The observations proposed here would be essentially "follow-up" observations of events discovered through ground-based observations. The sources are expected to be between 17th to 21st magnitude in I-band, for which the sensitivity of JWST is adequate in essentially any passband. However, the follow-up observations would require a rapid response time. For the first project (events observed towards the Magellanic clouds), the typical time scale of an event is about 30 days, and the discovery of the event occurs typically 10 days before the peak. Since it is crucial to observe close to the peak, this would require a response time of the order of 5 days. For the second project (planetary caustic crossing events), the ground-based alert comes from the observations of the first caustic crossing, and it is crucial to observe the second caustic crossing with JWST. Since the second caustic crossing (the time of which can be predicted precisely from the first observations) typically happens about 3 to 10 days after the first caustic crossing; this would require a response time of about 1 day.

It is important to carry out the observations in the same bandpasses as the ground-based observations in order to remove possible degeneracies. Since all the currently active and planned microlensing monitoring programs use the I-band as the main filter, these observations can be best carried out if JWST has capability to observe in I band. While a second set of ground-based observations in the near-IR wavelengths can be carried out from the ground, the discovery observations are always done in the I band, so there is no extra benefit in this additional step to meet the science objective.

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Science Case # 10
Title: Globular cluster brown dwarfs and the age of the Galaxy

Author: Neill Reid

Science Case:
The stars in the galactic halo are fossil remnants of the first major epoch of star formation in the Milky Way. Consequently, reliable age determinations for this population sheds crucial light on the earliest stages of galaxy formation. Globular clusters are the most prominent members of the halo, and the most tractable for age measurement. Conventional studies rely on fitting theoretical isochrones to the main sequence turnoff, but this technique is vulnerable to uncertainties in foreground reddening, in the distance estimate and in the models themselves – witness the substantial revisions in cluster ages that followed the Hipparcos-based subdwarf analyses.
An alternative, and entirely independent, approach is to use the cluster brown dwarf sequence. HST observations have reached the bottom of the main sequence in the two nearest clusters, NGC 6397 and M4, at apparent magnitude I= 24.5 and I=23.0 (K=21.5 and 20.0, respectively). The hydrogen burning limit for metal-poor dwarfs is ~0.072 M_. Halo brown dwarfs have been cooling for at least 10 Gyrs, and are therefore expected to have temperatures T<1000K and spectral types T4-T7, and absolute magnitude M_K~16 (comparable the Gl 229B).
Globular clusters are the product of a single-burst star-forming episode; thus, all cluster members are essentially coeval. Consequently, the magnitude difference between the top of the brown dwarf sequence and the bottom of the main sequence provides a direct measurement (via brown dwarf cooling curves) of the age of the cluster. Note that since this is a magnitude difference, the age estimate is not affected by uncertainties in either the foreground reddening or the cluster distance (although it is obviously dependent on the accuracy of the brown dwarf cooling tracks).
How sensitive to age is this estimator? The Burrows et al models for a 0.07 M_ brown dwarf predict a temperature of 964K, M_{bol}=18.0 and M_K=16.0 at age 10 Gyrs; 863K, M_{bol}=18.5 and M_K=16.5 at age 13 Gyrs. Observations of a reasonable number of nearby clusters can quantify the age distribution of the cluster system. Observations at multiple epochs would be required to separate cluster from the field; and L-band observations will also be necessary to distinguish brown dwarf and white cluster members.

Why JWST?
These observations require extremely high sensitivity at near-infrared wavelengths, coupled with high spatial resolution (image crowding) and a well-behaved PSF. A 13-Gyr-old 0.07 M_ brown dwarf is expected to have K=28.5 in M4 and K=29 in NGC 6397, the two nearest globular clusters. Resolving such objects will be still feasible for JWST, but extremely challenging for hypothetical ground-based 30-metre telescopes.

Science Case # 11
Title: Star Formation across the Galaxy: from Spitzer to JWST

Author: Massimo Robberto

Science Case:
The Spitzer Space Telescope, in particular the recently completed GLIMPSE legacy project, is mapping in the near to mid-IR most of the star formation activity in the Galaxy and ~70% of the molecular gas. Surveys like GLIMPSE are fundamental, as they enable us to put our understanding of the star formation phenomenon on a solid statistical basis. For example, the comparison of young stellar clusters and molecular clouds of different mass, size, morphology and extinction provides unique insights on the role of environment and triggering mechanism in the star formation process. On the other hand, the limited spatial resolution (~2") and wavelength coverage (4 broad-band filters centered at 3.6, 4.5, 5.8 and 8.0 micron) of Spitzer/IRAC, while enabling such a large and unbiased Galactic plane survey to be carried out, prevents detailed studies of the most interesting targets, like those regions that may host the earliest, most rapid and therefore elusive, phases of massive star formation. Even if one neglects the coarse spatial resolution of Spitzer and assumes that all point sources represent single sources, the four IRAC bands only allow for rather crude diagnostic. Since the distance of mid-IR sources is typically unknown, the most powerful tool is the 3.6-4.5 vs. 5.8-8.0 color-color diagram. Here most of the unreddened stars fall near to the (0,0) point and interstellar reddening moves them along a diagonal band across the diagram. However, other effects like the presence of circumstellar envelopes, disks, emission lines -including the PAH spectral features which fall within three of the four IRAC bands - provide a formidable source of confusion and errors. If we note that the IR excess of the most interesting sources, pre-main sequence stars with circumstellar disk, depends upon a variety of physical (acccreting vs. reprocessing disk, flaring angle, dust composition), evolutionary (disk clearing, dust settling) and geometrical factors (disk orientation with respect to the Earth and to all possible source of heating), then it is clear that the four IRAC colors cannot constrain the problem. In fact, they do not even allow to reliably distinguish between a star with a cleared inner disk, an externally ionized proplyd and a background galaxy. On may perhaps assimilate this situation to that of the IRAS satellite, which also surveyed the Galaxy with four bands and low spatial resolution. Note, however, that the IRAS bands (12,25, 60 and 100 micron) covered a much broader spectral range and allowed for a more reliable statistical identification of the individual sources than Spitzer/IRAC. Hence the need for an adequate follow up to Spitzer is even stronger.

Astronomers are already using ancillary data (2Mass survey, Spitzer/MIPS, pointed observations with large ground based telescopes) to clarify the nature of the brightest Spitzer sources. But in order to understand the key questions (how the IMF varies with the environment, the feedback of massive stars on star and planet formation, the mass spectrum of compact OB clusters etc.) one has to study in detail the stellar population of selected cluster. Only JWST, with its unique gain in spatial resolution, sensitivity and its rich complement of instruments, can attack and solve this problem.

Why JWST?

- In order to identify Spitzer/GLIMPSE sources and resolve for/discriminate extended objects (e.g. galaxies) and/or multiplicity, high resolution imaging with NIRCAM and MIRI will be required.
- Spectral classification of embedded Pre-Main-Sequence Star:

NIRSPEC will provide independent T_eff and log(g) estimates. For low mass stars the specral type cannot be derived by the color due to the degeneracy between intrinsic stellar color and extinction. NIRSPECwill work even for very late-type stars and Brown Dwarfs, since near-IR spectra of the features of H_2O vapor at 1.30-1.50 μm (hampered from the ground by the presence of atmospheric water vapor) and KI at 1.25 μm are excellent temperature and surface gravity diagnostics. Multi-object spectroscopy is needed, to cover a statistically significant volume.

Science Case # 12
Title: The Stellar Initial Mass Function in Young Clusters

Author: Donald F. Figer

Science Case:
The stellar initial mass function (IMF) is one of the most direct products of the star formation process. It describes the number of stars produced as a function of initial mass. The resultant distribution is observed to be nearly constant in all environments from 1 to 100 solar masses. Young clusters are the best laboratory for measuring this distribution because they contain coeval and equidistant populations of stars. The most massive clusters are unique in their suitability for measuring the mass function up to the highest mass stars. In addition, they can be used to directly test for an upper mass cutoff to the IMF. Such clusters contain thousands of stars and are usually very dense. In order to count their individual members, one must necessarily obtain high spatial resolution observations having stable point spread functions. This is the unique realm of large diffraction limited telescopes, i.e. JWST.

A combination of deep imaging and spectroscopy needs to be used to investigate massive star forming clusters in a range of environments in the Milky Way. The approach follows the recent work done in the nearby star-forming region of Orion, the Trapezium cluster. The basic idea is to sample the mass range as deeply as possible using spectroscopy to identify spectral types as a function of position in the observed near infrared color magnitude diagram (*K magnitude vs. H – K magnitude, "CMD").* These data, when coupled with near infrared (*JHK*) colors, will allow distributions of age and excess color (due to accretion disks) to be determined as a function of position in the CMD. The mass function follows from a ``best fit'' to model isochrones for massive stars (main sequence) and low mass stars (main sequence and/or pre-main sequence) accounting for the interstellar extinction toward each star (or group of stars in the CMD).

Why JWST?

The observations require superb image quality (~10 milliarcseconds) in order to reach the faintest magnitudes in these crowded clusters. A wide field of view is needed (~2 arcminutes) to efficiently cover the nearby targets and thus allow a determination of the mass function with position within a given cluster. Such studies will be a primary tool to study how the emergent mass spectrum depends on local stellar density. The spectroscopic observations require modest spectral resolution (R = 1000 to 3000), and again very good angular resolution; the crowded fields and target densities require integral field spectroscopy and multi-object capability.

Our Galaxy likely contains dozens of massive clusters that only JWST can observe for determining the IMF. As an example, JWST will be able to discern individual stars down to 1 Msun at a distance of 8 kpc in the Galactic disk at ~90% completeness level. The corresponding flux level is K~21.

Science Case # 13
Title: Knife-edge spectra of Jupiters circling nearby stars

Authors: P. McCullough, J. Valenti, and R. Gilliland

Science Case:
A transiting planet is interesting in at least three important ways: 1) the transit permits us to measure the physical characteristics of the planet such as its radius, mass (not $m \sin i$), density and ``surface'' gravity, 2) absorption spectroscopy has already permitted detection of an exoplanet's atmosphere (Charbonneau et al 2002), and 3) recently Spitzer has measured the planet's infrared light being blocked by the star during the secondary eclipse (Charbonneau et al. 2005; Demming et al. 2005). The primary eclipse permits us to search for satellites and Saturn-like rings orbiting the transiting planet and in due time we will measure the planet's albedo by observing the *visible* light reflected from the planet before it enters secondary eclipse (Brown et al. 2001).

These methods require exquisite precision that is only readily achievable for the planets transiting the bright stars observed with large apertures in the stable environment of space. The rapid and precisely predictable on/off nature of both the primary and secondary eclipses permits excellent calibration.

Why JWST?
The broadband observations done by Spitzer on HD 209458 (V=8) and TrES-1 (V=12) will be feasible at R=100 with JWST NIRSPEC allowing us to obtain emission spectra of THJs without coronagraphy (Figure below). The eclipse technique may be marginally feasible in integration times shorter than the egress and ingress durations (~1000 seconds), and such shorter integrations will be equivalent to *spatially-resolved* spectra of the planet, i.e. the star acts like a knife-edge slowly cutting across the planet's disk.

Various other items
Coronagraphy with JWST TFI will be important for detecting Jupiters (Sparks et al 2004) and measuring crude (spatially-integrated) emission spectra of them at 5 AU from their host stars.
In ``Astrobiology and JWST'' (JWST STSCI webpage), NIR spectral lines are illustrated in that document's Fig 8. Note that O_2 has deep bands at 0.7 μm. These are telluric bands and thus will be impossible to study reliably even from SOFIA. Also recall that the lines of Na (0.589 μm) and K (0.77 m)are the deepest atomic lines in absorption spectra of transiting planets.

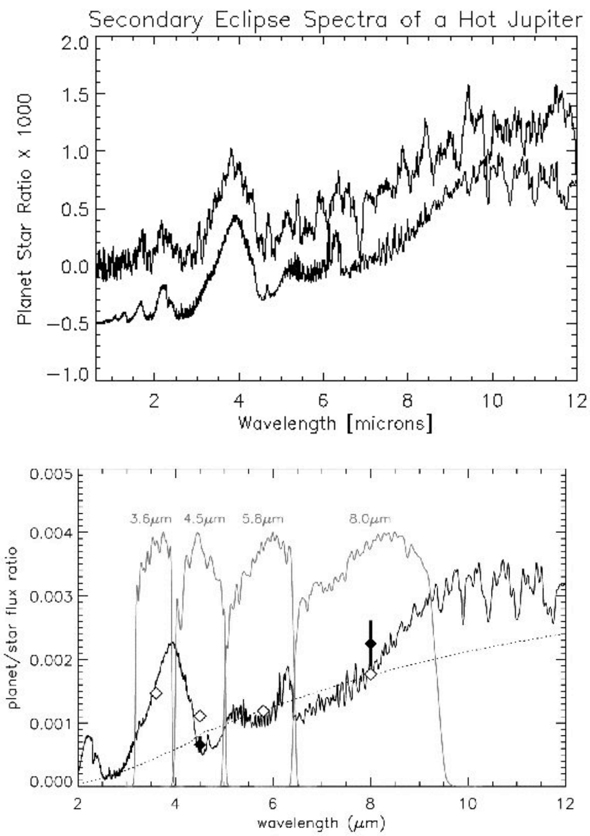

Figure: (Top panel) Simulated emission spectrum from a eclipsing hot Jupiter as observed with NIRSPEC. Assumptions: JWST Area=25 m^2; throughput = 0.1; Solar-type star at 100 pc; Emission spectrum of Peg 51; Difference of two 1000 sec integrations, one during and one after secondary eclipse; R=700 input spectrum (lower spectrum) from Sudarsky et al. (2003) or http://zenith.as.arizona.edu/~burrows/sbh/sbh.html; output spectrum (higher spectrum) has noise added and is smoothed to R=50; S/N is the lesser of 5000 per R=700 bin or Poisson-limited ($\lambda > 3.3$ μm). (Bottom panel) The spectrum for TrES-1 is compared to broadband Spitzer observations (from Charbonneau, et al. 2005). Due to a cooler star, the planet to star ratio for TrES-1 is two times larger (i.e. more favorable) than that of our Peg 51 simulation.

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Science Case # 14
Title: Disks and Planets around Massive White Dwarf

Author: Mario Livio

Science Case:
The merger of two white dwarfs (WDs) is an inevitable outcome in the evolution of some binary systems. In a recent sample of 348 white dwarfs, it has been found that about 15% of all WDs are more massive than 0.8 solar masses, and it has been concluded that more than 80% of these are the results of mergers.
The merger process itself has been studied in some detail, and it leads to a total dissipation of the lighter of the two WDs into a disk around the more massive component. Most of the mass in this disk is eventually accreted onto the central WD, but some fraction of the mass takes up the angular momentum, forming a much larger (in radius) disk, that is essentially 100% metals. According to a recent survey of the metallicities of more than 1000 stars, disks that are so metal-rich have a high probability of forming planets. We therefore find that dusty disks and planets are predicted to exist in an unexpected place - around massive WDS. The typical radius of such a disk (or the orbital radius of the planet) is predicted to be of a few AU (Livio, Pringle, & Wood; submitted to ApJ). Using a Monte Carlo radiation transfer code the emergent spectral energy distribution of the disk has been simulated (figure attached), and it shows a prominent 10 micron silicate feature.

Why JWST?
Detection and investigation of dusty disks around stars require the simultaneous presence of high angular resolution, and mid-IR imaging and spectroscopic capabilities. These capabilities will not be achieved by future 30-m telescopes.

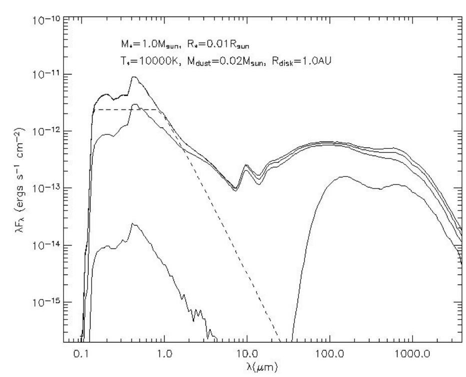

Figure: The emergent spectrum of the disk as obtained from Monte Carlo simulations. In general, the disk shows IR excess emission well above the stellar spectrum (the dashed line). The four solid lines are (top to bottom) for viewing angles of 20, 40, 60, and 80 degrees (respectively).

Science Case # 15
Title: Survey of Molecular Clouds for Giant Planets and Brown Dwarfs

Authors: A.B. Schultz (CSC/STScI), F. Bruhweiler (CUA), M. Rodrigue (UNR)

Science Case:
Knowledge of the evolution and IMF of sub-stellar objects including giant extrasolar planets (EGPs) and brown dwarfs (BDs), remains elusive.
Very precise radial velocity observations of nearby solar-like stars have revealed over 100 extrasolar giant planets. Of these, many are "51 Peg-like" or "roaster" EGPs with orbital periods of less than a few days. Current thinking is that these hot Jupiters are created at larger orbital distances and migrate inward. It may well be that many central stars devour (or eject) the planets that are created in their circumstellar disks. Thus, these observations may tell us little about the initial mass function (IMF) or frequencies of the giant planets.

Only a mere handful of the EGPs are known to be transiting planets. The orbit need not be exactly edge-on for a transit to be detected as long as the planet transits a small portion of the stellar disk. These hot Jupiter have nearly circular orbits as inferred from the Doppler measurements.
Assuming random alignment of the orbital inclination, the chance of alignment of the orbit to our line-of-sight is ~10%, implying that 1 out of 10 Jupiter extrasolar planets should transit the primary star. Yet, an HST/WFPC2 imaging campaign of the globular cluster 47 Tucanae failed to detect a single transiting planet (Gilliland et al. 2000).

One primary stellar characteristic that appears to dominate the detection of EGPs is metallicity. Stars with extrasolar planets tend to have higher metallicity than those without planets. In a radial velocity study of a large sample of mostly field stars, Fisher and Valenti (2005) find that as many as 25% of the stars with metallicity [Fe/H] > +0.3 dex have planets, while only ~3% of stars have planets with metallicity less than solar; i.e., -0.5 < [Fe/H] < 0.0. Clearly, stars with metallicities above solar are more likely to have extrasolar planets.

The globular cluster, 47 Tucanae, is metal poor ([Fe/H] = -0.67 dex). The null detection of planetary transits does not preclude the presence of EGPs in 47 Tucanae, but implies that the percentage of stars that have planets is extremely low.
Metallicity may not be the only possible culprit for the null detection for transiting planets. Stellar age may play a role. Another explanation might be that the high stellar density may have interfered with planet formation, or the less massive planetary bodies were possibly ejected from the cluster. The question as to whether or not low metallicity stars have planets is still open.

However, metallicity has become an indicator for the possible presence of planetary systems. It is thought that during planetary formation from a metal-rich cloud, the enhanced abundances of heavy elements enable rocky planetary cores to form relatively quickly, within a few million years. Since the expected lifetime of a circumstellar disk is

~4 million years, the faster a rocky core forms, the more hydrogen and helium the core attracts from the molecular cloud to become a giant planet. Another proposed mechanism for giant planet formation is cloud fragmentation. The cloud breaks up into multiple cores with smaller, low mass cores becoming planets.
The actual formation mechanism for giant planetary bodies as well as for brown dwarfs remains elusive. Snapshots at various ages are needed to construct a picture of planetary and BD evolution.

Why JWST?

Surveys of nearby molecular clouds, both ground-based IR and HST/NICMOS, have not found any viable low-mass planetary bodies. One candidate object, S Orionis 70 (Zapatero & Osorio et al. 2002), was later classified as a foreground BD (Burgasser et al. 2004). The failure to locate and identify low mass planetary bodies in the molecular clouds is primarily due to the faint magnitudes of these objects, extinction, as well as the resolution of the instruments. The models of Burrows et al. (1997) indicate a ~7 Jupiter mass object of age ~10 Myr would have an absolute magnitude H=14.1. A 1-2 Myr old object could potentially be 1-2 magnitudes brighter, and indistinguishable from a young, low-mass brown dwarf. With an absolute magnitude H ~12.5, the planetary body would have a magnitude at Orion (at 400 pc) of H ~20.5 which would result in a JWST estimated exposure time of ~5 seconds (S/N=10) at 1.6 microns.

JWST can identify and characterize giant planets and brown dwarfs in nearby molecular clouds using direct imaging; i.e., Orion (at 400 pc with age ~1 Myr), MBM~12 cloud (at 300 pc with age ~2 Myr), Serpens Cloud (at 260 pc with age ~3 Myr). We will observe with filters at 1.6, 4.5, 5.1, and 1.8 microns. Planetary and BD candidates will be identified based upon their infrared colors as predicted by Burrows et al (1997) and Baraffe et al. (2003). JWST observations will will be crucial to determining the substellar mass function, ascertain the binarity and disk frequencies, and to construct evolutionary tracks for for these objects. JWST will be able to reach to fainter limits at higher spatial resolution than is currently possible with HST/NICMOS or the Spitzer Space Telescope.

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Science Case # 16
Title: What JWST can do for Astrobiology

Authors: Ron Gilliland and Neill Reid

Science Case:
The science case for the synergy between astrobiology and JWST is fully developed and presented in the Report to NASA entitled `Astrobiology and JWST', edited by Sara Seager and Jonathan Lunine, and with contributions from many authors, including the two present ones.
Here the current JWST capabilities that are fundamental to preserve both for astrobiology studies, and for providing foundation science for TPF are listed again, in the same order given by the Report cited above.

Why JWST?
[Extracted from the Report to NASA `Astrobiology and JWST', page 3].

MIRI. The sensitivity of JWST/MIRI in the 5-27 mm region is unlikely to be surpassed by future 30-m ground telescopes. This capability enables studies of protoplanetary disks to reveal astrobiologically relevant gases and/or ices.

NIRSpec. This instrument is essential for characterizing transiting extrasolar planets, that are expected to be discovered both from the ground and with space-based telescopes. The short wavelength end will detect scattered light and planetary albedos.

NIRCam's and MIRI's Coronographs. These will enable imaging of young planets around nearby parent stars, and to study protoplanetary disks. Detection or non-detection of Jupiter-mass planets at 20-30 AU from the parent star will enable settling of the planet formation mechanism debate (accretion versus gravitational instabilities).

Control of stray and scattered light. At the level specified in the SRD, this control will enable investigations of dust disks, other circumstellar structures, faint extrasolar planets and substellar companions.