Astrophysics Strategic Mission Concept Studies

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From Cosmic Dawn to Our Solar System: Design Reference Science Program for the *Star Formation Camera* aboard the THEIA Space Telescope

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Abstract

We present the Design Reference Science Program for the *Star Formation Camera* (*SFC*; Scowen et al. poster #458.02), baselined as one of three primary instruments for the 4-m *THEIA* mission concept (see Spergel et al. #458.04). *SFC* is a wide-field (15′×19′, ≥280 arcmin^2), high-resolution (0.″018×0.″018 pixels), mid-UV–near-IR (190–1075 nm) dichroic camera and will deliver diffraction-limited images at $\lambda \geq 300$ nm in both a Blue (190–517 nm) and a Red (517–1075 nm) Channel simultaneously. Our aim is to conduct a *comprehensive* and *systematic* study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, and to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process.

Via a 4-Tier program, we will step out from the nearest star-forming regions within our Galaxy (Tier 1), via the Magellanic Clouds and Local Group galaxies (Tier 2), to other nearby galaxies out to the Virgo Cluster (Tier 3), and on to the early cosmic epochs of galaxy assembly (Tier 4). Interpretation of the panchromatic imaging is intimately tied to far-UV $R \gtrsim 30{,}000$ spectroscopic observations with the *Ultra-Violet Spectrograph* (*UVS*; Kembach et al. #458.01), also aboard *THEIA*. Each step will build on the detailed knowledge gained at the previous one. This program addresses the origins and evolution of stars, galaxies, and cosmic structure and has direct relevance for the formation and survival of planetary systems like our Solar System and planets like Earth.

SFC Design Reference Science Program: Star Formation as a Path from the Big Bang to People

Tier 1 — Star Formation within our Galaxy We aim to assemble a complete census of *all* high-mass star formation sites within 2.5 kpc of the Sun. We need to conduct (1) a comprehensive, pan-chromatic, wide-area imaging survey and (2) a far-UV spectroscopic survey of Young Stellar Objects (YSOs), protoplanetary disks, and their outflows. We aim to probe *all* aspects of the star formation process in different star formation environments. We want to learn how the detailed physical processes that operate on small scales (accretion, jets, shocks, photo-evaporation, bubbles and bulk flows, SNRs; e.g., Figs. 1 and 2) interact with those active on galactic scales, and characterize their imprint on lower resolution measurements. We aim to build the foundation for interpreting observations in more distant galaxies. The data will resolve billions of individual stars within, and along sightlines toward, these Galactic star-forming regions. We aim to learn if/how the Initial Mass Function (IMF) varies with the mode of star formation and metallicity.

Filters:	F212M	F262W	F330W	F432W	F212M	F372N/[O II]	F502N/[O III]	F486N/Hβ	F470N/He II	F280N/Mg II
	F547M	F775WW	F612W	F885W	F990M	F656N/Hα	F674N/[S II]	F953N/[S III]	F658N/[N II]	F632N/[O I]
Duration:										180 days

Tier 2 — Star Formation within the Local Group Moving outward, we will conduct a panchromatic imaging survey of both Magellanic Clouds (Fig. 3) and other star-forming Local Group galaxies in broad-band and nebular emission-line filters. We will also secure far-UV spectroscopy of up to ∼2000 OB-stars in the Clouds. We aim to (1) obtain a complete census of the richly varied stellar populations within the Clouds; (2) investigate feedback from massive stars, both in H II-region environments and in the diffuse, warm ISM, with access to O VI and to H_2 and HD at $30 < T < 300{,}000$ K; (3) quantitatively parametrize stellar clustering and star formation propagation; (4) determine how giant, starbursting H II-regions like 30 Doradus differ from more modest H II-regions within the Milky Way, and (5) determine the impact of metallicity by comparing broadly similar H II-regions within the Magellanic Clouds, our Galaxy, and other Local Group galaxies.

Filters:	F212M	F262W	F330W	F432W	F212M	F372N/[O II]	F502N/[O III]	F486N*/Hβ	F470N*/He II
	F547M	F775WW	F612W	F885W	F990M	F656N/Hα	F674N/[S II]	F953N*/[S III]	F632N*/[O I]
Duration:									180 days

*Selected emission regions only.

Tier 3 — Star Formation out to the Virgo Cluster Next, we will image a sample of ∼600 nearby galaxies out to the Virgo Cluster and study their resolved and unresolved stellar populations and ISM (e.g, Fig. 4), and immediate environments, in order to learn how their spatially resolved star formation histories and their ISM feature depend on galaxy mass (from dwarf to giant), structural type (E, S0, Sa–Sm, Im/Irr, and pathological morphologies that are rare today but common at high-z), metallicity, satellite systems, and larger cosmic environments. Via far-UV spectroscopy of background QSOs along sightlines through galaxies at $z < 0.2$, we will study the interface between galaxies and the Intergalactic Medium (IGM), and look for missing baryons. We also wish to understand how disk/spheroid properties relate to their galactic centers, and if/how disks are growing. We aim to sample the *full* parameter space of physical conditions and environments in which stars form.

Filters:	F212M	F330W	F262W	F432W	F212M	F373N/[O II]	F502N/[O III]	F487N/Hβ
	F547M	F612W	F775W	F885W	F990M	F659N/Hα+[N II]	F674N/[S II]	F632N/[O I]
Duration:								120 days

Tier 4 — Star Formation at Cosmic Dawn Lastly, we aim to understand in detail how galaxies formed from the perturbations in the primordial density field, the original metal enrichment of the IGM, and the late stages of its reionization through Lyα-emitters. We will sample the faint-end of the galaxy LF at high significance from $z \sim 8$ to 5 — the "cosmic dawn" of Pop II star formation and dwarf galaxy assembly — over an area that is sufficiently large to be free of the strong spatial variations due to cosmic variance. These dwarfs likely completed reionization of the universe. We furthermore aim to track the mass- and environment-dependent galaxy assembly from $z \sim 5$ to 1 through early-stage mergers ("*tadpole*" galaxies; Fig. 5) and constrain how Λ affected galaxy assembly. By studying faint variable objects — feeding weak AGN — we aim to understand how growth of SMBHs and galaxy spheroids kept pace through feedback processes.

Filters:	F241X	F312X	F385X	F465X	F262W	F212M	F212M	G213L
	F578X	F707X	F867X	F920M	F948M	F980M	F1020M	G745L
Duration:								120 days

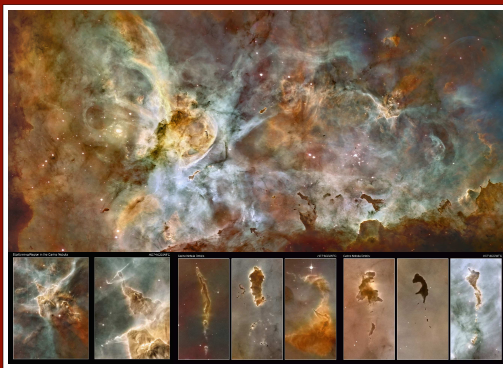

Fig. 1 — This recent *HST*/ACS mosaic of the Carina Nebula star formation region (Smith 2007) exemplifies the type of data product *SFC* should deliver in far fewer pointings, for a larger complement of astrophysically important broad- and narrow-band filters, and at higher angular resolution.

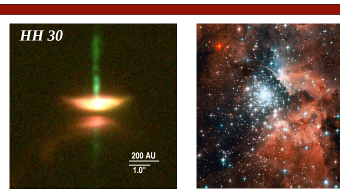

Fig. 2 — [*left*] *HST*/WFPC2 image of the polar jets and nearly edge-on protostellar disk around T Tauri star HH 30 at ∼140 pc. [*right*] *HST*/ACS image of stellar nursery NGC 3603 in Carina. Hot, massive stars dominate the light in this young Galactic cluster. High-resolution imaging and ultraviolet spectroscopy of individual objects is required to assess the complex feedback between these extreme objects and the development of the far more numerous, less massive stars. (*NASA/ESA/STScI*)

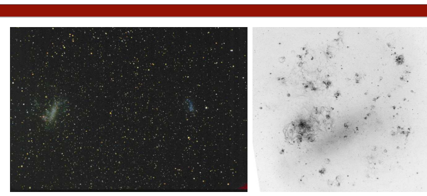

Fig. 3 — [*left*] Panoramic view of the Large and Small Magellanic Clouds, the nearest extragalactic testbeds (Courtesy: W. Keel, U. Alabama). [*right*] Map of the ionized gas within the LMC (Henize 1956). *SFC* will map both Clouds from 200–1100 nm through broad-band continuum and key diagnostic narrow-band emission-line filters.

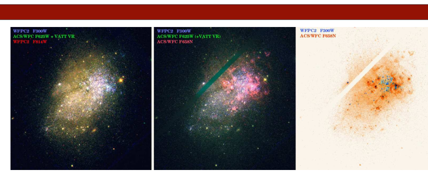

Fig. 4 — Three views of nearby NGC 3738 (Irr) that highlight: [*left*] the spatial distribution of stellar populations of various ages, [*middle*] the interplay between star formation and the ISM, and [*right*] the relation between hot young stars and the ionized ISM. Whereas *HST* observations like these tend to be shallow and rarely provide simultaneous full coverage through multiple filters and ≲10 pc resolution, *SFC* will not only allow systematic measurement of the star formation processes in galaxies, but also of their surrounding satellite systems.

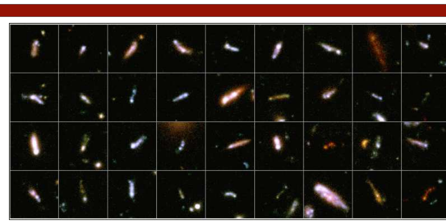

Fig. 5 — Early-stage mergers identified in the *Hubble* Ultra Deep Field (Straughn et al. 2006). Morphologies such as these are rare in the local universe, but are commonly seen at high redshifts.

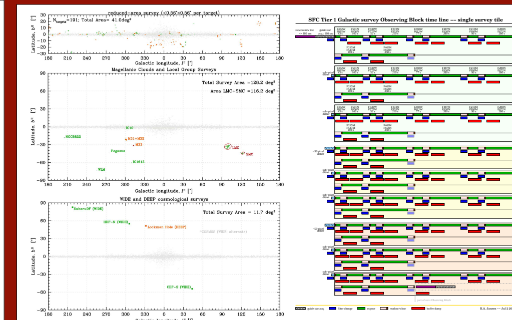

Fig. 6 — [*left*] Target fields for the comprehensive surveys of all Galactic star forming regions within ∼2.5 kpc from the Sun (*Tier 1*) and within the Magellanic Clouds and Local Group (*Tier 2*), and the DEEP and WIDE cosmological surveys (*Tier 4*). [*right*] Observing Block (OB) timeline for a single Galactic Survey tile (see poster #458.02 for details on the adopted dithering strategy).

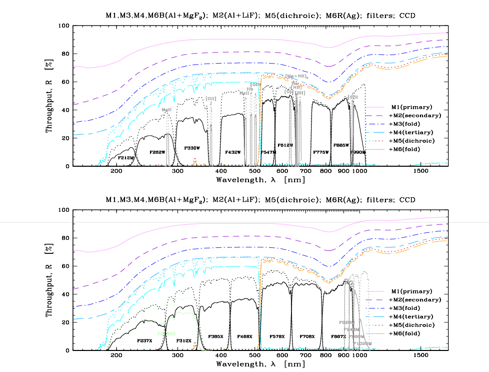

Fig. 7 — *SFC* filter throughput and cumulative contributions to that throughput by each of the optical components and detectors.

Table 1 — Overview of science-driven technical requirements for *SFC** and *UVS*.

Imaging requirements:	FOV cannot be substantially smaller than 19′×15′	(total area vs. depth requirement)
Focal plane geometry:	stable to ≲0.″00045 (0.025 pixel)	stable for ≳4 hrs
Point spread function:	diffraction limited at ≥300 nm and round to ≲10%	stable to ≲10% for ≳4 hrs
Pointing stability:	jitter ≲0.″004/sec (3σ) ; drift ≲0.″001 per 600 sec	stable for ≳4 hrs
Photometricity:	amplifier gain, A/D conversion, and QE stable to $\sim 10^{-5}$	stable for ≳4 hrs
Wavelength agility:	peak response 99%; ≳ 40% over 200–1050 nm range	access to full 185–1075 nm range
Filter requirements:	wheels must hold at least 16 blue, 18 red science filters and 2 grisms and 2 neutral density filters per channel	(goal: 2 × 18 science filters and 2 × 2 grisms and 2 × 2 ND)

Blue Channel:	F212M	F262W	F280N	F330W	F372N	F432W	F486N	F502N	(spare)	G213L	NDB1
	UV1	*UV2*	Mg II	*u*	[O II]	*B*	Hβ	[O III]		–	–
	212.8	262.3	280.9	330.2	373.5	432.7	486.1	502.3		313.0	–
	30.0	65.0	3.5	70.0	1.5	67.5	1.6	5.0		327.0	–
	F241X	F278XX	F312X	F385X	F467X	F373N	F470N	F487N	(spare)	G402M	NDB2
	UVX1	*UVXX*	*UVX2*	*UB*	*g*	[O II]	He II	Hβ		–	–
	241.0	278.7	312.5	385.9	467.9	374.0	470.1	487.8		402.0	–
	68.5	124.0	67.0	80.3	89.7	4.0	4.7	4.9		204.0	–
Red Channel:	F547M	F612W	F632N	F656N	F658N	F775W	F885W	F956N	F990M	G745L	NDR1
	y	$\mathcal{R}$	[O I]	Hα	[N II]	*i*	*z*	[S III]	$\mathcal{Y}$	–	–
	547.1	612.0	632.1	656.4	658.5	775.3	885.9	956.3	989.6	745.0	–
	47.5	81.5	6.3	2.0	2.0	100.0	110.0	9.6	52.0	558.0	–
	F578X	F659N	F674N	F707X	F867X	F920M	F948M	F980M	F1020M	G895M	NDR2
	$\mathcal{V}$	(Hα+[N II])	[S II]	$\mathcal{I}$	$\mathcal{Z}$	$Ly\alpha_{z\sim6.6}$	$Ly\alpha_{z\sim6.8}$	$Ly\alpha_{z\sim7.1}$	$Ly\alpha_{z\sim7.4}$	–	–
	579.7	659.5	674.7	707.4	870.6	920.0	948.0	979.7	1020.6	895.0	–
	116.8	8.7	8.1	143.5	174.5	28.1	28.0	35.7	27.9	330.0	–

Far-UV Spectroscopy (*UVS*):	must be able to access O VI at 103.2 nm and discriminate sources on scales of ∼0.″05	
Resolving power:	$R \gtrsim$ 30,000 over 100–175 nm range $R \gtrsim$ 6,000 over 100–300 nm range	(see: Sembach et al. poster 458.01)
Wavelength agility:	optimized for 100–115 nm response: Al+LiF	access to full 100–300 nm range

*For each filter, the four rows list the filter name, an alias or feature the filter aims to capture, the central wavelength (in nm) and FWHM in nm. Most narrow-band filters are sufficiently wide (1%) and centered to accomodate relative velocities with respect to the Sun of $-500 \lesssim cz \lesssim +2500$ km/s. Within our own Galaxy and in the Local Group, Hα and [N II] emission must be separable, requiring the narrower F656N and F658N, and also the narrower F372N and F486N filters ($-500 \lesssim cz \lesssim +500$ km/s).

THEIA/*SFC* as a Community Facility

As *THEIA* is a flagship-class mission concept, *SFC*'s design life is 10 years. Beyond and interspersed with the Design Reference Science Program outlined in this poster, the duration of which will not exceed a maximum of 600 days, *SFC* will be a powerful and versatile facility to the astronomical community, whether used as primary or parallel instrument. For examples, we refer to the Seager et al. poster #458.08.

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