Astrophysics Strategic Mission Concept Studies

From Cosmic Dawn to Our Solar System: A Next-Generation UV--Optical Space Facility for the Study of Star Formation

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Abstract

We summarize our science case for a UV–optical space facility that includes a wide-field mid-UV–near-IR (190–1100 nm) dichroic camera and a far-UV (100–175 nm) high-resolution spectrograph. We then present two possible implementations for such a facility: a camera and spectrograph on a 4 m-class planet finding and characterization mission (presently under study as part of NASA's ASMCS program), and a proposed concept for a dedicated 1.65 m *Star Formation Observatory*. 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. 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 such as Earth.

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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]

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]

*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]

Tier 4 — Star Formation at Cosmic Dawn **Lastly, we aim to understand in detail how galaxies formed from perturbations in the primordial density field, the original metal enrichment of the IGM, and final 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 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

SFO or *THEIA*/*SFC* as a Community Facility

Whereas much of the proposed 5-year *SFO* mission would be devoted to the survey program outlined above, *THEIA* is a flagship-class mission concept with a design life of 10 years. Beyond and interspersed with its design sience program, *SFC* will be a powerful and versatile facility to the astronomical community, whether used as primary or parallel instrument.

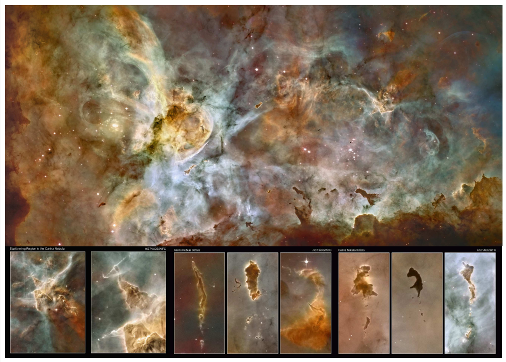

Fig. 1 — This recent *HST*/ACS mosaic of the Carina Nebula star formation region (Smith 2007) exemplifies the type of data product *SFO*/*SFC* should deliver in far fewer pointings, for a larger complement of astrophysically important broad- and narrow-band filters, and at higher angular resolution.

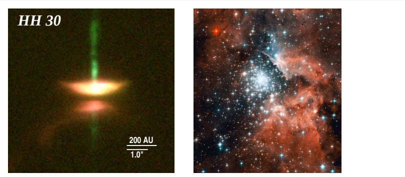

Fig. 2 — [*left*] *HST*/WFPC2 image of the polar jets and nearly edge-on protostellar disk around T Tauri star HH 30 at ~140 pc. [*right*] *HST*/ACS image of stellar nursery NGC 3603 in Carina. Hot, massive stars dominate the light in this young Galactic cluster. High-resolution imaging and ultraviolet 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*)

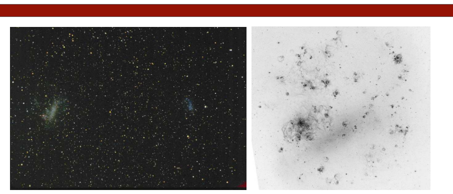

Fig. 3 — [*left*] Panoramic view of the Large and Small Magellanic Clouds, the nearest extragalactic testbeds (Courtesy: W. Keel, U. Alabama). [*right*] Map of the ionized gas within the LMC (Henize 1956). *SFO*/*SFC* will map both Clouds from 200–1100 nm through broad-band continuum and key diagnostic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

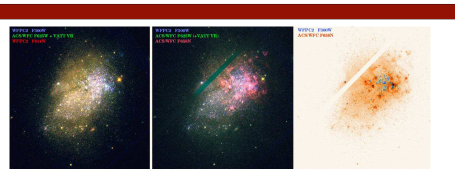

Fig. 4 — Three views of nearby NGC 3738 (Irr) that highlight: [*left*] the spatial distribution of stellar populations of various ages, [*middle*] the interplay between star formation and the ISM, and [*right*] the relation between hot young stars and the ionized ISM. Whereas *HST* observations like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

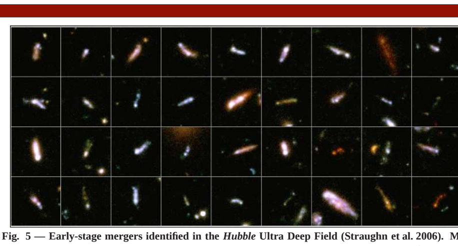

Fig. 5 — Early-stage mergers identified in the *Hubble* Ultra Deep Field (Straughn et al. 2006). Morphologies such as these are rare in the local universe, but are commonly seen at high redshifts.

The *Star Formation Observatory* (*SFO*)

***SFO* is a medium-class mission concept for a 1.65 m UV–Optical space telescope, proposed to NASA in Nov 2007. The design under consideration, inserted in an L2 orbit, will provide 100 times greater imaging efficiency and >10 times greater spectroscopic efficiency below 115 nm than existed on previous missions. *SFO* combines focussed capabilities unique to space and that no other planned NASA mission will provide.**

The telescope is a Three-Mirror Anastigmat (TMA) and will feed two instruments: a near-UV/visible (190–1100 nm) wide-field dichroic camera, and a low- and high-resolution ($R \lesssim 40{,}000$) UV (100–320 nm) spectrograph. To access wavelengths shortward of 115 nm, we use far-UV optimized Al+LiF mirror coatings and recent advances in Micro-Channel Plate (MCP) detector technology. The camera has a Focal Plane Array consisting of 3×3 3500×3500-pixel CCD detectors, delivering a field of view in excess of 17′×17′ (>250 arcmin^2), and will use a dichroic to create optimized UV/blue (190–517 nm) and red/near-IR (517–1100 nm) channels for simultaneous observations in 2 bandpasses. It employs detectors that offer substantial quantum efficiency gains while suffering lower losses due to cosmic rays. Both multi-band imaging *and* far-UV spectroscopy contribute essential information that will revolutionize our understanding of the many complex aspects and interplays of the star formation process.

Table 1 — Overview of science-driven technical requirements for *SFO*

Imaging requirements:	FOV cannot be substantially smaller than 17′×17′	(total area vs. depth requirement)
Focal plane geometry:	stable to ≲ 0.″001 (0.017 pixel)	stable for ≳ 4 hrs
Point spread function:	diffraction limited at ≳ 200 nm and round to ≲10%	stable to ≲10% for ≳ 4 hrs
Pointing jitter:	≲ 0.″006 (0.1 pixel)	stable for ≳ 4 hrs
Photometricity:	amplifier gain, A/D conversion, QE, stable to $\sim 10^{-5}$	stable for ≳ 4 hrs
Wavelength agility:	peak response 99%; ≳40% over 205–1050 nm range	access to full 190–1100nm range

Filter requirements:	wheels must hold at least 10 blue and 12 red filters (goal: 2×12 filters)								
Broadband:	F262W	F278X*	F330W	F432W			F612W	F775W	F885W
	UV2	*UVW*	*u*	*B*			*r*	*i*	*z*
Mediumband:	F218M				F547M	F980M	F990M	F1020M	F1050M
	UV1				*y*	Ly$\alpha_{z\sim7.1}$	*Y*/Ly$\alpha_{z\sim7.2}$	Ly$\alpha_{z\sim7.4}$	Ly$\alpha_{z\sim7.6}$
Narrowband†*:*	F280N	F373N	F470N	F487N	F502N	F632N	F659N	F674N	F956N
	Mg II	[O II]	He II	Hβ	[O III]	[O I]	Hα+[N II]	[S II]	[S III]

Far-UV spectroscopy:	must be able to access O VI at 103.2 nm and discriminate sources on scales of ~0.″05	
Resolving power:	$R \sim 40{,}000$ over 100–175 nm range	(2 gratings)
	lower-resolution covering full bandpass	(1 grating)
Wavelength agility:	optimized for 100–115 nm response	access to full 100–175 nm range

*Ultra-wide UV filter with $\lambda_c \sim 278$ nm and FWHM ~125 nm; †narrow-band filters must capture emission redshifted to ~2500 km s^{-1}.

The *Star Formation Camera* (*SFC*)

***SFC* is a proposed instrument for *THEIA*, a 4 m space telescope concept (P.I. D. Spergel). *THEIA* requires insertion into an L2 halo orbit and will be equipped with a total of three main instruments: the *eXtrasolar Planet Characterizer* (*XPC*; P.I. D. Spergel, Princeton), a coronagraph that works in concert with a free-flying occulter spacecraft; the *UltraViolet Spectrograph* (*UVS*; P.I. K. Sembach, STScI), a far-UV spectrograph that will provide high-resolution ($R \sim 30{,}000$) access to wavelengths as short as 100 nm; and the *Star Formation Camera* (*SFC*; P.I. P. Scowen, ASU), a near-UV/visible (190–1100 nm) wide-field dichroic camera.**

Like *SFO*, *THEIA* employs a Three-Mirror Anastigmat (TMA) design. While its 4 m primary mirror will have a Al+MgF_2 overcoat, its secondary will be Al+LiF overcoated to provide *UVS* access to wavelengths shortward of 115 nm. *SFC* will provide diffraction-limited imaging at 300 nm and, with minimal dithering, will allow Nyquist sampling of the 4 m PSF over the full 190–1100 nm wavelength range. Its has a field of view of ~19′×15′ (>275 arcmin^2), sampled with 0.″018×0.″018 pixels, and will use a dichroic to create optimized UV/blue (190–517 nm) and Red/near-IR (517–1100 nm) channels for simultaneous observations in 2 bandpasses. Its massive Focal Plane Arrays will employ detectors that offer substantial quantum efficiency gains and that suffer lower losses due to cosmic rays.

The telescope and camera design under consideration will provide >100 times greater imaging efficiency than existed on previous missions and open up a new regime in wide-field high-angular resolution imaging, allowing significant resolution into stars of galaxies out to the Virgo Cluster.

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
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).

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