Beyond the Cosmic Veil: Star and Planet Formation Research after SIRTF and NGST

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Abstract. How do planets form from circumstellar disks of gas and dust? What physical processes are responsible for determining the final masses of forming stars and ultimately the initial mass function (IMF)? The Hubble Space Telescope has made major contributions in helping to address these fundamental questions. In the next decade, the Space Infrared Telescope Facility (SIRTF) and the Next Generation Space Telescope (NGST) will build on this heritage in the near- to far-infrared. However several crucial questions will remain. We review recent progress made in star and planet formation with HST, summarize key science objectives for SIRTF and NGST, and suggest problems that would be uniquely suited to a large aperture UV/optical space-based telescope. We focus on studies that take advantage of high spatial resolution and the unique wavelength range not accessible from the ground such as: 1) circumstellar disk structure and composition (resolved images of dust and UV spectroscopy of gas); and 2) extreme populations of young stars in the local group (UV imaging and spectroscopy of massive star-forming regions). An 8m UV/O space telescope operating from 1100–6000 Å over fields of view 4–10' and with spectroscopic capabilities from R = 3,000–10,000 down to < 1000 Å would be a powerful tool for star and planet formation research.

1. Introduction

Star and planet formation will remain key themes in the NASA Origins Program through the next decade and beyond. During this time, the community will enjoy access to: 1) continued HST operation with STIS, NICMOS, ACS, COS, and WFC–3 with wavelength coverage from 0.1150–2.5 μm; 2) SIRTF with launch in early 2003 (lifetime ∼ 5 years) covering the wavelength range from 3–160 μm; and 3) NGST scheduled for launch in 2010 with projected 5 year mission covering the wavelength range 0.6–28 μm. Because important processes in star and planet formation occur over a wide range of temperatures, multi-wavelength observations are required in order to make significant progress (see overview by Hartmann this volume).

Both SIRTF and NGST will execute programs aimed at understanding the emergence of planetary systems from circumstellar disks around young stars, and the origins of stellar masses. Approved SIRTF guaranteed time programs
will focus on circumstellar disk evolution and the nature and frequency of brown
dwarf objects. In addition, three of the six adopted Legacy Science Programs
(GLIMPSE, From Molecular Clores to Planet–Forming Disks, Formation and
Evolution of Planetary Systems) will directly impact star and planet formation
research ([http://sirtf.caltech.edu/SSC/legacy/](http://sirtf.caltech.edu/SSC/legacy/)). Two of the five themes in the
Design Reference Mission for the NGST (The Birth and Formation of Stars
and The Origins and Evolution of Planetary Systems) deal with similar topics
([http://ngst.gsfc.nasa.gov/science/drm.html](http://ngst.gsfc.nasa.gov/science/drm.html)).

Observations in the UV/optical range are also important to obtain a com-
plete picture of star and planet formation. Key observations include: 1) sampling
the Wien peak of massive star energy distributions; 2) measuring important gas
diagnostics for infall/outflow; and 3) studying resolved images of dust disks. As
in the infrared spectral regime, space offers unique capabilities for UV/optical
astronomy such as the accessible range from 912–3000 Å, and diffraction–limited
imaging over a large field of view at wavelengths < 1 µm.

Here, we concentrate on two areas where a large aperture UV/Optical space
telescope could make substantial contributions. We begin by identifying key
issues, review the legacy of HST in each area, summarize the promise of SIRTF
for studies of circumstellar disks and NGST for investigations concerning the
origin of the IMF, and suggest parameters required in order for a UV/optical
space telescope to realize its potential for star and planet formation research.

2. Evolution of Circumstellar Disks

Why should we care about the evolution of circumstellar disks around young
stars? Because their study holds the promise of connecting observations of disks
observed in the Milky Way as a function of age with the origin and evolution
of our own solar system. Disks are the mostly likely sites of planet formation
giving rise to extra–solar planets such as those detected around sun–like stars in
the solar neighborhood. Ultimately we wish to know whether planetary systems
are common or rare in the Universe. In addition, disk accretion is an important
part of the star formation process. Does it help provide “feedback” into the
surrounding interstellar medium and thus a regulating mechanism for the de-
termination of stellar masses? What effects does it have on pre–main sequence
evolution?

Our current understanding of the evolution of circumstellar disks surround-
ing young stars is limited by available observations. High resolution spectro-
scopic observations have suggested a connection between the accretion of ma-
terial through a disk and mass loss in powerful outflows (e.g. Edwards et al.
1994). Through ground–based near–IR studies of young clusters, it appears that
inner disk accretion terminates on timescales < 10 Myr for most stars (Haisch
et al. 2001; Hillenbrand et al. 2002). Photometric monitoring and spectroscopic
observations have suggested a link between stellar rotation and the presence or
absence of a disk (e.g. Bouvier et al. 1993). Studies of outer disks (1–10 AU)
require mid– to far–infrared observations. A number of groups have suggested
that substantial evolution occurs in dust disks at these radii from 10–100 Myr
(see Meyer & Beckwith 2000 for a recent review). Millimeter wave observations
2.1. Legacy of Hubble

The Hubble Space Telescope (HST) has provided a rich legacy of imaging and spectroscopic observations that have revolutionized the study of circumstellar disks around young stars. The first images of the dark disks seen in silhouette against the bright background of the Orion Nebula provided direct confirmation of the disk hypothesis that even the most ardent skeptics find difficult to refute (e.g. McCaughrean & O’Dell 1996; Figure 1). Subsequent studies have offered numerous examples of objects seen edge–on where a favorable viewing geometry provides a wealth of detailed knowledge about individual objects (e.g. Burrows et al. 1996). Monitoring programs over several years have also enabled proper motion studies of accretion–powered jets that provide direct tests of theoretical models (Hartigan et al. 2001). Coronographic observations with STIS and NICMOS (Schneider & Silverstone this volume) utilize high contrast imaging as a tool to probe dust structure and composition. Wide–field imaging studies have provided insight concerning large–scale mass–loss and interactions with the surrounding interstellar medium (Bally et al. 2002). Finally, UV spectroscopy is proving to be a powerful diagnostic tool to study accretion processes (Ardila et al. 2002) and the atomic and molecular gas content of disks through absorption–line observations along favorable lines of sight (e.g. Vidal–Madjar et al. 1994). Long–slit diffraction–limited imaging spectroscopy has also shed light on the complex relationships between star/disk systems and the surrounding interstellar medium (Grady et al. this volume).
2.2. The Promise of SIRTF

The Space Infrared Telescope, the last of NASA’s “Great Observatories” and the first new mission of the NASA Origins program, will be launched in early 2003 and provide unprecedented mid- and far-infrared sensitivity for studies of circumstellar disks. Through a suite of guaranteed time programs and the Legacy Science Program, SIRTF will make major contributions to our understanding of the structure and evolution of circumstellar disks around young stars. One program, the Formation and Evolution of Planetary Systems (Meyer et al. 2002), is aimed directly at studying dust disks around solar-type stars and placing our solar system in context. Through construction of spectral energy distributions from 3–160 μm for 350 stars of spectral type F8–K3 we hope to: 1) characterize the transition from primordial dust disks to debris disks by tracing evolution in the amount, distribution, and composition of dust; and 2) examine the diversity of planetary systems through their dynamical effect on dust. Through spectroscopic observations of warm (50–200 K) molecular hydrogen gas we hope to constrain the timescale for gas disk dissipation and giant planet formation. These programs, which build directly on the heritage of IRAS and ISO, will leave a rich legacy for follow-up observations with NGST as well as a large aperture UV/optical space telescope.

2.3. Requirements for UV/O Space Telescope

What should we require from a UV/optical space telescope (UV/O–ST) for studies of planet formation? Spatial resolution of order 0.3 AU for the nearest T Tauri stars (3 mas at 100 pc and 1100 Å) would enable us to: 1) possibly resolve the disk/jet interface providing a detailed understanding of the accretion process and insight into the star/disk interaction that may mediate stellar angular momentum evolution; and 2) detect large gaps in disks created through the dynamical interaction of giant planets with dust debris. In addition to spatial resolution, sensitivity to study gas disks at R = 10,000 is required in order to: 1) measure accretion rates <10^{-10} M⊙/year (c.f. Johns-Krull et al. 2000) and 2) extend limits on H2 and CO gas in disks to levels comparable to SIRTF (c.f. Figure 1). Finally, 4–10’ fields of view from 1100–6000 Å are required to trace the accretion–driven mass loss history of young stars by observing shock diagnostics over a range of velocities. Such studies can constrain: 1) the angular momentum loss of PMS star/disk systems through energetic winds; and 2) the deposition of kinetic energy into the turbulent interstellar medium providing a support mechanism for collapsing clouds. An 8m UV/O–ST meets these requirements.

3. The Origins of Stellar Masses

How did the universal star formation rate evolve over cosmic time? How do galaxies, including our own Milky Way, assemble themselves? How are stars and planets formed? In order to quantitatively address all of these issues, one

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1For additional information see [http://feps.as.arizona.edu](http://feps.as.arizona.edu)
fundamental question must be answered: what physical processes determine the shape of the initial mass function of stars and sub–stellar objects? This question has plagued astronomers since the initial mass function was first introduced by Salpeter (1955). Its construction requires translation of an observed luminosity function into a mass function through adoption of an appropriate mass–luminosity (M–L) relation. Because high mass stars exist on the mass sequence for shorter lifetimes and because they are rare in comparison to lower mass stars, even construction of the field star IMF requires the assumption that: 1) the IMF is the same everywhere; and 2) it has remained the same for all time. These two assumptions have not been tested over the full range of available star–forming environments. Recent work by Massey et al. (1995), Scalo (1998), Reid et al. (1999), Kroupa (2001) and references therein have led to extensions of the field star IMF into new mass regimes as well as refinements in the characterization of its shape. Yet, even with the strong assumptions outlined above, uncertainties in the galactic birthrate complicate corrections for massive star evolution and adoption of time–dependent M–L relationships for sub-stellar objects in well–mixed stellar populations. Newly formed star clusters are ideal laboratories to investigate the IMF over the full range of stellar and sub–stellar masses with a minimum of assumptions.

3.1. Legacy of Hubble

Through observations that have complemented ground–based work, HST has provided intriguing hints concerning answers to the above questions. Studies of mass functions with WFPC2 and NICMOS in the field (Gould et al. 1997), the bulge (Holtzman et al. 1998), spheroid (Gould et al. 1998) and globular clusters (Paresce & De Marchi 2000) all point toward a stellar IMF that is similar in a variety of star–forming environments. Observations of young clusters with NICMOS, where brown dwarfs are more easily detected due to their high “pre–main sequence” luminosities, suggest that the universality of the IMF extends into the sub–stellar range (Luhman et al. 2000; Najita, Teide, & Carr 2001). Massey & Hunter (1998) have utilized the FOS to study the IMF in the low metallicity R 136 cluster in the Large Magellanic Cloud (Figure 2). The rapid post–main sequence evolution of massive stars creates degeneracies in the analysis of color–magnitude diagrams that require classification spectroscopy in order to accurately derive the IMF. Massey and collaborators find that the IMF above 10 M⊙ does not vary over a range of 2.0 dex in metallicity. However, recent near–infrared photometric studies of massive star formation in the inner galaxy with NICMOS on HST have raised the possibility of an unusual power–law IMF above 5 M⊙ in the heavily embedded Arches cluster (Figer et al. 1999).

3.2. The Promise of NGST

Does the Initial Mass Function (IMF) truncate somewhere below the hydrogen burning limit? Theoretical speculations abound. One conjecture is that the star–forming process is essentially self–regulating through some negative feedback mechanism. For example, accretion of material onto the central protostar drives a powerful bi–polar outflow which could disrupt the remnant infalling envelope (Adams & Fatuzzo, 1996). Balancing the mechanical energy between infall and outflow for typical molecular cloud cores suggests a characteristic mass
of $\sim 0.25 \, M_\odot$. An opposing view holds that the distribution of star–forming units in a collapsing cloud core is determined by fragmentation processes which in turn depend on the initial conditions of the local interstellar medium (e.g. temperature, density, metallicity). For example, the mass scale for a gravitational perturbation to become unstable in a uniform density medium, the Jean’s Mass, is roughly 0.7 $M_\odot$ when averaged over the observed range of densities in nearby molecular clouds. Indeed such a preferred scale is observed as a break in the power–law distributions that characterize the surface density of companions in the Taurus dark cloud (Larson 1995). As the fragments collapse, the local gas density increases. Provided the material remains at a constant temperature, the Jean’s mass will decrease driving smaller and smaller regions unstable (hierarchical fragmentation). However, the minimum mass for fragmentation is fixed at the point where the condensing core becomes opaque to its own radiation, preventing further sub–fragmentation at a constant temperature (e.g. Spitzer 1978). Under conditions typical of nearby clouds this limit is $\sim 10M_{JUP}$. Large spectroscopic surveys will be needed to build robust estimates of the IMF and distinguish between these theories. With its combination of high angular resolution, accessible wavelength range, and sensitivity, NGST will be able to obtain NIR spectra for hundreds of $10^6$ yr objects down to $1 \, M_{JUP}$ viewed through $A_V < 25^m$ of extinction within 500 pc of the Sun in a few hours of integration.

Nearby regions of massive star formation (R 136, NGC 3603, the Arches cluster) have commanded considerable attention as local analogs to “super star clusters” observed in interacting galaxies (e.g. O’Connell et al. 1994) that are proximate enough for detailed studies of the resolved stellar populations. With few exceptions, most studies show that the IMF of these regions of extreme star formation are consistent with the field star IMF that characterizes the solar neighborhood down to varying low mass limits $> 1M_\odot$. Each of these regions contains dozens of stars $> 10 \, M_\odot$ which according to the field star IMF should be accompanied by $\sim 10^5$ stars down to the hydrogen burning limit. Yet very little is known concerning the IMF in regions of extreme star formation below $1.0 \, M_\odot$. Theory suggests that lower metallicity regions might contain hotter gas due to a lack of molecular cooling and therefore exhibit higher Jean’s mass on average (Nakamura & Umemura 2002). The starburst phenomenon is often associated with a top–heavy IMF as well as an upper mass cutoff suggested by models of their spectral evolution. In order to constrain the mass–to–light ratio in unresolved stellar populations over cosmic time, it is crucial to understand the shape of the IMF as a function of metallicity and environment in regions of extreme star formation. Our best hope is to study in detail star–forming events in the Milky Way and the local group that approach the activity of starbursts. NGST will be able to obtain spectra for objects below the hydrogen burning limit in clusters aged 1–3 Myr with $A_V = 0–10$ from the Galactic Center out to the distance of the LMC.

### 3.3. Requirements for UV/O Space Telescope

What capabilities are required for an UV/O–ST in order for it to make major advances in understanding the origin of the initial mass function? Maintaining a wavelength range from 1100–6000 $\AA$ will enable a UV/O–ST to study the formation of high mass stars in regions of low extinction throughout the local
group over a wide range of stellar temperatures (spectral types later than K0 to earlier than O5). Spatial resolutions of 200 AU (3 mas at the distance of the LMC and 1100 Å) will result in resolution of many wide binary systems and minimize the nebular background often associated with regions of massive star formation. Spectral resolution (and sensitivity) at R > 3000 is required for classification of the hottest stars, a necessary step in order to derive an accurate IMF in regions of extreme star formation. Fields of view 4–10’ are required in order to separate clusters from field populations and assess local environments which could influence their dynamical evolution. An 8m UV/O–ST would enable studies of nearby starbursts with resolution and sensitivity comparable to HST studies of massive star formation in the LMC (Figure 2).

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