Hubble Space Telescope

Cycle 13 GO Proposal

# The Low-Mass IMF of the Super Starcluster R136: Answering the $64,000 Question


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Instruments: ACS

Proprietary Period: 12

Cycle 13 primary orbits: 25

## Abstract


The R136 super star-cluster located in the LMC contains the largest number of high mass stars known. Thanks to previous work with HST, the IMF at the high-mass end is well characterized. Now we are proposing to answer a question first posed by Hans Zinnecker (1998, 1999) as the "64 thousand dollar question"---what does this extreme environment contain by way of low-mass stars? Using archival WFPC2 data, Sirianni et al (2000) suggest that the IMF power-law undergoes an abrupt change in slope at an unexpectly high mass, 2.8Mo, with a Salpeter (Gamma=-1.35) slope turning into a nearly flat distribution (Gamma=-0.3), implying that R136 is extremely top-heavy in terms of massive stars. The result is consistent with recent theoretical work which suggests that super starclusters form in highly turbulent regions which in turn favor production of top-heavy IMFs. However, the Sirianni et al. result for low-mass stars rests on a slope derived from a very narrow range of masses near (or beyond) their completness limit. Simulations of the effects of crowding on photometric accuracy and on completeness suggest that by using the HRC mode of the ACS we can do far better, as the finer scale greatly reduces the crowding limit by more than 2 magnitudes. This will allow us to to reliably measure the IMF down to 0.9Mo at 5 half-light radii, and 0.6Mo at 7 half-light radii. We propose to undertake this study and give a definitive answer to Hans' question.

## Investigators:

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Number of investigators: 7

## Target Summary:

| Target | RA | Dec | Magnitude |
|---|---|---|---|
| R136 | 05 39 0.00 | -69 06 0.00 | V = 9.5, E(B-V)=0.38 |

## Observing Summary:

| Target | Config Mode and Spectral Elements | Flags | Orbits |
|---|---|---|---|
| R136 | ACS/HRC Imaging F435W | | 25 |
| | ACS/HRC Imaging F555W | | |
| | | Total orbit request: | 25 |

## Scientific Justification

### Introduction

Understanding the kinds of stars that form in super star-clusters and what processes control their formation represents an essential first step in understanding the star formation and element production histories of galaxies over the lifetime of the universe. Young super star-clusters comprising upwards of $10^6$ stars in a volume of $\sim 10$ pc$^3$ rank among the most spectacular objects in the universe. These young (1-3 Myr) analogs of globular clusters are found in abundance in galaxy mergers (e.g. M82, O'Connell et al. 1995) classical star-bursts (e.g., NGC 1569, O'Connell, Gallagher, & Hunter 1994), and normal irregular galaxies (e.g. R136 in the LMC, Campbell et al. 1992). Super star-clusters are expected to be the dominant features in pre-galactic clumps and just forming galaxies at high redshifts.

If we can determine the outcome distribution of stellar masses in these regions, we can use this distribution to inform our understanding of the underlying physical processes (protostellar density? chemical composition?) that control the IMF, which in turn shapes the chemical enrichment history of galaxies. We propose here to determine whether the distribution of stellar masses in the nearest example of a young rich, dense supercluster (R136 in the LMC, with an estimated density of $10^3 M_\odot$ pc$^{-3}$) is different from that found in more mundane, lower density star-forming regions ($\sim 10\ M_\odot$ pc$^{-3}$) for a typical OB Association core (e.g. the Orion Nebula Cluster, or ONC); see Hillenbrand & Carpenter (2000). R136 represents an ideal target for such a study both because it is young (1-2 Myr old) and dynamically unevolved. Its low-mass stellar population has not yet reached the main sequence, and is thus relatively bright and accessible to accurate measurement. If the IMF in this extreme star-forming environment proves to be different, then we can begin to assess how the IMFs in superclusters affect (a) the mass tied up in slowly evolving low-mass stars compared to that in high-mass stars; (b) the relative amount of material recycled from massive stars to the amount locked up in stars less massive than the sun; and (c) as a consequence, the total mass of heavy elements produced and ultimately dispersed into the intergalactic medium for a given cluster mass.

To date, studies of the shape of the high-mass end of the initial mass function in young, star-forming regions have largely been restricted to a few dozen OB associations in the Milky Way Galaxy and other Local Group galaxies. From examination of these regions it appears that the shape of the IMF over the decade 10 to 100 $M_\odot$ is remarkably the same (e.g. Massey, 2003). The same shape holds for the high-mass stars of the super starcluster R136 (Massey & Hunter 1998).

What of the lower mass stars? In low density star-forming regions located within $\sim$1 kpc of the sun, the IMF shape is best matched by a power law distribution for masses $>\sim 1 M_\odot$ ($N(m)$dm $\sim$ M$^\gamma$ dm, where $\Gamma = (\gamma + 1) = -1.35$ is a good representation; cf., Salpeter, 1955). At lower masses, the IMF flattens and has a slope of $\Gamma = -0.25$ at $M < 0.5 M_\odot$. (e.g., Hillenbrand 1997; Kroupa 2001; Meyer et al. 2000).

Sirianni et al. (2000) have studied the R136 supercluster using many archival images taken with WFPC2, and confirm the result by Hunter et al. (1995, 1996) that above 2.8$M_\odot$ the IMF is well fit with a power law with $\Gamma = -1.35$ (i.e., Salpeter). However, Sirianni et al. (2000) find that there is a dramatic break in the IMF slope at $\sim 2.8 M_\odot$, below which $\Gamma \sim -0.27$ (see Fig. 1). Is this turn-over in the IMF at higher masses than usually observed ($2.8M_{\odot}$ vs. $0.5M_{\odot}$) real, and if so, does it reflect the effect either of the extraordinarily high density of this cluster or its lower metal content (1/2 that of the sun as judged from analysis of the O/H ratio in the associated H II region)?

The SENSE of this result – a stellar mass function weighted heavily toward higher mass stars – is anticipated by theory. For example, McKee & Tan (2003) and Elmegreen & Shadmehri (2003) suggest that dense star–forming regions are characterized by high turbulent speeds, which in turn may result in formation of protostars of higher initial density and higher time averaged infall/mass accretion rates. In turn, this combination of circumstances appears (theoretically!) to produce 'top heavy' IMFs – IMFs that favor the production of very high mass stars. If correct, we might expect to observe a higher fraction of high ($M > 3M_{\odot}$) compared to low mass stars in our target cluster. Lower metallicity regions (characterized by lower cooling rates) might also tend to favor the formation of higher mass stars.

Robust confirmation of a "top heavy IMF" in R136 with a dramatic change in slope at $M \sim 3M_{\odot}$ would represent a breakthrough in our understanding of conditions that control the IMF. Doing so depends critically on significantly extending the baseline in stellar mass over which the IMF is observed directly. Achieving this goal requires overcoming the deleterious effects of extreme crowding in the R136 environment. Crowding confounds deriving accurate magnitudes and colors for cluster stars owing to the fluctuating background produced by large numbers of faint, overlapping stellar images. Without good photometry, it is impossible to construct a luminosity function – sine qua non for estimating an initial mass function.

We propose here to exploit the superb image quality and Nyquist sampling of stellar images at optical wavelengths provided by the High Resolution Camera (HRC) of the Advanced Camera for Surveys, which together enable photometry to luminosities four times deeper and to thus extend studies of the IMF a factor of two smaller than has been possible with to date with WFPC2.

**Approach**

We plan to image R136 with the ACS HRC at B and V using exposures calculated to provide a S/N of 25 at the crowding limit (B =25.5; V =24.8 mag). At 5 half-light radii ($5R_c$) crowding will dominate the errors, introducing a 20% uncertainity in the photometry, although the error on $B - V$ will be only 10%. By $7.5R_c$ photometric errors will dominate. We thus expect to reliably determine the IMF down to $0.9M_{\odot}$ at $5R_c$, and $<\sim 0.6M_{\odot}$ at $7.5R_c$. Our approach to deriving $N(M)$ involves the following steps:

(1) Derive the distribution of stellar ages $N(t)$ from the observed distribution of pre-main sequence stars in B-V, V color magnitude diagram, combined with computed pre-main sequence (PMS) evolutionary tracks (Siess et al. 2000).

(2) Use the photometric and spectroscopic study of Hunter et al. (1995) and Massey & Hunter (1998), to estimate the distribution of interstellar extinction, $N(A_v)$.

(3) Construct a best-estimate of a reddening-corrected V-band luminosity function, N(V) derived from the the observed $N(V)$ and $N(A_v)$ derived as above.

(4) Transform V luminosity to stellar mass by using the ZAMS relationship between V and mass for stars M$> 3M_{\odot}$, and the relationship beween V, mass and age for the PMS tracks of Siess et al. (2000). The choice of models is not critical because differences in PMS tracks are modest

for masses $M > 0.5M_{\odot}$, the mass range of interest for this proposal. For a given age, there is a one-to-one relationship between $V$ and mass. Because there appears to be a (modest) range of ages represented among the PMS stars in R136 (Hunter et al. 1995; Sirianni et al. 2000), we require knowledge of V vs. $M$ vs. age (from PMS) as well as knowledge of $N(t)$ as deduced in (1) above.

Combining 1-3 will lead to a best estimate of $N(M)$ along with statistical constraints on the uncertainties (see Hillenbrand & Carpenter (2000) who use maximum likelihood techniques to estimate $N(M)$ for the ONC). Our plan is to compare our HST results with results derived from existing BV photometry of the ONC, whose members span a similar range in age – thus enabling a differential determination of IMFs between R136 and the ONC.

**Estimating the Limits of the ACS Observations**

Olsen et al. (2003) quantify the effects of crowding on photometric accuracy using analytical techniques, and then verify their predictions using numerical experiments carried out for specific astronomical targets. We apply their methods to a cluster with the observed central surface density and brightness profile of R136 (Mackey & Gilmore 2003). To estimate the limiting luminosities at B and V band, we assume as input these surface densities, along with the assumptions (a) that the mass function of R136 is identical to that found by Hillenbrand & Carpenter (2000) for the ONC; and (b) that this mass function can be transformed to the luminosity functions in B and V using a 2 Myr pre-main sequence isochrone with abundance Z=0.01 (Siess et al. 2000). The resulting limiting magnitudes due to crowding are listed in Table 1 as a function of cluster radius, along with the mass limits corresponding to the crowding limits, again assuming a transformation between mass and luminosity derived from the 2 Myr pre-MS isochrone described above.

The power of Nyquist-sampled ACS HRC images is visually demonstrated in Figs. 2 and 3, where we illustrate the simulated performance of WFPC2 and the ACS. The ability of the HRC to extend the “crowding limit” will enable us to robustly determine the shape of the IMF down to masses a factor of 2 smaller than achievable with WFPC2 (see Fig. 1 and Table 1).

**Why not NICMOS?**

Zinnecker et al. (1999) have carried out NICMOS H-band observations of R136 with goals similar to those described above. However, our analysis of the effects of crowding on H-band images (with 3x the PSF diameter as that of ACS at V) demonstrate that photometric errors from crowding preclude an accurate determination of $N(M)$ much below $\sim 2M_{\odot}$.

**Why not the Ground?**

Given the increasing power of adaptive optics systems on large ground-based telescopes, why do we propose ACS observations at B and V as opposed to J, H and K band observations with Gemini or Keck? Beyond the fact that R136 can not be observed from Keck or Gemini North and that Gemini South has no AO system, the primary reason is that the PSF delivered by HST to ACS is both constant and well-characterized over a 27” field of view. In crowded fields in particular, the ability to derive accurate photometric measurements depends critically on both PSF spatial and temporal stability – readily achieved with HST ACS, but highly problematic with current generation AO systems.

References

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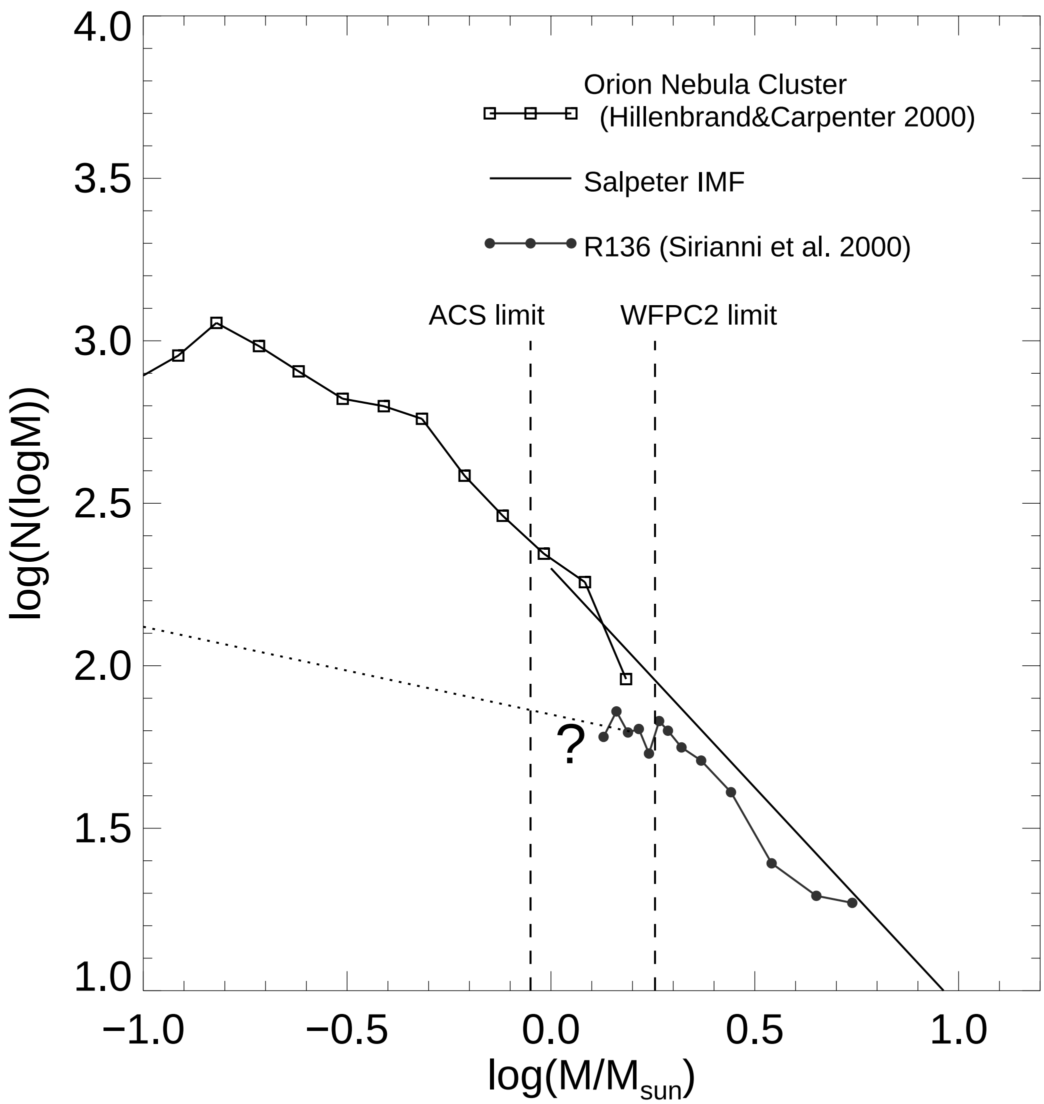


Figure 1: The mass function in the Orion Nebula Cluster (ONC; Hillenbrand & Carpenter 2000) compared to that in R136 (Sirianni et al. 2000). The mass function in the ONC follows a Salpeter IMF down to $\sim 0.5 M_{\odot}$, below which it flattens. By contrast, Sirianni et al. find that the R136 mass function, while consistent with Salpeter at high masses, flattens to a shallow slope of $\Gamma = -0.27$ for $M <\sim 3 M_{\odot}$ and remains flat down to 1.35 $M_{\odot}$, If the shallow mass function continues down to 0.1 $M_{\odot}$ in R136 (dotted line), then *most* of the mass in R136 is contributed by stars with masses $> 3 M_{\odot}$! The dashed vertical lines indicate the WFPC2 (right) and predicted ACS (left) completeness limits for a region located at 5 half-light radii from cluster center (regions A and B of Siranni et al. 2002). The predicted limiting mass (0.9$M_{\odot}$) is consistent with the limit derived by Sirianni et al. for regions A and B. At larger distances from the cluster center, our proposed observations should enable us to reach a limit of $0.6 M_{\odot}$ before the photometric errors begin to dominate.

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Table 1. Crowding limits for ACS/HRC and WFPC2/PC

| Filter | Radius ($\times r_c$) | ACS/HRC 20% photometric error[a] 50% completenss | WFPC2/PC 20% photometric error[a] 50% completeness |
|---|---|---|---|
| $B$ | 1 | $M_B = +1.2$, $m = 2.8 M_\odot$ | $M_B = -2.5$, $m = 7.0 M_\odot$ |
| | 2 | $M_B = +3.0$, $m = 2.4 M_\odot$ | $M_B = +0.2$, $m = 3.4 M_\odot$ |
| | 5 | $M_B = +6.8$, $m = 0.8 M_\odot$ | $M_B = +4.8$, $m = 1.6 M_\odot$ |
| | 7.5 | $M_B = +9.0$, $m = 0.3 M_\odot$ | $M_B = +6.2$, $m = 0.9 M_\odot$ |
| $V$ | 1 | $M_V = +0.2$, $m = 3.6 M_\odot$ | $M_V = -2.2$, $m = 7.0 M_\odot$ |
| | 2 | $M_V = +2.2$, $m = 2.4 M_\odot$ | $M_V = +0.2$, $m = 3.6 M_\odot$ |
| | 5 | $M_V = +5.2$, $m = 0.9 M_\odot$ | $M_V = +3.2$, $m = 2.0 M_\odot$ |
| | 7.5 | $M_V = +7.2$, $m = 0.4 M_\odot$ | $M_V = +5.0$, $m = 1.0 M_\odot$ |

[a]Note that because the errors are highly correlated the photometric error in $B-V$ is actually less than that in either filter; i.e., 10% rather than 20%.

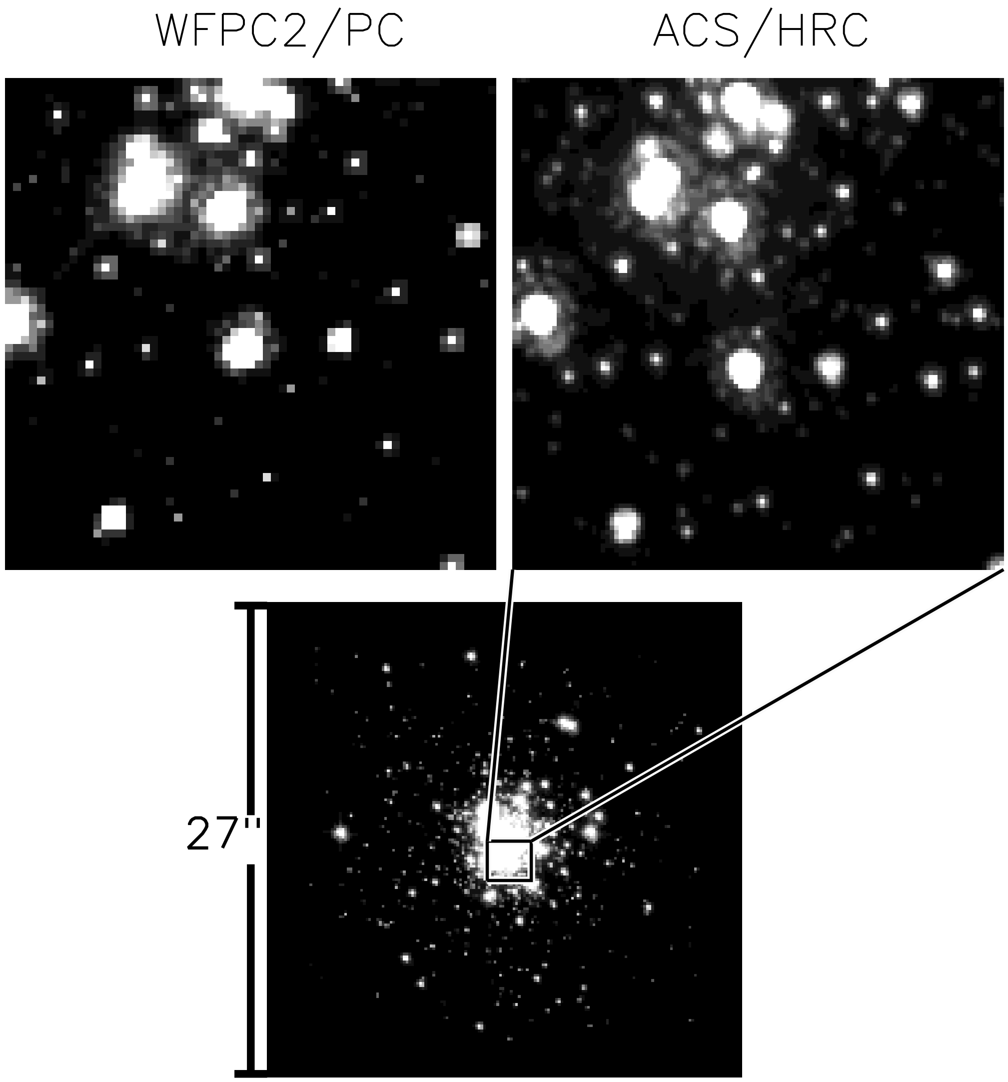


Figure 2: Simulated WFPC2/PC and ACS/HRC F555W images of R136. To simulate the cluster, we randomly selected stars from the ONC mass function (extended to 100 $M_{\odot}$ using a Salpeter IMF slope; Hillenbrand & Carpenter 2000), calculated their $B$ and $V$ magnitudes using a 2 Myr pre-main sequence isochrone (Siess et al. 2000), adjusted the magnitudes assuming an LMC distance modulus of 18.5 and $E(B-V)$=0.38, and distributed them spatially according to the R136 surface brightness profile as derived by Mackey & Gilmore (2003) from archival WFPC2 images. The total luminosity of the simulated cluster is in good agreement with integrated photometry of R136. We then used TinyTim (Krist & Hook 2003) to produce simulated WFPC2/PC and ACS/HRC PSFs, which we convolved with our artificial images. The images were scaled by the exposure times listed in our Description of Observations; finally, we added Poisson noise and read noise appropriate for the proposed number of exposures. The images at top compare the PC and HRC simulated images in a $3 \times 3''$ region in the core of the cluster, demonstrating the advantage of the HRC's smaller pixel size in doing photometry in extremely crowded fields. The relative paucity of resolved fainter stars in the WFPC2 image reflects directly the rapidly declining completeness caused by crowding, as also shown by the H-R diagrams of Fig. 3.

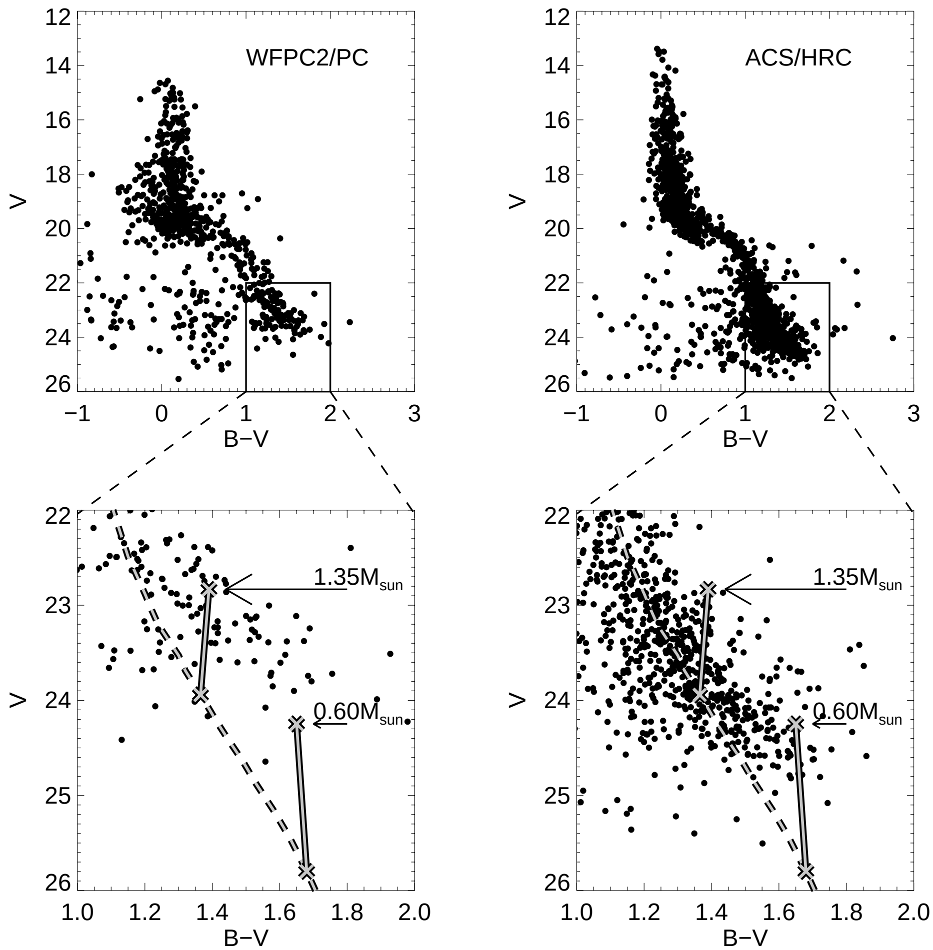


Figure 3: WFPC2/PC and ACS/HRC color-magnitude diagrams derived from the simulated images described in Fig 2. The panels on top show the full CMDs derived from our DAOPHOT/ALLSTAR photometry of the simulated images; our photometric reductions included deriving PSFs from the images themselves. The bottom panels show a blown-up view of the faintest stars measured in the WFPC2/PC and ACS/HRC images. The dashed lines indicate the input isochrone used to generate the simulation. The solid lines with crosses mark the theoretical locations of stars with the masses indicated; the faint ends of each line correspond to an age of 2 Myr, while the bright ends mark stars with ages of 0.5 Myr. The depth of the simulated WFPC2 CMD closely matches the observed CMD of Sirianni et al. (2000), whose claim of detection of 1.35 $M_\odot$ stars derives from stars with ages thought to be 0.5–1 Myr. Our proposed ACS observations will extend the R136 mass function to $0.9 M_\odot$ (50% completness) at 5 half-light radii, and to $\sim 0.6 M_\odot$ in the outer cluster regions where photometric errors will dominate over those due to crowding.

## Description of the Observations

We use the HRC because of its fine pixel sampling, and the good match of its field of view to the size of the cluster. Unfortunately, R136 is only very marginally located in a CVZ, and so we have assumed only a normal visibility period of 58 minutes.

We aim our observations to achieve a S/N of 25 at V=24.8 and B=25.5, which is where crowding produces a 10% photometric error at the surface brightness of 5 cluster core radii. Under many conditions, this would be trivial, but in R136 the issue is compounded by the fact that there are numerous bright massive stars. The brightest of these will saturate in 10 sec at V, and 13 sec at B! After conferring with Ron Gilliland, we've concluded that we can tolerate saturating by a factor of 3 without too much bleeding down columns and into adjacent rows.

We therefore plan to co-add many 30 sec (V) and 40 sec (B) exposures. According to the ACS ETC, each 30-sec V exposure will reach a S/N of 1.7 at V=24.8 when measured through an optimal-sized aperture. Similarly, each 40-sec B exposure will reach a S/N of 1.2. Since the noise is totally dominated by the read-noise, we can compute that in order to achieve a S/N of 25, we will need $(25/1.7)^2 = 216$ V exposures, and $(25/1.2)^2 = 434$ B exposures.

The Primer suggests assuming an overhead of 1 min/exposure for the HRC. This would then require 216 x (1 min + 0.5 min) = 324 minutes for the V-exposures, plus 434 x (1min + 0.67 min)= 725 minutes for the B-band exposures. We actually checked this with the Phase II tool, and found that this estimate was slightly optimistic: the overhead for a single exposure is 40 sec (rather than a minute) but every 16 images the HRC has to dump the data to the recorder; this requires 6 minutes. So, on average each V band exposure will require 103 sec to obtain (rather than 90 sec), and each B-band exposure will require 113 sec (rather than 100 sec). Thus the total time for the exposures (including this overhead) will be 371 minutes ($V$) and 818 minutes ($B$), or a total of 20.4 orbits. Given that we are restricted to a maximum of 5 orbits because of the SAA, and that there will be an additional overhead of 0.5 orbits per 5-orbit visit (6 minutes to acquire the guide star, 2.5 minutes to prepare the ACS, and 5 minutes to reacquire the guide star on each subsequent orbit), the total we need comes to 20.4 + 2.5 = 24.9 orbits, and we are thus asking 25 orbits, to be done in 5 visits.

## Special Requirements

## Coordinated Observations

## Justify Duplications

Although many previous B and V images have been taken with WFPC2, we are here using the finer sampling offered by the ACS/HRC to push down the crowding limits.

## Previous Related HST Programs

Strom has been PI or Co-I on the following HST programs:

- GO-2265+4163 “The Formation and Evolution of Solar Nebulae Surrounding Pre-Main Sequence Stars”. This project resolved the jet emerging from DG Tau on a 10 AU scale, thus placing constraints on the origin of collimated outflows from YSO. Publication:
  - Kepner, J., et al. 1993, ApJ, 415, L119
- GO-5355 “The Binary Frequency Among Solar-type Stars in Young Clusters”. This project compared the binary fraction in NGC2024 and the Trapezium with other nearby star-forming regions and the field. Our results suggest an excess of PMS binaries over main-sequence binaries with the same separations. In addition, we found no evidence that the fraction of binaries formed in relatively dense clusters differs from that characterizing low-density star-forming regions. Publication:
  - Pagett, Strom, & Ghez, 1997, ApJ, 477, 705
- GO-7418 (Padgett, PI) “NICMOS Imaging of Young Stellar Object Circumstellar Nebulosity”. This project was aimed at studying six YSOs in the Taurus star formation regions; the NICMOS photometry established that the NIR emission is dominated by light scattered from dusty circumstellar material distributed in a region 10-15 times the size of the solar system. Publication:
  - Padgett, Brandner, Stapelfeldt, Strom, Terebey, & Koerner 1999, AJ, 117, 1490
- GO-9846 (Meyer, PI) “The Origins of Sub-stellar Masses: Searching for the End of the IMF”. This project studied 6 fields in the star-forming region NGC 1333 with NICMOS. Publication
  - Meyer et al. 2000, in Formation of High Mass Stars in Clusters