Hubble Space Telescope

Cycle 13 GO Proposal

Spectroscopic Binaries in the R136 Cluster: Measuring the Masses of the Highest Mass Stars to Test Stellar Models

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Scientific Category: HOT STARS
Scientific Keywords: ATMOSPHERES AND CHROMOSPHERES, ECLIPSING BINARIES, MAIN SEQUENCE STARS, STELLAR EVOLUTION AND MODELS, MASSIVE STARS

Instruments: STIS
Proprietary Period: 12
Cycle 13 primary orbits: 60

Abstract

The mass-luminosity (M-L) relationship is poorly constrained for high mass stars, yet it serves as the formalism for interpreting all of high-mass star-formation and evolution. Binary massive stars offer the ONLY direct means of firmly determining the upper-end of the M-L relationship, but four criteria must be met: (1) the system must be at a known distance, so that photometry can be converted to absolute visual magnitude, (2) the system must eclipse, so the orbital inclination can be found, (3) the system has to have a sufficiently long period so that the stars are detached, with minimal interaction effects between them, and (4) the stars need a sufficiently large velocity separation so that stellar atmosphere models can be used to determine the effective temperature and hence the conversion from visual to bolometric luminosity. The paucity of high-mass binaries which meet these criteria is well known, with the highest mass binary studied no more than 30Mo until a few years ago. Using HST/STIS we obtained velocities and light-curves for several massive systems in the R136 supercluster, finding the highest mass binary known, with a mass of 57Mo. This is still modest compared to what we expect to find in this rich cluster (M>150Mo), and our STIS imaging revealed that four stars that were even brighter showed the signature of eclipses. From previous FOS spectroscopy we know that all four of these are of spectral type O3, the hottest and most luminous class, and hence the most massive of stars. Here we are proposing to obtain high S/N blue and H-alpha spectra (as well as white-light imaging) in order to determine orbit solutions for these newly found interesting systems. In addition we will be able to model both these and R136-038 (the 57Mo record holder) and compare the Keplerian masses with those inferred from the stellar atmosphere models (M~gR^2) and stellar evolutionary models (from L and Teff). The crowding of the R136 supercluster, which contains hundreds of stars in the central few arcseconds, requires the superb spatial resolution of HST/STIS to isolate stars on the slit.

Investigators:

	Investigator	Institution	Country
PI	Dr. Philip Massey	Lowell Observatory	USA/AZ
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CoI	Dr. Kathleen Eastwood	Northern Arizona University	USA/AZ
CoI*	Dr. Artemio Herrero	Instituto de Astrofisica de Canarias	Spain
CoI*	Dr. Ignasi Ribas	Universidad de Barcelona	Spain

Number of investigators: 5

* ESA investigators: 2

Target Summary:

Target	RA	Dec	Magnitude
R136-007	05 39 0.00	-69 06 0.00	V = 13.0 +/- 0.1, E(B-V)=0.38
R136-015	05 39 0.00	-69 06 0.00	V = 13.6 +/- 0.1, E(B-V)=0.38
R136-024	05 39 0.00	-69 06 0.00	V = 14.1 +/- 0.1, E(B-V)=0.38
R136-025	05 39 0.00	-69 06 0.00	V = 14.1 +/- 0.1, E(B-V)=0.38
R136-038	05 39 0.00	-69 06 0.00	V = 14.6 +/- 0.1, E(B-V)=0.38

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
R136-007	STIS/CCD Imaging 50CCD STIS/CCD Spectroscopic G430M (4451) STIS/CCD Spectroscopic G750M (6581)	DUP	60 (4x15)
R136-015	STIS/CCD Imaging 50CCD STIS/CCD Spectroscopic G430M (4451) STIS/CCD Spectroscopic G750M (6581)	DUP	0
R136-024	STIS/CCD Imaging 50CCD STIS/CCD Spectroscopic G430M (4451) STIS/CCD Spectroscopic G750M (6581)	DUP	0

Target	Config Mode and Spectral Elements	Flags	Orbits
R136-025	STIS/CCD Imaging 50CCD	DUP	0
	STIS/CCD Spectroscopic G430M (4451)		
	STIS/CCD Spectroscopic G750M (6581)		
R136-038	STIS/CCD Imaging 50CCD	DUP	0
	STIS/CCD Spectroscopic G430M (4451)		
	STIS/CCD Spectroscopic G750M (6581)		
		Total orbit request:	60

■ Scientific Justification

The mass of a star is its most important property. Although the chemical composition and angular momentum can play significant secondary roles in determining the evolution of a star (particularly of a massive star), it is the star's mass which determines the rate at which nuclear reactions occur in the core, and thus determines the course of its life's journey through the H-R diagram.

For the highest mass stars, we expect the mass-luminosity relationship to be much flatter than the $L \propto M^4$ law that characterizes solar-type stars: for high-mass stars the primary opacity source becomes scattering from free electrons, as higher interior temperatures result in more complete ionization, and simple arguments lead us to expect a mass-luminosity relation with $L \propto M$ (Shu 1982). In practice, modern evolutionary models (e.g., Schaller et al. 1992 and subsequent papers from Maeder's group) yield $L \propto M^2$ for zero-age-main-sequence (ZAMS) stars in the mass range $25-120\mathcal{M}_\odot$. But, these interior models are characterized by many uncertainties and physical simplifications (Maeder & Conti 1994), and the details, such as whether or not convective overshooting is included, matter considerably. It is only now, for example, that the effects of stellar rotation are being included in such models, with significant results (Langer 1998, Maeder & Meynet 2000).

Yet, we rely on these models for interpreting much of the astrophysics related to hot, massive stars, such as the relative number of Wolf-Rayet stars and O-type stars in differing environments (Massey, Johnson, & DeGioia-Eastwood 1995, Massey & Johnson 1998), or the turn-off masses and ages in young clusters (Massey, Waterhouse, & DeGioia-Eastwood 2000). Furthermore, the need for accurate models extends even beyond stellar evolution: the masses that these models predict (as a function of position in the HR diagram) are also the basis for determining the initial mass function and upper mass "cut-offs", which are the fundamental parameters of our understanding of massive-star star formation (see review in Massey 2003).

How good are these stellar evolutionary models? Herrero et al. (1992) noted a significant "mass discrepancy" for masses determined from the evolutionary models compared to those determined using *stellar atmosphere* models. The stellar atmosphere models yield values of stellar effective temperature, ($T_{\rm eff}$), surface gravity (g), radius (R), and luminosity (L), and the so-called "spectroscopic mass" can be inferred from $M = g/g_\odot \times R^2$. These masses can then be compared by taking the model atmosphere's determination of $T_{\rm eff}$ and L, and comparing that to the mass needed by the stellar evolutionary models at that point in the H-R diagram. Early comparisons were quite scary, with the stellar evolutionary models predicting a factor of 2 higher masses than the spectroscopic mass. Improvements in the atmosphere models (the inclusion of sphericity, improved line-blanketing) have reduced, but not eliminated, this mass discrepancy (Herrero 2002; Herrero et al. 2002; Repolust, Puls, & Herrero 2003).

What is really needed is an empirical check on the mass-luminosity relationship for high-mass stars, and this comes about simply from binary orbit solutions if some criteria are met: (a) the system has to be eclipsing, so the orbital inclination can be determined, (b) the distance of the system has to be accurately known, (c) the stars have have a sufficiently long period (> 3 days in the case of a massive star) so that mass-transfer is unlikely to have played a role, and (d) the stars need a sufficiently large velocity separation so that stellar atmosphere models can be used to determine $T_{\rm eff}$ and hence the bolometric correction.

In the mid-1990s we and others had pushed the limits as far as they could be pushed using new data on a variety of known systems (Burkholder, Massey, & Morrell 1997; Penny, Gies, & Bagnulolo 1999). Nevertheless, the highest mass star for which there was a satisfactory orbit was still only $30\mathcal{M}_\odot$. A break through came when Massey & Hunter (1998) obtained FOS spectroscopy of stars in the R136 "supercluster" in the LMC in Cycle 6. They found that the cluster contained more stars of O3-type (the hottest, and presumably the most massive and luminous) than known everywhere else, and that in addition, four of these early-type stars showed the double absorption lines that indicated that they were binaries (Massey & Hunter 1998). A Cycle 8 followup with STIS obtained photometry and spectroscopy of these four systems.

One of these stars, R136-038, consists of an O3 V + O6 V pair with a 3.4 day period, and a nice eclipse (Fig. 1). The derived orbital mass of the primary is $57\mathcal{M}_\odot$, making this the highest mass binary known (Massey, Penny, & Vukovich 2002). Comparison of the Keplerian masses with those predicted by stellar evolutionary models, however was hindered by our inability to model the stars based on our spectra. Not being sure what we would find (eclipses were confirmed only during the course of the observations), we had planned our spectroscopy to reach only the modest S/N needed in order to measure radial velocities, rather than the much higher quality needed for modeling efforts, particularly the detection of the critical He I $\lambda4471$ line, which is quite weak in O3 stars. Even co-adding all of our spectra (after making appropriate velocity shifts) failed to reach the S/N needed to detect this weak line. Nor did we observe the region around Hα, also needed for the modeling efforts. As a result, we were only able to adopt some approximate $T_{\rm eff}$ (and hence an even more approximate conversion from absolute visual magnitude to bolometric luminosity) based upon the star's spectral type. For stars of the O3 class, this is particularly problematic, given that the class is degenerate, as all stars with He I $\lambda4471$ weaker than 150mÅ are lumped together. The masses we derived from the orbits are fairly consistent with the masses of the evolutionary tracks (Fig. 2), but note the stars' locations slightly to the left of the beginning of the tracks (i.e., younger than the ZAMs). Either this is due to binary evolution—tidal forces or some such—or it's an indication of how approximate our assumptions were. In addition, the fact that we couldn't model the star meant we had no means of testing the stellar atmosphere "spectroscopic mass" ($M \sim gR^2$) with the right (Keplerian) answer. So, although our discovery was treated with much fanfare, and made it into the popular press as the "highest mass binary yet found", the truth was that the astrophysical questions we would most have liked to have answered weren't, as we had been reluctant to propose to obtain high S/N spectra before establishing that we could detect the presence of eclipses, and we were just lucky that three of the four systems showed them.

However, nature has provided us an even better opportunity. The STIS images of R136 we obtained in Cycle 8 revealed not only eclipses for the stars we were observing spectroscopically, but also for four additional stars (Fig. 3). We *know* that these four must be binaries; one of them (R136-024) even shows incipiently-resolved double lines in our single-epoch FOS spectrum (Massey et al. 2004). Furthermore, all four of these are brighter and more luminous than R136-038, the high mass record-holder. All have "composite" O3If* or O3 III spectral types; the lack of obvious He I in the *combined* spectrum means that the individual components must *both* be of spectral type O3, and hence even more massive than R136-038. *These four systems cry out for the additional spectroscopy and photometry that will permit orbit solutions in order to determine Keplerian masses.*

We will observe R136 during 15 carefully spaced visits of 4 orbits each. For the purposes of *just* the orbit solutions, we need only limited S/N (~ 50) exposures in the blue. Yet, here we propose to obtain the higher S/N (~ 90 per visit, > 150 when all the double-lined phases are shifted and co-added) needed for modeling. This requires exposure times that are nearly twice as great, and in addition, we are also planning to obtain Hα observations during each visit. Why not wait until we have orbit solutions, and then propose for the higher S/N data at specific phases in later Cycles? After all, about one-third to one-half of these visits will be at single-line phases, when even tomographic techniques cannot resolve the components, and hence some of the "extra" exposure time needed for the high S/N, and the Hα exposures, will be wasted. We've considered this carefully, and concluded this would be a false economy. In order to determine the best orbital elements (and particularly the most accurate masses) in a very limited number of visits (15), we are using a very clever timing technique developed by Abi Saha, as described under "Special Requirements". The proof of this technique comes in our previous R136 studies: with only 15 visits we were able to determine the masses of our stars to a much greater accuracy than typically achieved for massive binaries (see review by Gies 2003), despite the fact that most studies use many more epochs. To do this, we make use of the fact that the error in the masses go linearly with the error in the period; thus for a 1% mass determination we only need to determine a 5-day period to an accuracy of 0.05 days. Over a period of a year, though (75 orbits), this uncertainty would amount to 3.7 days—more than half a period—and we would have no idea when to reobserve to obtain only double-phase data. We could alternatively obtain very accurate periods, but this would require many more than 15 visits. Typical ground-based observations use perhaps 50 epochs to nail down an orbit. (See, for instance, Gies et al. 2002, who determined the period of HD115071 to 0.001% but required 75 observations, some from the plate-vaults, that had been obtained over 46 years.) So, we are convinced that our plan is the most efficient way of achieving our astrophysical goal.

We therefore propose a program to obtain radial velocity data *and* modeling data on the four new eclipsing systems plus R136-038. As with our previous studies of R136, these data can *only* be done with the high spatial resolution of HST/STIS, given the extreme crowding, as hundreds of stars exist within a region of a few arcseconds. Massey et al. (2004)'s recent UV spectroscopy has resulted in good determinations of the stellar-wind terminal velocities (needed for the modeling) for a large number of single O3 stars in R136, and we will make use of their average value in our study, as we would never be able to resolve the two components in the broad P Cygni lines of our stars. With our new data we will be able to determine both the evolutionary mass and stellar-atmosphere "spectroscopic mass", and compare these to the "true" mass—that determined from simple Newtonian mechanics. Given the presence of eclipses and the early spectral types, we know we will emerge from this with solid determinations of the masses of the highest mass stars known.

References

Burkholder, V., Massey, P., & Morrell, N. 1997, ApJ, 490, 328

Gies, D. R. 2003, in A Massive Star Odyssey, from Main Sequence to Supernova, IAU 212, p. 91

Gies, D. R., Penny, L. R., Mayer, P., Drechsel, H., & Lorenz, R. 2002, ApJ, 575, 1050

Herrero, A. 2002, in A Massive Star Odyssey, from Main Sequence to Supernova, IAU 212, p. 3

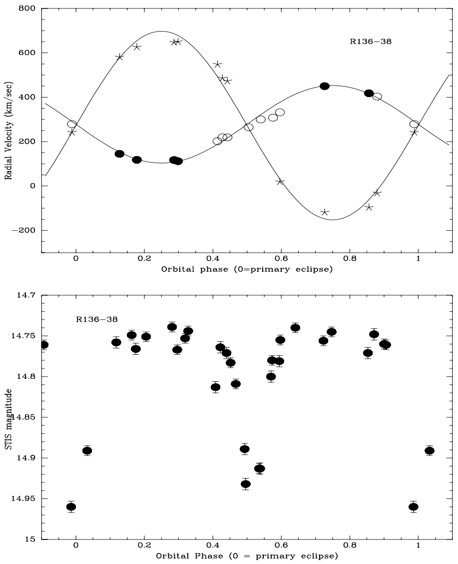

Figure 1: The highest mass binary known consists of an O3 V+O6 V pair, with masses of $56.9 \pm 0.6\ \mathcal{M}_\odot$ and $23.4 \pm 0.2\mathcal{M}_\odot$. Our Cycle 8 observations obtained the radial velocity curve at the top, where solid points show the motion of the primary, and asterisks show the motion of the secondary; the open circles are single-lined phases, not used in the determination of the orbit, but which follow the primary. Below is the light-curve, also obtained with STIS, which sets the orbital inclination to 80.5°. From Massey et al. (2002).

Herrero, A., Kudritzki, R. P., Vilchez, J. M., Kunze, D., Butler, K., & Haser, S. 1992, A&A, 261, 209

Herrero, A., Puls, J., & Najarro, F. 2002, A&A, 396, 949

Langer, N. 1998, A&A, 329, 551

Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227

Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143

Massey, P. 2003, ARA&A 41, 15

Massey, Bresolin, F., Kudritzki, R. P., Puls, J., & Pauldrach, A. W. A. 2004, ApJ, submitted (ftp://ftp.lowell.edu/pub/massey/haw.ps)

Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180

Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995, ApJ, 454,151

Massey, P., & Johnson, O. 1998, ApJ, 505, 793

Massey, P., Penny, L. R., & Vukovich, J. 2002, ApJ, 565, 982

Massey, P., Waterhouse, E., & DeGioia-Eastwood 2000, AJ, 119, 2214

Penny, L. R., Gies, D. R., & Bagnulolo, W. G. 1999, in The Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies, IAU 193, p. 86

Repolust, T, Puls, J., & Herrero, A. 2003, A&A, in press (http://www.usm.uni-muenchen.de/people/puls/papers/Ostars.pdf)

Schaller, G, Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Shu, F. H. 1982, *The Physical Universe* (Mill Valley: Univ Science Books), p. 146

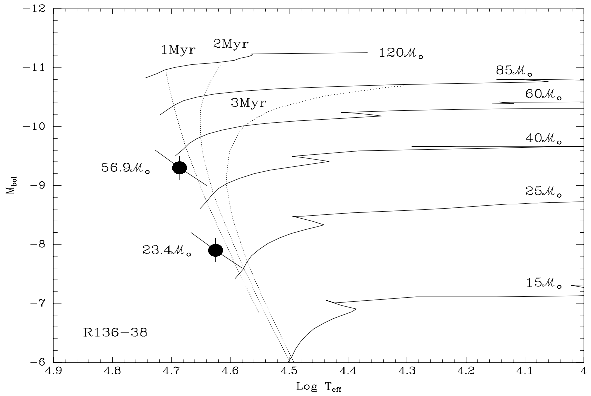

Figure 2: The locations of the R136-038 components in the H-R diagram are shown. Error bars denote the change in location due to a 5% error in the effective temperature scale, and due to uncertainties in the magnitude difference in the two components. The evolutionary tracks (solid lines) are for $z = 0.008$ and come from Schaerer et al. (1993). The dotted lines are isochrones for 1, 2, and 3 Myr, computed from the same models. Note that the stars fall somewhat to the left of the beginning of the tacks (zero age main sequence), possibly due to errors in the assigned effective temperatures (Massey et al. 2002).

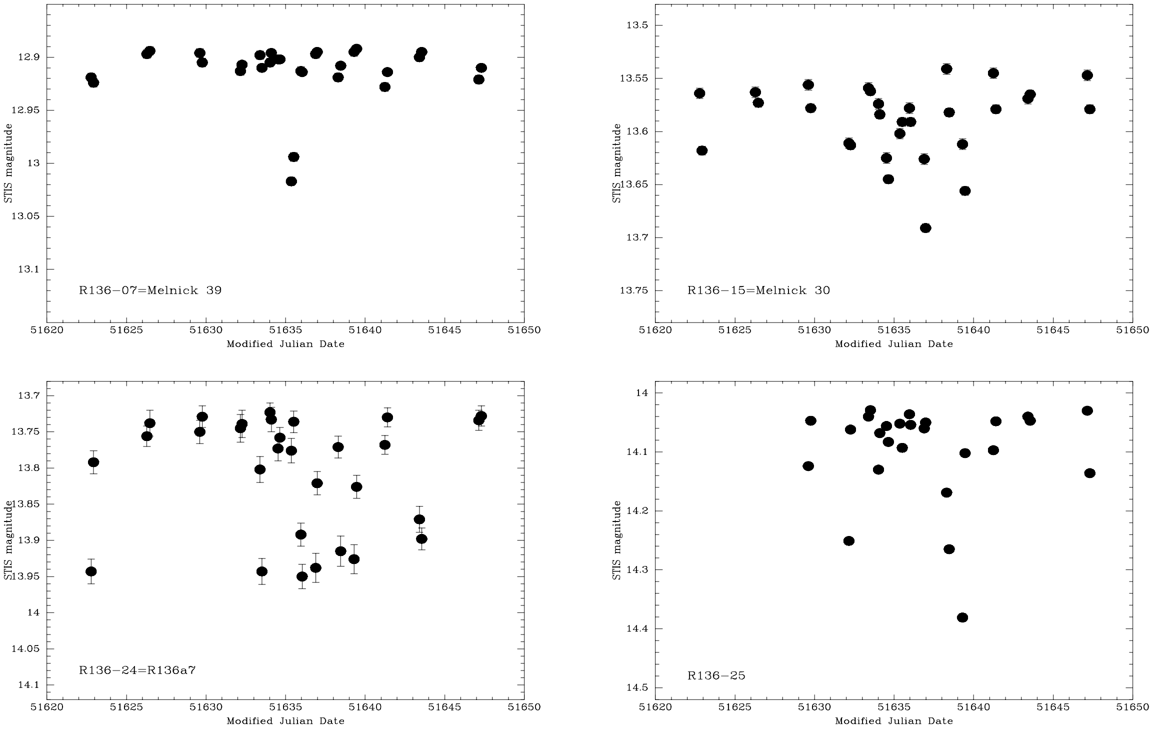

Figure 3: Photometry of our Cycle 8 STIS images revealed 5 new light variables, 4 of which show variations typical of eclipses. The periods could not be uniquely determined from these photometric data, and hence the photometry is shown unphased. The light variability is seen primarily in the middle of the time range, as it is then that the observations were most closely spaced, and hence most likely to show eclipses. Spectroscopy is needed to produce orbit solutions (Massey et al. 2002).

Description of the Observations

R136 lies in a CVZ but because of our timing requirements (see the next section) we cannot take advantage of this. Instead, we will use the standard visibility period of 58 minutes.

Our observing strategy is similar to what we successfully employed in our Cycle 8 observations (Massey, Penny, Vukovich 2002 ApJ, 565, 982). Each of our 15 visits will require 4 orbits each. We will begin each visit by taking a short pair (1sec+1sec) of STIS images of the entire cluster with the LP filter for photometry. We will then acquire our first spectroscopy target, which is sufficiently well separated from the rest of the cluster to be acquired directly using standard STIS/ACQ; this star will then also serve as our offset for the other five targets. (All of these stars are within an arcminute of each other.) We will then take spectra of all five stars using the G430M grating centered at 4451Å (to include Hγ, He I $\lambda 4471$, and He II $\lambda 4542$), with "small angle maneuvers" (SAMs) to offset from one target to the next. The S/N of these blue observations needs to be high (90), requiring us to dither along the slit to 3 positions. Note that although we typically need S/N of 120 to successfully model stars with such weak He I $\lambda 4471$, we will co-add all of the double-lined phases after appropriate velocity shifts, so our final spectra will have considerably higher S/N.) We will then switch to the G750M grating and repeat the procedure, this time aiming for a more modest S/N of 50 in order to determine the mass-loss rates from the Hα profile; dithering will not be needed, but we will do a CR-SPLIT=2. The visit will end with another pair of STIS images of the entire cluster. (The STIS images before and after are required in order to obtain complete light-curves.)

1. Guide star acquisition (beginning of 1st orbit): 6 minutes
2. STIS image of cluster: (few seconds)
3. STIS overhead for imaging: 5 minutes
4. STIS/ACQ of offset star: 6 minutes
5. SAM to R136-007: 0.5 minute
6. STIS overhead for first G430M exposure: 5 minutes
7. Exposure time G430M R136-007 (total of 3 positions): 10 minutes
8. STIS overhead for 2 additional exposures R136-007: 2 minutes
9. SAM overhead for dithering along slit R136-007: 1 min
10. SAM to R136-015: 0.5 minutes
11. Exposure time G430M R136-015: 29 minutes (ends in 2nd orbit)
12. Guide star re-acquisition: (beginning of 2nd orbit) 5 minutes
13. STIS overhead for 3 exposures R136-015: 3 minutes
14. SAM overhead for dithering along slit R136-015: 1 min
15. SAM to R136-024: 0.5 minute
16. Exposure time G430M R136-024: 16 minutes
17. STIS overhead for 3 exposures R136-024: 3 minutes
18. SAM overhead for dithering along slit R136-024: 1 min
19. SAM to R136-025: 0.5 min
20. Exposure time G430M R136-025: 25 minutes
21. GS re-acquire (beginning of 3rd orbit): 5 minutes

22. STIS overhead for 3 exposures R136-025: 3 minutes
23. SAM overhead for dithering along slit R136-025: 1 min
24. SAM overhead offset to R136-038: 0.5 min
25. Exposure time G430M R136-038: 40 min
26. STIS overhead for 3 exposures R136-038: 3 minutes
27. SAM overhead for dithering along slit R136-038: 1 min
28. Guide star re-acquisition: (beginning of 4th orbit): 5 min
29. STIS overhead for first exposure of G750M grating: 5 minutes
30. Exposure time G750M for R136-038: 10 min
31. STIS overhead for second exposure of G750M R136-038: 1 minute
32. SAM to offset to R136-025: 0.5min
33. Exposure time G750M R136-025: 7 min
34. STIS overhead for two G750M R136-025 exposures: 2 minutes
35. SAM to offset to R136-024: 0.5 min
36. Exposure time G750M R136-024: 7 min
37. STIS overhead for two G750M R136-024 exposures: 2 minutes
38. SAM to offset to R136-015: 0.5 min
39. Exposure time G750M R136-015: 4 min
40. STIS overhead for two G650M R136-015 exposures: 2 minutes
41. SAM to offset to R136-007: 0.5 minutes
42. Exposure time G750M R136-007: 3 minutes
43. STIS overhead for two R136-007 exposures: 2 minutes
44. STIS image: (few seconds)
45. STIS overhead for imaging: 5 minutes
46. End of 4th orbit and END of VISIT

Special Requirements

Timing is critical not only in comedy (Penn & Teller 1997, *How to Play in Traffic*, p. 103), but also in determining orbit solutions when the periods are not know a priori. We plan to use the same procedure as we did in our successful Cycle 8 proposal, and separate our visits by intervals determined by a geometrical series. This scheme was originally developed by Abi Saha for observing Cepheids as part of the distance scale key project. As in Cycle 8, we'll ask for intervals of 0.5×1.175^n (days), where n=1,14 (Massey, Penny, Vukovich 2002, ApJ, 565, 982). Simulations show this provides uniformly good phase coverage for periods from 1 to 30 days (Fig. 4). The longest gap between successive visits will be 3.7 days and the shortest 0.5 days, and will span an observing "season" of 24 days. We will put our shortest intervals in the middle and the longer intervals towards either end for optimal performance. Scheduling this proved straight-forward in Cycle 8, as some slop (0.2 days) between when we would like to be scheduled, and when we can actually be scheduled, makes little difference, as shown below.

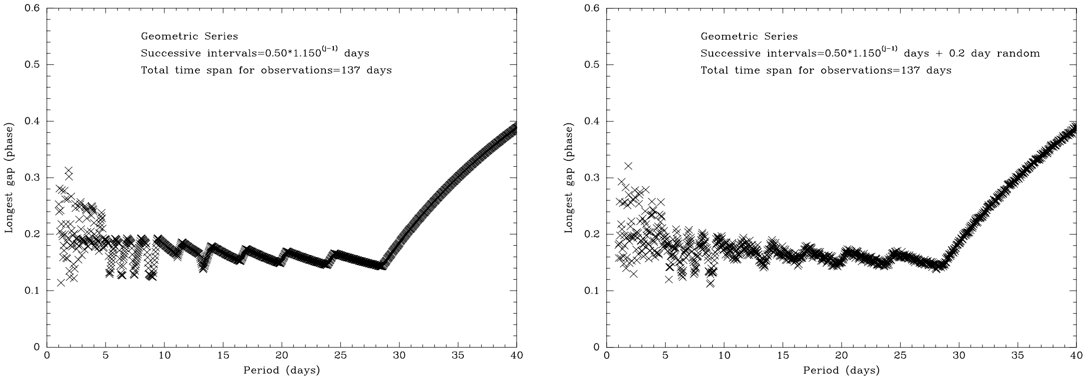

Figure 4: Our simulations demonstrate that we obtain good phase coverage for all periods from 1 to 30 days when we time the intervals using our geometrical series. The plot on the right shows that a random slop of 0.2 days in our scheduling makes little difference on the resulting phase coverage.

Coordinated Observations

Justify Duplications

Orbit solutions require repeated observations.

Previous Related HST Programs

Massey has been PI or CoI on the following *HST* proposals:

- **"Stellar Winds in M31, M33 and NGC6822":** GO-1150 (Cycle 1, Hutchings PI), GO-2581 (Cycle 1, Bianchi PI), GO-3954 (Cycle 2, Hutchings, PI), GO-5179 (Cycle 4, Hutchings, PI), GO-5494 (cycle 5, Bianchi, PI), GO-6567 (cycle 6, Bianchi, PI). These were early attempts to use *HST* (both with GHRS and FOS) to obtain UV spectra of hot stars in M31 and M33 (and subsequently NGC 6822). The data and analysis were published in the following papers (excluding meeting abstracts):
    - Hutchings, Bianchi, Lamers, Massey, & Morris 1992 ,"Hubble Space Telescope Spectroscopy of OB Stars in M31", ApJ, 400, 35
    - Bianchi, Lamers, Hutchings, Massey, Kudritzki, Herrero, & Lennon 1994, "Ultraviolet and Optical Spectroscopy of a B Supergiant Star in M31", A&A, 292 , 213
    - Haser, Lennon, Kudritzki, Puls, Pauldrach, Bianchi, & Hutchings 1995, "The Stellar Wind of an O8.5 I(f) Star in M31", A&A, 295, 136
    - Bianchi, Hutchings, & Massey 1996, "The Winds of Hot Stars in External Galaxies. III. UV Spectroscopy of O and B Supergiants in M31 and M33", AJ, 111, 2303

  - Bianchi, Clayton, Bohlin, Hutchings, Massey 1996, “Ultraviolet Extinction by Interstellar Dust in External Galaxies: M31”, ApJ, 471, 203
  - Bianchi, Scuderi, Massey, & Romaniello 2001, “The Massive Star Content of NGC 6822: Ground-Based and Hubble Space Telescope Photometry”, AJ, 121, 2020

- **“The Evolution of Massive Stars: Closing the Loop Observationally...”:** GO-5998 (Cycle 5, PI Massey), GO-7464 (Cycle 7, PI Massey). These two projects were intended to complement on-going ground-based studies of coeval regions in M31 and M33. In GO-5998 I obtained WFPC2 images of selected OB associations in these two galaxies in order to see establish whether particular high luminosity stars were single or simply blends undetected from the ground; the data were then used to improve the ground-based photometry. These data were then used to select stars for further spectroscopic observations , with the MMT and KPNO 4-m telescopes. A STIS/CCD proposal was then awarded time (GO-7464) in order to obtain spectra of the stars that had proven too difficult (crowded) to do from the ground. The ground-based spectroscopic part of the program was delayed while the MMT underwent its conversion to 6.5-m, and the subsequent commissioning pains. Now that the telescope is functional I hope to have the total project completed next year. The data have been partially published in:

  - Massey, Bianchi, Hutchings, & Stecher 1996, “The UV-brightest Stars of M33 and Its Nucleus: Discovery, Photometry, and Optical Spectroscopy”, ApJ, 469, 629
  - Massey, Armandroff, Pyke, Patel, & Wilson 1995, “Hot Luminous Stars in Selected Regions of NGC 6822, M31, and M33”, AJ, 110, 2715
  - Massey 1998, “Observations of the Most Luminous Stars in Local Group Galaxies”, in Stellar Astrophysics for the Local Group, ed. A. Aparicio, A. Herrero, and F. Sanchez (invited series of lectures), 95

- **“Star Formation in the Prototype Super Star Cluster R136”:** GO-6417 (Cycle 6, PI Massey). This was the first study to obtain spectra of a significant number of stars in the R136 cluster in the LMC, demonstrating that the IMF was Salpeter, and that whatever the mass is of the highest mass star, we have yet to encounter it in nature. Publications included:

  - Massey & Hunter 1998, “Star Formation in R136: A Cluster of O3 Stars Revealed by Hubble Space Telescope Spectroscopy”, ApJ, 493, 180
  - Massey & Hunter 1998, “R136: A Cluster of O3 Stars” (invited talk), in Boulder-Munich II: Properties of Hot, Luminous Stars, ed. Howarth (ASP), 355
  - Massey 1998 “The Initial Mass Function of Massive Stars in the Local Group” (invited review), in The Stellar Initial Mass Function, 38th HerstmonceuxConf., ed. Gilmore & Howell (ASP), 17
  - Hunter 1999 “The Stellar Population of R136” (invited talk), in New Views of the Magellanic Clouds, IAU Symp. 190, ed. Suntzeff, Hesser, & Bohlender (ASP), p. 217

  - Walborn et al. 2002 “A New Spectral Classification System for the Earliest O Stars: Definition of Type O2”, AJ, 123, 2754
  - The resulting papers generated a great deal of public interest: Our work was featured on the Univ. of Texas’ STARDATE radio program broadcast March 13, 1998, was included in Astronomy Magazine’s June 1998 “Astronews”, and appears in the January 1998 Sky and Telescope (“Hubble Spies Supermassive Stars”)

- **“Tests of Stellar Models Using Four Extremely Massive Spectroscopic Binaries in the R136 Cluster”:** GO-8217 (Cycle 8, PI Massey). We had previously (GO-6417) discovered four extremely early-type stars in the R136 cluster that showed double absorption lines, suggesting that they were spectroscopic binaries. In this program I went after them with STIS/CCD in order to obtain radial velocities and light-curves to produce orbits and Keplerian masses to compare these to evolutionary models. We discovered the highest mass binary yet known (57 $\mathcal{M}_\odot$), and established excellent agreement with the evolutionarymodels. We also discovered four eclipsing light-variables in this cluster, which form the basis of the present proposal. The study was published in:
  - Massey, Penny, & Vukovich 2002, “Orbits of Four Very Massive Binaries in the R136 Cluster”, ApJ, 565, 982
  - In addition, a press release invited by the AAS for the Jan 2001 meeting resulted in a very nice popular article in the the June 2002 Sky and Telescope (News Notes).

- **The Physical Parameters of the Hottest, Most Luminous Stars:** GO-7739 (GO-6417 “carryover” time in Cycle 7, PI Massey), GO-8633 (Cycle 9 snap, PI Massey), and GO-9412 (Cycle 11, PI Massey). We are using STIS/FUV-MAMA data to obtain data on stellar winds in the hottest and most massive stars in the Magellanic Clouds, combining this with high S/N, high resolution optical data obtained at CTIO. Our “snap” program in Cycle 9 had a very poor completion rate, and so the Cycle 11 TAC kindly assigned us sufficient time to complete the project. The “carryover” Cycle 7 time (from our Cycle 6 R136 program) obtained high S/N optical data on R136 stars, which are being combined with this for two papers. The first of these has now been submitted:
  - Massey, Bresolin, Kudritzki, Puls, & Pauldrach 2004, “The Physical Parameters and Effective Temperature Scale of O-type Stars as a Function of Metallicity. I. A Sample of 20 stars in the Magellanic Clouds”, ApJ, submitted. (http://www.lowell.edu/users/massey/pub/haw.ps)

- **“The Mass-Luminosity Relationship for High Mass Stars”:** GO-9097 (Cycle 10, PI Massey). We examined about a dozen “nearby” O-type stars (out to 2 kpc) with the FGS looking for previously unresolved binaries that would be suitable for long-term monitoring with HST/FGS to determine orbits. We’ve found several, and are submitting a proposal for the current cycle.

- **“The Physical Parameters and Stellar Winds of Hot, Massive Stars at High Metallicity: O-stars in the Andromeda Galaxy”:** GO-9794 (Cycle 12, PI Massey). The data for this Cycle 12 program are still being taken.
- **“A He-rich O2-3 Star in the LMC: Freakish Relic or Paradigm Shifter”:** GO-9795 (Cycle 12, PI Massey). This Cycle 12 program obtained a UV spectrum of an interesting He-rich O3-3 star we discovered in the LMC. We have just been granted time on the DuPont telescope in December 2004, and will obtain optical radial velocity before publishing.