NOAO Observing Proposal *Longterm proposal* **Panel:** *For office use.*
Date: March 29, 2005 **Category:** Massive Stars

Taking Things to the Extreme: Using High Mass Stars to Resolve the Mass Discrepancy

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:

The mass of a star is arguably its most fundamental property, and yet for high-mass stars there is a long-standing systematic difference between the masses determined from stellar evolutionary models, and those found from stellar atmosphere models. For the hottest stars, this mass discrepancy may amount to a factor of two or more. This proposal seeks to resolve this discrepancy by using high-mass binaries. This will allow the Co-Is to make critical comparisons between the masses determined by these two indirect methods with those found from simple Newtonian physics using the orbit solutions. More than simply identifying which approach gives the right answer, the results of this study will provide needed guidance to our theoretician colleagues both to know in what areas the models are reliable, and in what areas further improvement is needed. The approach will be to identify eclipsing binary systems photometrically in the first year, using frequent imaging of OB associations and clusters known to contain a wealth of high-mass stars, both in the Milky Way and in the Magellanic Clouds. This is the goal of the present proposal. Once these systems are identified, we will obtain radial velocities for orbits, and the high S/N data needed for stellar atmosphere modeling, using the facilities of Las Campanas. The observational program outlined here is ambitious, but all of the pieces are in place; the critical first step is to identify eclipsing systems, which can be readily accomplished with the 1.3-m synoptic queue.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-1.3m	ANDI + CCDIR	5	bright	Aug - Jan	Aug - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

N/A—observations are to be done in queue service mode.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Arguably the mass of a star is its most important property. According to the classic Russell-Vogt theorem, it is the mass, along with the chemical composition, that should determine all of the other properties of a star as a function of time. (Today we also recognize that the angular momentum at birth also has a significant influence on subsequent evolution, particularly for high-mass stars; see Maeder & Meynet 2000.) Here we propose to extend our knowledge of the mass-luminosity relationship to stars of the highest masses, and resolve once and for all a long-standing disagreement between the masses found from stellar evolutionary models and those from stellar atmosphere codes. For massive, luminous stars, the ability to deduce reliably the mass from other properties is doubly important: it provides a critical check on stellar evolutionary theory, as well as providing the means for studying star formation processes both in the Milky Way and in neighboring galaxies, where the initial mass function is measured either via luminosity functions or by direct comparison with evolutionary tracks in an H-R diagram (see Massey 1998, 2003 for recent reviews). The high end of the initial mass function is also used routinely to calculate star formation rates in external galaxies (DeGioia-Eastwood et al. 1984, and many others).

However, the analysis of the spectra of O-type stars using modern stellar atmospheres yield masses that can be a factor of two or more smaller than that found by stellar evolutionary models (Fig. 1). The spectroscopic mass (Kudritzki & Hummer 1990) is derived simply from the surface gravity and stellar radius of the star, i.e., $M_{\rm spect}/M_\odot = (g/g_\odot) \times (R/R_\odot)^2$. The surface gravity g is found primarily by fitting the Balmer profiles in the optical, a method which is quite sensitive. If the star's distance and reddening are known, the absolute magnitude and bolometric luminosity can be calculated, yielding the stellar radius R. This mass discrepancy was first noted by Herrero et al. (1992), and has been the subject of much argument and debate during the past decade.

We propose here to resolve this discrepancy by directly measuring the masses of a sample of binary O stars, and computing both their evolutionary and spectroscopic masses. Analysis of eclipsing double-lined spectroscopic binaries will yield masses directly from Newton's laws. If the periods are sufficiently long (in general, greater than 3 to 5 days) then the stars will not have interacted, and the orbits will tell us whether the spectroscopic or evolutionary masses are correct.

Why has this not been done already? This approach has certainly been tried by a number of us (Burkholder, Massey, & Morrell 1997; Penny, Gies, & Bagnuolo 1999; Massey, Penny, & Vukovich 2002; Penny et al. 2003) with varying degrees of success. The fundamental problem has been the scarcity of suitable systems. Massive stars are rare, and the higher the mass, the rarer the star. In order to yield lower limits on the masses, a system has to be comprised of two stars with similar luminosity in order for the radial velocities of both stars to be measurable. (Most known early-type binaries meet this criterion, although this may be a selection effect; see Garmany, Conti, & Massey 1980 and Mason et al. 1998.) To yield actual values for the masses – rather than just the minimum masses – the system needs to be eclipsing in order to determine the orbital inclination.

Thus our approach is to first identify eclipsing binaries by photometrically monitoring OB associations known to be rich in massive stars. We will follow this up in subsequent years by spectroscopy of these systems. When we are done we will be able to make critical comparisons between the masses determined by the two indirect methods (stellar atmosphere modeling and stellar evolutionary theory) with those found from simple Newtonian physics. More than simply identifying which approach gives the "right" answer, the results of this study will provide needed guidance to our theoretician colleagues, both in order to know in what areas the models are reliable, and in what areas further improvements are needed. The observational program outlined here is ambitious, but all of the pieces are in place; the critical first step is to identify suitable eclipsing systems.

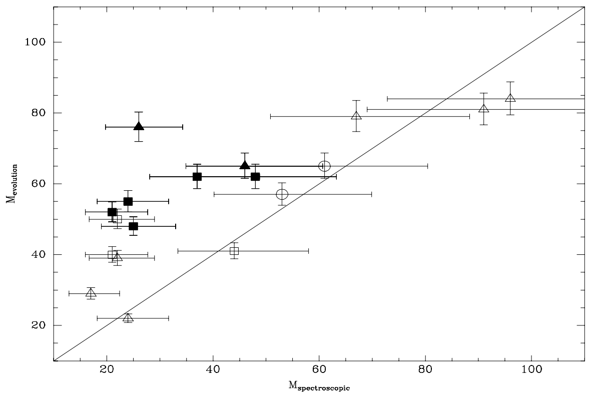

Figure 1: The Mass Discrepancy for Magellanic Cloud Stars. The evolutionary masses are plotted as a function of the spectroscopic mass for a sample of stars studied in the SMC and LMC by Massey et al. (2004, 2005). The circles represent supergiants, the triangles represent giants, and the squares represent dwarfs. The filled symbols are stars hotter than 45,000 K; nearly all of these show a significant mass discrepancy, with the evolutionary mass systematically larger than the spectroscopic mass. The line shows the expected 1:1 relationship between the two determinations of mass. Adapted from Massey et al. (2005).

- Burkholder, Massey, & Morrell 1997, ApJ, 490, 328
- DeGioia-Eastwood et al. 1984, ApJ, 278, 56
- Drissen et al. 1995, AJ, 110, 2235
- Garmany, Conti, & Massey 1980, ApJ, 242, 1063
- Hanson, M. M. 2003, ApJ, 597, 957
- Havlen & Moffat 1977, A&A 58, 351
- Herrero et al. 1992, A&A, 261, 209
- Kudritzki & Hummer 1990, ARA&A, 28, 303
- Maeder & Meynet 2000, ARA&A, 38, 143
- Mason et al. 1998, AJ, 115, 821
- Massey 1998, in the Stellar Initial Mass Function, ed. Gilmore & Howell, 17
- Massey, 2003, ARA&A, 41, 15
- Massey et al. 2002, ApJ, 608, 1001
- Massey et al. 2005, ApJ, 627, in press (astro-ph/0503464)
- Massey, DeGioia-Eastwood, & Waterhouse 2001, AJ, 121, 1050
- Massey & Hunter 1998, ApJ, 493, 180
- Massey & Johnson 1993. AJ, 105, 980
- Massey, Parker, & Garmany 1989, AJ, 98, 1305
- Massey, Penny, & Vukovich 2002, ApJ, 565, 982
- Massey, Waterhouse, & DeGioia-Eastwood 2000, AJ, 119, 2214
- Moffat, Drissen & Shara 1994, ApJ, 436, 183
- Moffat & Vogt 1973, A&AS, 10, 135
- Penny, Gies, & Bagnuolo 1999, in Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies, IAU Symp 193, ed. van der Hucht, Koenigsberger, & Eenens, 86
- Penny et al. 2003, in A Massive Star Odyssey: From Main Sequence to Supernova, IAU Symp 212, ed. van der Hucht, Herrero, & Esteban, 216
- Sung & Bessell 2004, AJ, 127, 1014

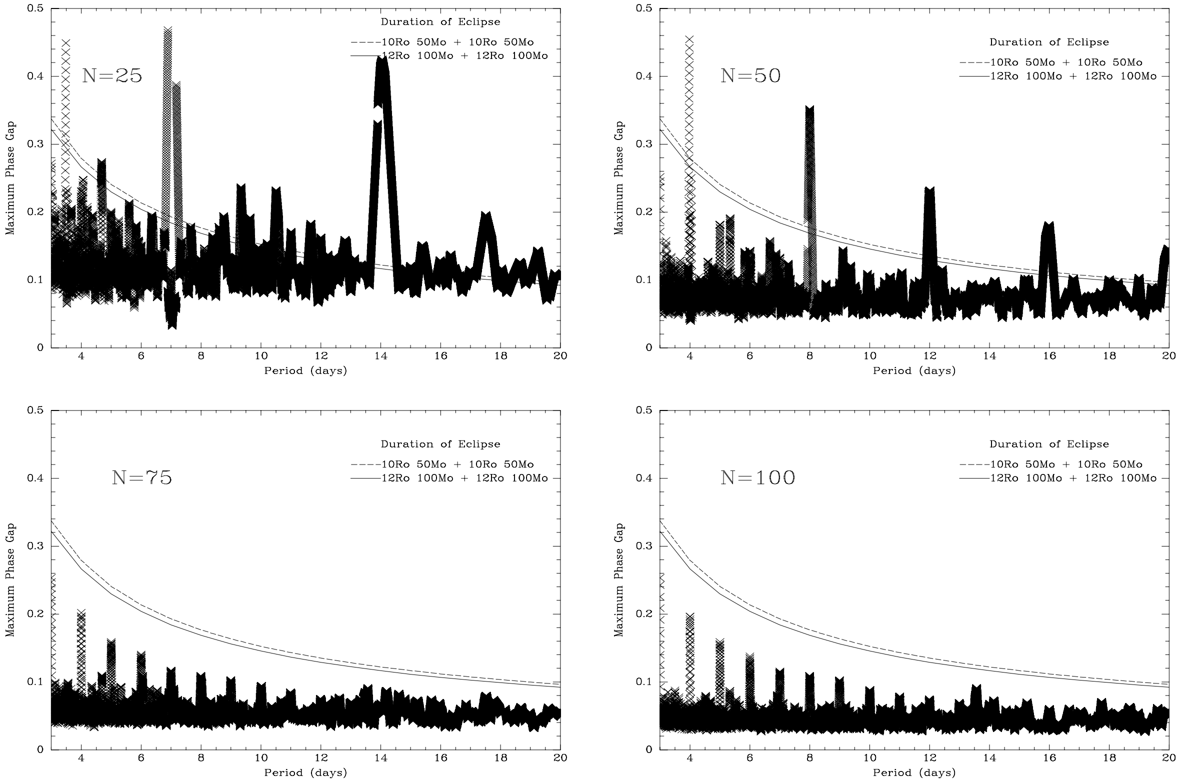

Figure 2: We have simulated the phase coverage we would obtain for N observations evenly spaced during 6 months, with a random factor in the spacing by a day or two (for weather), and with the assumption that the observations are obtained at a random time within ±3 hrs of the the field being on the meridian. The closely-spaced points give the maximum gap in phase coverage as a function of the period for different values of N. The half-light eclipse duration for a circular orbit (and inclination of 90 degrees) are shown for two stars with $10\mathrm{R}_\odot$ and $50\mathrm{M}_\odot$ each (dashed line) and for $12R_\odot$ $100\mathrm{M}_\odot$ stars (solid line). This shows that 25 or 50 observations aren't quite good enough to be sure not to miss an eclipse, while 75 or 100 observations per field should do a great job, even with the (expected) aliasing from the sidereal period. We can do this for all five of our fields with just 5 nights of observing (30 minutes a night on 100 nights).

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

Overall Plan: The first year (2005B and 2006A) we will *identify* eclipsing binaries and *determine periods* using the images that we are asking for in this proposal. We are requesting "long-term status" at this time **only** to cover this imaging; this is needed for coverage of both the low-metallicity Magellanic Clouds and Galactic clusters. The second year we will then use the Dupont telescope at Las Campanas Observatory to obtain radial velocities (access through collaborator Nidia Morrell), and we may also apply for SOAR spectroscopy. Together these data will provide orbit solutions. Year 3 we will obtain high S/N spectra at the most highly separated double-lined phases, using Magellan and IMAX, in order to do atmospheric modeling to determine the spectroscopic masses. (The evolutionary masses are already known, given the photometry and spectral types.)

Target Selection: When asked why he robbed banks, "Slick" Willie Sutton (1901-1980) was famously said to have replied, "Because that's where the money is." We have used a similar philosophy to select the OB associations and we will observe (Table 1). All of these fields are rich in the most massive, luminous stars, and we expect an abundance of suitable binaries to be found. All are known to contain stars whose bolometric luminosities place them above $100M_{\odot}$. The angular sizes are well matched to the 1.3-m 6'x6' field-of-view. In addition, our project includes the northern Cyg OB2 "supercluster" (Hanson 2003), for which we will image at Lowell.

Cluster	α_{2000}	δ_{2000}	size (arcsec)	#O stars with $M_V < -5$	distance (kpc)	Refs.
Southern Spring (2005B):						
SMC-N346	00:59:00.0	−72:10:30	5	16	66	1
LMC-R136*	05:38:42.5	−69:06:30	0.5	46	50	2,3
LMC-LH41	05:18:42.5	−69:14:12	6	14	50	4
LMC-LH90	05:36:12.0	−69:13:30	4	18	50	4
LMC-LH101	05:39:03.0	−69:29:54	5	17	50	4
Southern Fall (2006A):						
Tr14/16	10:44:44.0	−59:45:00	(2)x6	17	3.2	5,6
NGC3603*	11:15:09.1	−61:16:17	0.5	35	6.9	7.8.9
Cl 1715-387	17:19:00.5	−38:48:52	4	7	2.8	6,10
Pismis 24	17:25:00.0	−34:12:00	6	7	2.5	6,11

*Although R136 and NGC3603 are quite crowded, 1.5" seeing will still allow us to do useful work in the peripheries of these clusters. Refs: (1) Massey, Parker, & Garmany 1989; (2) Massey & Hunter 1998; (3) Massey et al. 2002; (4) Massey,Waterhouse, & DeGioia-Eastwood 2000; (5) Massey & Johnson 1993; (6) Massey, DeGioia-Eastwood, & Waterhouse 2001; (7) Moffat, Drissen & Shara 1994; (8) Drissen et al. 1995; (9) Sung & Bessell 2004; (10) Havlen & Moffat 1977; (11) Moffat & Vogt 1973.

Number of Observations: We gave some considerable thought to how many synoptic observations we need of our clusters. Our experience in modeling high-mass binaries suggested that the answer was about 50 to 100, and we confirm this in Fig. 2, where we have applied monte-carlo simulations to the problem. The *duration* of an eclipse (full-width at half eclipse depth) will be $R/\pi a$, where R is the stellar radius and a is the semi-major axis, for edge-on systems. Since $a = (m_1 + m_2)^{1/3} P^{2/3}$ by Kepler's third law, we can approximate how long an eclipse should last as a function of orbital period for typical masses and main-sequence radii. These are shown by the solid and dashed lines in Fig. 2. Given N observations evenly spaced through-out the semester (with random factors to account of gaps due to weather and for time-of-night), what is the maximum gap in phase coverage for different periods? We want the gap size to be less than the duration of an eclipse, after all! We see that our gut feeling was right: $N = 100$ should do fine.

Proprietary Period: 18 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have an NSF grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

For the identification of O-type binaries, we will make use of Lowell facilities to image Cyg OB2. In the second year, we will use the DuPont telescope at Las Campanas, with the newly re-commissioned B&C Spectrograph, for the primary spectroscopic observations; we may choose to also apply to NOAO for supplemental SOAR spectroscopy. SMARTS time on the CTIO 0.9-m may be used (through Co-I Gies' access) to fill in any gaps in the light-curves. The following year we will obtain high S/N spectra of the systems at critical double-lined phases using Magellan time.

A collaborative NSF proposal to cover this work is currently under review. If successful, it will provide travel funds, partial salary support, and publication costs; if not, these costs will be assumed by our home institutions.

Long-term Details *If you are requesting long term status, list the observing runs (telescope, instrument, number of nights) requested in subsequent semesters to complete the project.*

We need coverage over two semesters to obtain both our Magellanic Cloud and Galactic clusters. In 2006A we will need for an additional 5 nights on the 1.3-m. Obtaining data in both semesters is needed to see if there is a metallicity-dependent problem with the stellar atmosphere (or stellar evolutionary) models: the Magellanic Clouds provide a laboratory where the metallicities are 1/5th (SMC) and 1/2 (LMC) that of the Milky Way.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

Recent (2002-2005) allocation of time for the PI:

2004B-070, 2004A-200: "The Physical Parameters of Red Supergiants: When Massive Stars Are As Cool As They Get": 5 nights CTIO 4-m Nov 2004 (2004B-070); 10 nights KPNO 2.1-m plus 5 on the CTIO 1.5-m (2004A-200). The results for the Galactic sample (2004A-200) appear in Levesque, Massey, Olsen, Plez, Josselin, Maeder, & Meynet, ApJ, submitted, and received a great deal of press attention as a result of our press release at the San Diego AAS meeting

http://www.lowell.edu/press_room/releases/recent_releases/largest_star_rls.html

The results for the Magellanic Clouds (2004B-070) are undergoing analysis, and form the basis for a proposal being submitted this semester.

Target of Opportunity: "Spectroscopy of a Newly Found Dwarf Irregular", 2 hrs kindly granted by Richard Green on the 2.1-m with GoldCam, April 2003. The data appear in Massey, Henning, & Kraan-Korteweg, 2003, AJ, 126, 2362

2002B-218, 2004B-280 "The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andromeda Galaxy", 1 clear night on the MMT in Sept 2004, and 0.5 clear nights on the MMT in Sept 2002. Some of these data have been published in Massey & Holmes 2002, ApJ, 580, L35; the reductions of HST spectra and subsquent modeling is in progress.

Recent papers (2002-2005) based upon NOAO data for the PI:

- Levesque, E. M., Massey, P., Olsen, K. A. G., Plez, B., Josselin, E., Mader, A., & Meynet, G. 2005, "The Effective Temperature Scale of Galactic Red Supergiants: Cool, But Not As Cool As We Thought", ApJ, submitted
- Massey, P., Puls, J., Pauldrach, A. W. A., Bresolin, F., Kudritzki, R. P., & Simon, T. 2005, "The Effective Temperature Scale of O-type Stars as a Function of Metallicity. II. Analysis of 20 More Magellanic Cloud Stars, and Results from the Complete Sample", ApJ, 627, in press (astro-ph/0503464)
- Silva, D. R., Massey, P., DeGioia-Eastwood, K., & Henning, P. A. 2005, "The Distance and Metallicity of the Newly Discovered, Nearby Irregular Galaxy HIZSS3, ApJ, in press (astro-ph/0501545).
- Massey, P., Bresolin, F., Kudritzki, R. P., Puls, J., & Pauldrach. A. W. A. 2004, "The Effective Temperature Scale of O-type Stars as a Function of Metallicity. I. A Sample of 20 Stars in the Magellanic Clouds", ApJ, 608, 1001
- Di Stefano et al. 2004, "Supersoft X-Ray Sources in M31", ApJ, 610, 247
- Huang, W., Gies, D., Massey, P., & Conti, P. S. 2004, "Stellar Rotation in the Young Cluster M17, IAU Symposium 215, 67
- Walborn et al. 2004, "A CNO Dichotomy Among O2 Giant Spectra in the Magellanic Clouds", ApJ, 608, 1028
- Massey, P., & Olsen, K. A. G. 2003, "The Evolution of Massive Stars. I. Red Supergiants in the Magellanic Clouds", AJ, 126, 2867

- Bianchi, L., Bohlin, R., & Massey, P. 2003, “The Ofpe/WN9 Stars in M33”, ApJ, 601, 228
- Massey, P., Olsen, K. A. G., & Parker, J. W. 2003, “The Discovery of A 12th Wolf-Rayet Star in the Small Magellanic Cloud”, PASP, 115, 1265
- Massey, P., Henning, P. A., & Kraan-Korteweg, R. C. 2003, “A Neighboring Dwarf Irregular Galaxy Hidden By the Milky Way”, AJ 126, 2362
- Morrell, N. I., Ostrov, P. G., Massey, P., & Gamen, R. 2003, “Hodge 53-47: An Early O-type Double-lined Binary in the SMC”, MNRAS, 341, 583
- Massey, P., and Holmes, S. 2002 ”Wolf-Rayets in IC10: Probing the Nearest Starburst”, ApJ 580, L35
- Snow, T. P., Zukowski, D., and Massey, P. 2002, ”The Intrinsic Profile of the 4428A Diffuse Interstellar Band”, ApJ, 578, 877
- Massey, P. 2002 ”A UBVR CCD Survey of the Magellanic Clouds”, ApJS, 141, 81.
- Slesnick, C. L., Hillenbrand, L. A., and Massey, P. 2002, ”The Star Formation History and Mass Function of the Double Cluster h and Chi Pesei”, ApJ, 576, 880
- Niemela, V. S., Massey, P., Testor, G., & Gimenez Benitez, S. 2002, “The Massive Wolf-Rayet Binary SMC WR7”, MNRAS, 333, 347
- Walborn et al. 2002, “A New Spectral Classification System for the Earliest O Stars: Definition of Type O2”, AJ, 123, 2754
- Zaritzky, D. et al. 2002, “The Magellanic Clouds Photometric Survey: The Small Magellanic Cloud Stellar Catalog and Extinction Map”, AJ, 123, 855

Observing Run Details for Run 1: CT-1.3m/ANDI + CCDIR

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

We are asking for 100 (synoptic) observations of each of 5 fields in the Magellanic Clouds during 2005B. The exposure times are quite short (1-2 sec) and will be obtained in the V filter; two consecutive exposures will eliminate any cosmic rays. The observations are well suited to the queue mode in which the 1.3-m operates, and we ask for the observtions to be (more or less) evenly spaced throughout the semester.

We ask for 5 nights based upon 3 minutes/target (slew) plus 2x1.5 min per image (readout plus exposure time for two consecutive exposures through the same filter), or 6 minutes/observation/target, or 30 minutes/night for all five target fields. Thus, 100 observations x 30 minutes = 50hrs, or 5 10-hr nights.

As demonstrated in Fig. 2, 100 observations well distributed through-out 2005B should do a good job of adequate phase coverage.

For 2006A we have another four (Galactic) fields, and will be require an another 5 nights distributed throughout that semester.

Instrument Configuration

Filters: 5
Grating/grism:
Order:
Cross disperser:

Slit:
Multislit: no
λ_{start}:
λ_{end}:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.: no

R.A. range of principal targets (hours): 0 to 6

Dec. range of principal targets (degrees): -75 to -60

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.10.