NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 30, 2003 **Category:** Massive Stars

The Physical Parameters of Red Supergiants: When Massive Stars Are as Cool as They Get

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

We are proposing here to determine the spectral energy distributions for a sample of Galactic red supergiants in order to compare both the relative fluxes *and* line strengths to those predicted by the new generation of MARCS stellar atmosphere models. This will allow an accurate effective temperature scale to be established for solar-metallicity RSGs. Our eventual goal is to extend this study to the Magellanic Clouds, in order to test how metallicity affects the temperature scale of RSGs.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	KP-2.1m	GCAM	5	bright	Feb	Feb
2	CT-1.5m	CSPEC + L1K	6	bright	Mar	Feb - Apr
3	KP-2.1m	GCAM	5	bright	Jul	Jul
4						
5						
6						

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

None.

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.*

We tend to equate "massive stars" with "hot stars", owing to the fact that while on the main-sequence these objects are spectroscopically identified as O-type stars, with effective temperatures of 30,000°K or more. Among the evolved stages of massive stars, most attention has been given to the spectacular Luminous Blue Variables, which are hot stars near their Eddington limit shedding mass at a prodigious rate (η Car, S Dor), and the enigmatic Wolf-Rayet stars, with high effective temperatures and optically thick winds. We sometimes overlook the fact that the majority of massive stars spend a significant fraction of their lives as red supergiants (RSGs) with extremely cool effective temperatures and gigantic radii. The RSG phase is important in two ways: (1) It provides an important mechanism for shedding mass prior to the Wolf-Rayet stage, and (2) The relative number of RSGs and WRs provide a very sensitive test of stellar evolutionary theory.

The stellar evolution of a massive star is hard to model owing to the complications of mass-loss; in addition, the tracks are sensitive to the treatment of convection and mixing (Maeder & Meynet 1987, Maeder & Conti 1994). Recent emphasis has been on the role that rotation plays in mixing in massive stars (Maeder & Meynet 2000, 2002). An excellent observational database has been growing which allows critical comparison between theory and observation. An example is shown in Fig. 1, where we see that the relative fraction of RSGs and WRs is a very strong function of metallicity (Massey 2003). This is in the sense predicted by Maeder et al. (1980): at low metallicities there is less mass-loss and hence it is harder to produce a WR, as this requires stripping off the outer layers of the star until processed material is revealed at the surface. But we also see in Fig. 1 that quantitatively none of the models fit the observed trend very well (Massey 2003).

In part, this comes about from a "dirty little secret" of modern evolution models: they simply don't produce red supergiants that are as cool and luminous as those observed. We show this in Fig. 2, which is taken from our recent study of RSGs in the Magellanic Clouds. Earlier (pre-1988) models *did* produce appropriate RSGs, but a new treatment of convection was adopted by the Geneva and Padova groups, and since that time the $> 20\mathcal{M}_\odot$ tracks don't go far enough to the red.

However, large uncertainties exist in converting the observational quantities to physical properties. The effective temperature scale of RSGs is poorly determined, and an uncertainty of even 150°K in $T_{\rm eff}$ leads to a 1.0 mag uncertainty in the bolometric correction for the cooler supergiants (Massey & Olsen 2003, Table 3). Although interferometric data provide a fundamental calibration of red *giants*, there are simply not enough nearby red *super*giants (Dyck et al. 1996, 1998). Instead we must rely upon stellar atmosphere models, but these have simply not included a sufficiently good treatment of molecules until now. This lack has been corrected by the new generation of MARCS models which are now becoming available (Plez 2003; Gustafsson et al. 2003; Josselin & Plez 2003).

Massey & Olsen (2003)'s recent study of RSGs in the Magellanic Clouds (MCs) confirms an effect seen by Elias et al. (1985) from fewer data: there is a shift in the distribution of spectral types with metallicity, with the average type in the Milky Way M2 I, in the LMC M0-1 I, and in the SMC K5 I (Fig. 3). We suggest that this is just a reflection of the fact that the metal content is lower in the MCs, and that the spectral types are based upon the strength of the TiO lines. This would require RSGs in the MCs to be 100°K (LMC) or 300°K (SMC) cooler than their Galactic counterparts. But to test this we need better data to compare to these new models.

Here we are proposing to refine the effective temperature scale of Galactic RSGs using absolute spectrophotometry (i.e., relative continuum fluxes *and* TiO line strengths) with the new MARCS models. After we have demonstrated this technique for a sample of Galactic stars, we intend to propose to extend this work to the lower metallicity stars of the Magellanic Clouds.

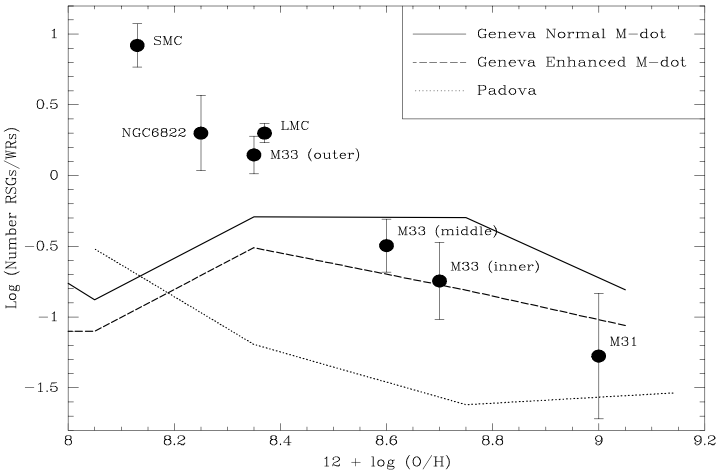

Figure 1: The relative number of RSGs and WRs changes by 2 orders of magnitude over just 0.8 dex in oxygen abundance. This is easy to understand in the sense that at lower metallicities a massive star will spend a greater fraction of its He-burning lifetime as a RSG than a WR as the mass-loss rates will be lower, and hence it will be harder to "peel down" the outer layers of the star to reveal the nuclear-processed material that characterizes a WR. None of the current evolutionary models (solid and dashed lines) reproduce this trend, however. The figure is from Massey (2003, Annual Reviews Astron & Astrophy, 41, 15).

References

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Dyck, H. M., van Belle, G. T., & Thompson, R. R. 1998, AJ, 116, 981

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Josselin, E., & Plez, B. 2003, in Sem. de l'Astrophys. Fran., ed. Combes, Barret, & Contini, p. 222

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

Massey, P., & Olsen, K. A. G. 2003, AJ, 126, (Dec issue), in press (astro-ph/0309272)

Plez, B. 2003, in GAIA Spectroscopy: Science, and Technology, ed. U. Munari, p. 189

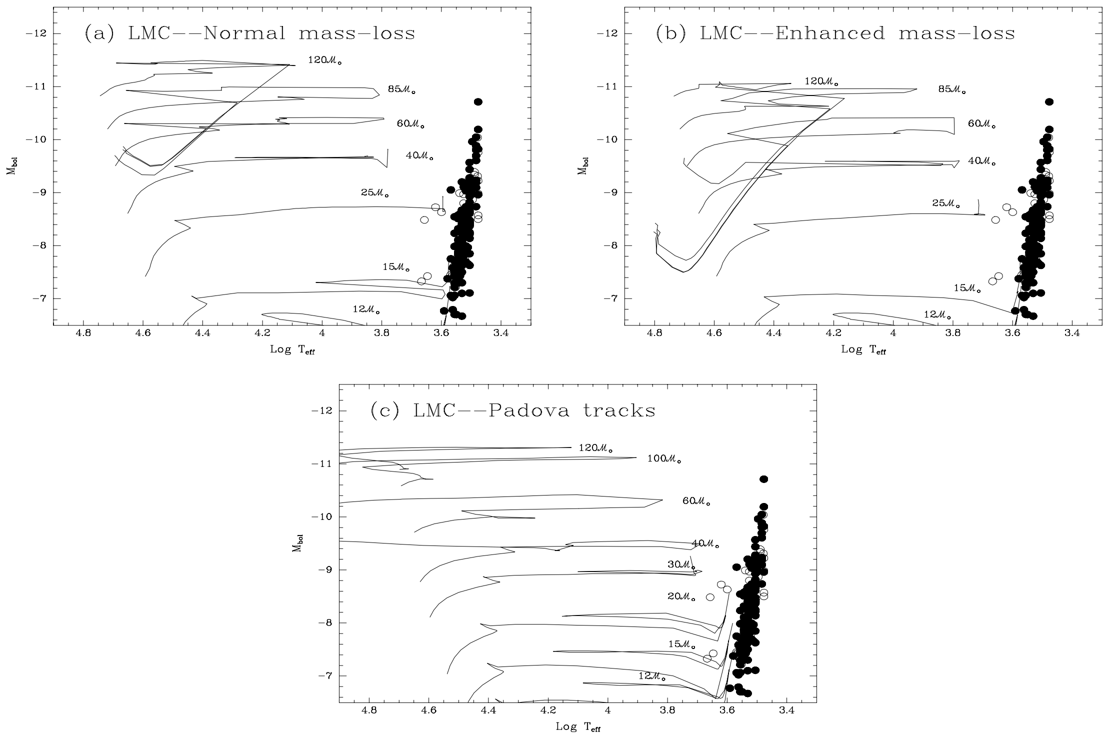

Figure 2: The location of the LMC RSGs in the HRD is compared to three sets of $Z = 0.008$ evolutionary tracks. Although there are plenty of RSGs of initial masses $\geq 40\mathcal{M}_{\odot}$ present (judging from the luminosities), none of the tracks produce RSGs as cool and luminous as these—the tracks stop well to the blue side of the observed sequence. The same effect is seen for the SMC and the Milky Way. This figure is from Massey & Olsen (2003, AJ, 126, (Dec issue) , in press).

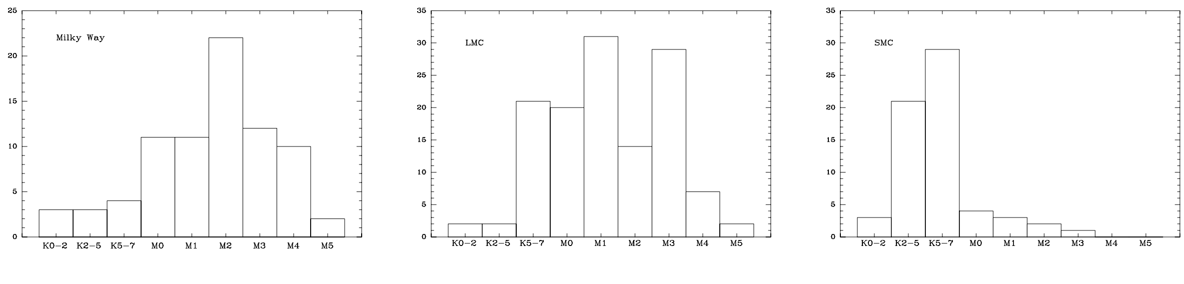

Figure 3: Histograms of the spectral types found in the Milky Way (Elias et al. 1985, Table 20) and the LMC and SMC (Massey & Olsen 2003, Tables 1 and 2). There is a progression towards earlier type with decreasing metallicity (i.e., Milky Way to LMC to SMC). The spectral classification scheme is based purely on the *strengths* of the TiO bands, and hence a lower metallicity will make a star of a given effective temperature appear earlier. Put another way, RSGs in the SMC and LMC should be cooler (and hence more bolometrically luminous) than Galactic stars of the same spectral type. From Massey & Olsen (2003, AJ, 126, (Dec issue) in press).

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)*

Previous comparisons between RSG models and observational data have been based primarily on broad-band photometry, with $V-R$ generally recognized as a good effective temperature indicator, while $B-V$ is sensitive to both effective temperature and surface gravity (Massey 1998, ApJ, 501, 153). However, the new generation of MARCS models allows us to perform a far more sensitive comparison, using both the relative spectral energy distribution *and* the strengths of the TiO lines. The latter, afterall, form the basis for the spectral types in the first place. A similar study has been attempted by Oestreicher & Schmidt-Kaler (1998, MNRAS 299, 625) who used a preliminary form of the models and found better agreement than that produced by the Kurucz ATLAS9 models, but the data we are proposing to obtain here will be of much higher quality (better resolution, greater wavelength coverage) and will be compared to an improved (and final?) version of the MARCS models.

We have selected a sample of Galactic RSGs that are known to lie in OB associations and clusters that have relatively well established values for $E(B-V)$, providing us with a starting point to de-redden the observed spectral energy distributions and produce intrinsic fluxes. This provides a much more sensitive test than just the broad-band colors, although the latter can readily be synthesized from our data. Observations with two different gratings will provide complete coverage from 3500Å to 9500Å. With this, we can synthesize B, V, and R (the latter is usually lacking for these stars) but more to the point we can directly compare the de-reddened spectral energy distributions to those produced by the models. Our spectral resolution will be 3Å (blue) to 5Å (red), more than adequate for comparing the line strengths of the numerous TiO bands to that predicted by the models. With a comprehensive grid of T (3,000°K to 4,000°K at 100°K intervals) and surface gravities appropriate to supergiants ($\log g$=0.0, -0.5, and -1.0) we will be able to determine an accurate (50°K) effective temperature scale for these stars.

Our sample includes 80 RSGs with multiple examples of each spectral subtype (K2.5 I to M5 I). The stars are ridiculously bright (V=7 to 9, typically, corresponding to B=9 to 11), and our exposures will be a few seconds to a few minutes for a S/N of 100. Our major overhead will be the need to constantly adjust to the parallactic angle. 5 to 6 nights are requested for each sample (two in the north and one in the south) as two gratings settings are needed in the north, and three in the south, for complete coverage. (Although these stars are somewhat variable, their spectral types will not change during a single run!)

The new generation of MARCS models computed by collaborator Plez are derived from the original Gustafsson et al. (1975, A&A, 42, 407) plane-parallel, LTE, line-blanketed models, which included convective and radiative flux conservation. Subsequent improvements included the introduction of spherical symmetry, the technique of opacity sampling, and vast improvements to both the continuum and line opacities. The current version of the MARCS code is a final merging of all these changes, along with an update of the opacities and chemical equilibriums. About 600 molecular species are included. Further details can be found in Plez (2003) and Gustafsson et al. (2003).

Proprietary Period: 18 months

Use of Other Facilities *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.*

This program is based upon observations we obtained at CTIO in October 2001.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, 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 (2000-2003) allocation of time:

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, (Nov issue), in press, astro-ph/0308080

2002B-218: The Evolution and Physical Parameters of Massive Stars at High Metallicity: O Stars in the Andromeda Galaxy", 3.5 nights MMT Sept 2002. We obtained only 0.5 nights out of 3.5 nights scheduled, due to weather, but published what we were able to get in a nice ApJ Letters paper Massey & Holmes 2002, ApJ, 580, L35

$\boxed{\star}$ **2001A-062:** A *UBVR* Survey of the Magellanic Clouds, 6 nights CTIO Curtis Schmidt April 2001: Massey 2002, ApJS 141, 81

2001B-002: The Wolf-Rayet Content of IC10, 2 nights Mayall 4-m Sept 2001: Massey & Holmes 2002, ApJ, 580, L35

2000B-010: A Survey of Local Group Galaxies Currently Forming Stars, on-going survey project. We are current with all of our data reductions, and are completing the photometric analysis. Some data appear in Di Stefano et al. 2003, ApJ, submitted.

$\boxed{\star}$ **2001B-227:** The Red Supergiant Content of the Magellanic Clouds, 3 nights CTIO 4-m Hydra, October 2001. This work forms the basis for the present proposal. The paper has now been accepted, and is scheduled for the Dec 2003 AJ (Massey & Olsen 2003, AJ, 126, in press).

1999B-099; 2000B-070: Where Do Wolf-Rayet Stars Come From? CTIO 1.5-m 5 nights October 2000; 6 nights October 1999: Massey & Duffy 2001, ApJ 550, 713; Niemela et al. 2002, MNRAS, 333, 347

Recent papers (2000-2003) based upon NOAO data:

Massey, P. 2003, "The Massive Star Content of the Local Group: Implications for Star Formation and Stellar Evolution", ARA&A, 41, 15

Bianchi, L., Bohlin, R., & Massey, P. 2003, "The Ofpe/WN9 Stars in M33", ApJ, submitted

Di Stefano et al. 2003, "Supersoft X-Ray Sources in M31", ApJ, submitted, astro-ph/0306440

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, in press (Nov issue), astro-ph/0308237

Massey, P., Henning, P. A., & Kraan-Korteweg, R. C. 2003, "A Neighboring Dwarf Irregular Galaxy Hidden By the Milky Way", AJ 126, in press (Nov issue), astro-ph/0308080

Massey, P., & Olsen, K. A. G. 2003, "The Evolution of Massive Stars. I. Red Supergiants in the Magellanic Clouds", AJ, 126, in press (Dec issue), astro-ph/0309272

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., & Holmes, S. 2002 "Wolf-Rayet Stars in IC10: Probing the Nearest Starburst", ApJ 580, L35

Massey, P. 2002, "A UBVR CCD Survey of the Magellanic Clouds," ApJS, 141, 81

Massey, P. 2002, "Observational Constraints on Massive Star Evolution" (invited review), in *A*

Massive Star Odyssey, from Main Sequence to Supernova, IAU 212, ed. van der Hucht, Herrero, & Esteban, 316.

Slesnick, C. L., Hillenbrand, L. A., & Massey, P. 2002, "The Star Formation History and Mass Function in the Double Cluster h and Chi Persei", ApJ, 576, 880

Snow, T. P., Zukowski, D., & Massey, P. 2002, "The Intrinsic Profile of the 4428Å Diffuse Interstellar Band", ApJ 578, 877

Niemela, V. S., Massey, P., Testor, G., & Benitez, S. G. 2002, "The Massive Wolf-Rayet Binary WR7 in the SMC", MNRAS, 333, 347

Walborn et al. 2002, "A Giant O2-O4 Spectral Classification Study", AJ, 123, 2754

Bianchi et al. 2001,"The Massive Star Content of NGC 6822. Ground-based and *HST* photometry, AJ, 121, 2020.

Massey, P. & Duffy, A. S. 2001, "A Deep Search for Wolf-Rayet Stars in the Small Magellanic Cloud", ApJ, 550, 713.

Massey, P., DeGioia-Eastwood, K., & Waterhouse, E. 2001, "The Progenitor Masses of Wolf-Rayet Stars and Luminous Blue Variables Determined from Cluster Turn-offs. II. Results from 12 Clusters in the Milky Way", AJ, 121, 1050.

Massey, P., Waterhouse, E., & DeGioia-Eastwood 2000, "...I. Results from 19 OB Associations in the Magellanic Clouds", AJ, 119, 2214.

Massey, P., & Foltz, C. 2000, "The Spectrum of the Nigh Sky Over Mount Hopkins and Kitt Peak: Changes After a Decade", PASP, 112, 566.

Massey, P., 2000, "An Unprecedented Change in the Spectrum of S Doradus: As Cool As It Gets", PASP, 112, 144.

Observing Run Details for Run 1: KP-2.1m/GCAM

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).*

This run needs to be as early in the semester as possible, peferably the first week of February, as the northern Milky Way rapidly slips away from us. During this first run, we will concentrate on the large number of RSGs in the Per OB1 association (2:00, +60°), with a smattering of targets throughput the rest of the night (i.e., Aur OB1, Gem OB1). Our targets are bright (V=7-9, B=9-11) and will require just a few minutes of integration per star to achieve excellent S/N. At the 2.1-m we will observe each star with two gratings: No. 26 (λ3500-λ5900) and No. 58 (λ5400 to λ9200). This gives us complete coverage in the optical, and will allow us to synthesize B, V, and R colors as well as obtain good resolution measurements of the lines.

In order to maintain good relative fluxes we will observe each star at the parallactic angle. This introduces significant overhead of course, as the telescope must be moved to zenith first. Fortunately many of our early Feb objects are in the same general part of the sky.

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: 26,58	Multislit:	Corrector:
Order: 1st, 1st	$\lambda_{\rm start}$: See above	Collimator:
Cross disperser:	$\lambda_{\rm end}$: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 2:00

Dec. range of principal targets (degrees): +60

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

Observing Run Details for Run 2: CT-1.5m/CSPEC + L1K

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).*

At CTIO we will concentrate on the RSGs found in the Carina arm, principally Car OB1 and OB2 (11:00, -60°). Thus, time in late Feb/early March would be ideal. We will use gratings 26 (λ3500 to λ5200) and grating 58. The latter will require two separate grating tilts for comparable coverage to the north, i.e., λ5000 to λ7500 and λ6700 to λ9200. In order to observe each target at the parallactic angle we will have to adjust the spectrograph rotation several times during the night, something we have done many times with this system. (Alternatively, since the slit is remotely controled at the 1.5-m, we may opt to expose twice—once with the slit open to 5-8" for good relative fluxes, and a second time with a nominal slit setting for good resolution.)

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: 26, 58	Multislit:	Corrector:
Order:	$\lambda_{\rm start}$: See above	Collimator:
Cross disperser:	$\lambda_{\rm end}$: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 11:00

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

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

Observing Run Details for Run 3: KP-2.1m/GCAM

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).*

During our July run at Kitt Peak, we will concentrate on the remaining northern Milky Way fields, primarily in Cygnus, with Cep and Cas observable at the end of the night. We will use the same set up as for the Feb run, i.e., gratings No. 26 (λ3500-λ5900) and No. 58 (λ5400 to λ9200).

Instrument Configuration

Filters:	Slit:	Fiber cable:
Grating/grism: 26, 58	Multislit:	Corrector:
Order:	λ_{start}: See above	Collimator:
Cross disperser:	λ_{end}: See above	Atmos. disp. corr.:

R.A. range of principal targets (hours): 19 to 01

Dec. range of principal targets (degrees): +20 to +60

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

NOAO observing proposal LaTeX macros v2.9.