McGill University

PHYS-641 – Observational techniques of modern astrophysics

MOCTAC

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December 2 2022

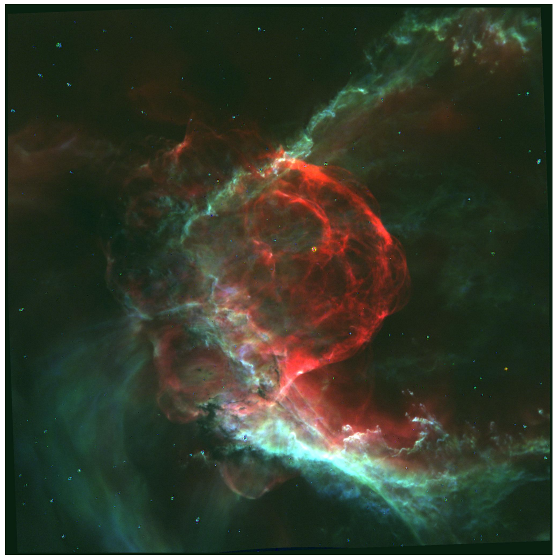


Figure 1: Composite image with data from SITELLE. *Red* : Hα(λ6563)Å emission, *Green* : [NII]$\lambda\lambda$6548 + 6583Å emission and *Blue* : [SII]$\lambda\lambda$6717 + 6731Å emission.

1 Scientific Justification

The evolution of massive star is well studied but many uncertainties persist. The most massive stars are thought to pass through a Wolf-Rayet (WR) phase before exploding to a supernova. A lot of mass is lost through strong winds during the pre-WR phases. The circumstellar medium gets pushed away and ionized by this influx of matter. Many WR stars are then often accompanied by a bubble shaped nebula. Therefore, a good understanding of these nebulae can help us retrace the mass loss history of these WR stars and then verify or test the accuracy of evolutionary models.

Recent observations of the WR bubble nebula NGC 2359 with the instrument SITELLE an imaging Fourier transform spectrometer at Canada-France-Hawaii Telescope (CFHT) in the visible part of the spectrum have shown the presence of multiple emission lines coming from the ionized medium. This data helped us distinguish two structures, an arc which is emitting lines of low ionization states such as [NII], [SII] and [OII] and a bubble which does not emit in these spectral lines but in lines of higher ionization states like [OIII] and the recombination Balmer lines of hydrogen. Maps of the flux of some of these lines are presented at figure 1.

Some of these lines, [OII] doublet and [SII] doublet, are useful diagnostics to determine the electron density of the gas. For example, the ratio of the flux of [SII] lines λ6717Å/λ6731Å is said to be a good diagnostic for electron densities between 10^2 and

10^4 cm^{-3} (see Osterbrock and Ferland (2006)). The problem is the fact that these lines of low ionization states are only coming from the arc structure of the nebula which is not our primary interest. Therefore, we need a new diagnostic of electron density for the bubble. From what we said earlier the gas of the bubble is at a higher ionization state so the new diagnostic should be at least the second ionization of an atom.

A useful tool to see the possible theoretical line diagnostics for electron densities is the code PyNeb by Luridiana et al. (2014)[1]. The line diagnostic we will focus on is the one with the doublet of [ClIII]. It is the ratio of the fluxes $\lambda5538$Å$/\lambda5518$Å. The diagnostic produced with PyNeb is shown at the figure 2. It is likely to find [ClIII] emission in the nebula because we see emission of O^{++} which has a higher ionization potential than the Cl^{++}.

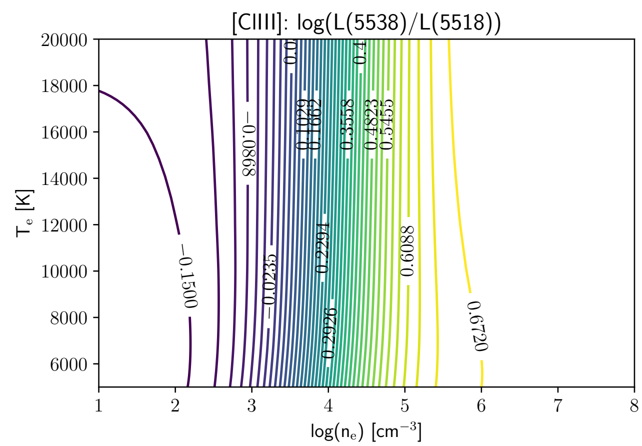


Figure 2: Electron density diagnostic from the line ratio of the [ClIII] doublet.

The electron density has been calculated from [OII] and [SII] lines for the arc structure around the bubble. We found a superior limit at $\log(N_e) = 2$. We do not know yet what will be the electron density in the bubble but we expect it to be somewhat close to the one found in the arc. The ratio of the flux of the [ClIII] lines, for a density of 10^2 cm^{-3}, is around $10^{-0.15} = 0.708$ on the figure 2. Let's see what S/N ratio we would need for each line to have a good precision on this ratio (say at the second decimal). The uncertainty on the ratio F_1/F_2 by error propagation is obtained like

$$\delta\text{ratio} = \sqrt{\left(\frac{\delta F_1}{F_2}\right)^2 + \left(\frac{F_1}{F_2^2}\delta F_2\right)^2}$$

[1] Available at Christophe Morisset's github page https://github.com/Morisset/PyNeb_devel

where F_1 is the flux of the $\lambda 5538$Å line and F_2 is the flux of the $\lambda 5518$Å line.

If the uncertainty on the flux is the same for both lines we have

$$\delta\text{ratio} = \delta F \sqrt{\left(\frac{1}{F_2}\right)^2 + \left(\frac{F_1}{F_2^2}\right)^2}$$

$$\frac{F_2}{\delta F} = \frac{1}{\delta\text{ratio}} \sqrt{1 + \text{ratio}^2}$$

So at a line ratio of 0.708 with uncertainty of 0.01, the S/N ratio for the second line would have to be 122.5.

$$\frac{F_1}{\delta F} = \frac{1}{\delta\text{ratio}} \sqrt{\left(\frac{F_1}{F_2}\right)^2 + \left(\frac{F_1^2}{F_2^2}\right)^2} = \frac{1}{\delta\text{ratio}} \sqrt{\text{ratio}^2 + \text{ratio}^4}$$

And the S/N ratio on the first line would have to be of 86.8. So we are limited by the S/N ratio of the second line. And we need an even bigger S/N ratio if the electron density has to be in the left part of figure 2 so at a lower density than 10^2 because it is where the ratio values start to plateau.

The resolution needed to resolve this doublet is

$$R = \frac{\lambda}{\Delta\lambda} = \frac{5538}{5538 - 5518} = 277$$

which is not difficult to attain for most spectrographs. The hardest part will be to get a good S/N ratio.

2 Technical Justification

We propose to use the Gemini Multi-Object Spectrograph (GMOS) at Gemini observatory. GMOS offers multiple observing modes such as multiple slits/objects by a mask configuration and an integral field unit. The offered field of view (FOV) in multi objects mode with a mask with slits is 5.5 arcmins squared and the FOV for multi object in integral field unit mode is 5×7 arcsec^2. Since the nebula is 11 arcmin wide in the sky, to use the IFU would limit us to only one part of a filament of the bubble. We prefer to use the multi object mode to have measurements of a couple filaments.

The grating which has the best efficiency for our lines of interest is **G5323** which peaks around 500 nm[2].

The positions desired for the slits are shown at figure 3.

[2]see `http://www.gemini.edu/sciops/instruments/gmos/newplots/newgratings/B600_G5303.png` from GMOS website

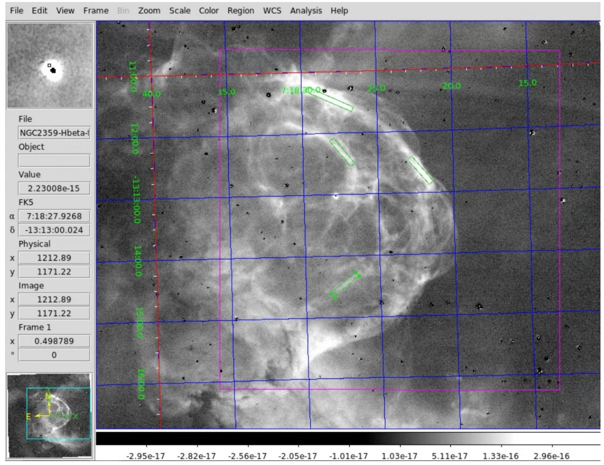


Figure 3: Image of a SAOImage window showing the desired positions of the slits (in green) inside the GMOS FOV (in magenta). The FK5 coordinate grid is also shown. The image used to place the slits is the Hβ emission map, the units of the colorbar are [erg s^{-1} cm^{-2} $Å^{-1}$]

Observations of NGC 2359 have been made with VLT-UVES on December 2 2003 by Esteban et al. (2017) with a slit of $3{\times}8$ arcsec^2 . They observed the [ClIII] doublet in a lower part of the nebula. Nonetheless, they found that the [ClIII] emissions are 1% that of the Hβ emission. So we expect the lines of [ClIII] to be faint at $\sim 1{\times}10^{-18}$ erg s^{-1} cm^{-2} $Å^{-1}$ arcsec^{-2}.

Here spectral resolution is not of that much importance compared to the signal to noise ratio we're trying to obtain, so 5 arcsecs wide slits can be chosen.

Now we use the exposure time calculator of GMOS. Our procedure to have an estimate of the flux is to use our Hβ data and one of the slits of figure 3. We calculate the sum of the flux inside a slit that we divide by 100 to have an estimate of one of the [ClIII] line flux. We get a value of 2.6e-15 erg s^{-1} cm^{-2} and choose a 5 arcsec wide slit and time integration of 2 hours 12 mins 54 secs. We find a SNR just between 120 and 130.

In brief, we propose to use **GMOS at Gemini South** with the **B600_G5323** grating which has a good efficiency close to our wavelengths of interest 5538Å and 5518Å. The exposure time needed to attain a sufficient SNR for our science objective is of **2 hours 12 mins 54 secs** even in not perfect sky condition (see integration time calculator results at the end of document).

References

Esteban, C., Fang, X., García-Rojas, J., and Toribio San Cipriano, L. (2017). The radial abundance gradient of oxygen towards the Galactic anti-centre. , 471(1):987–1004.

Luridiana, V., Morisset, C., and Shaw, R. A. (2014). Pyneb: a new tool for analyzing emission lines - i. code description and validation of results. *Astronomy and Astrophysics*, 573.

Osterbrock, D. and Ferland, G. (2006). *Astrophysics Of Gas Nebulae and Active Galactic Nuclei*. University Science Books.

Gemini Integration Time Calculator
GMOS-S - 2022B.1.1.4

Click here for help with the results page.
Read noise: 4.1
fraction of source flux in aperture = 1.00
derived image size(FWHM) for a point source = 1.00 arcsec

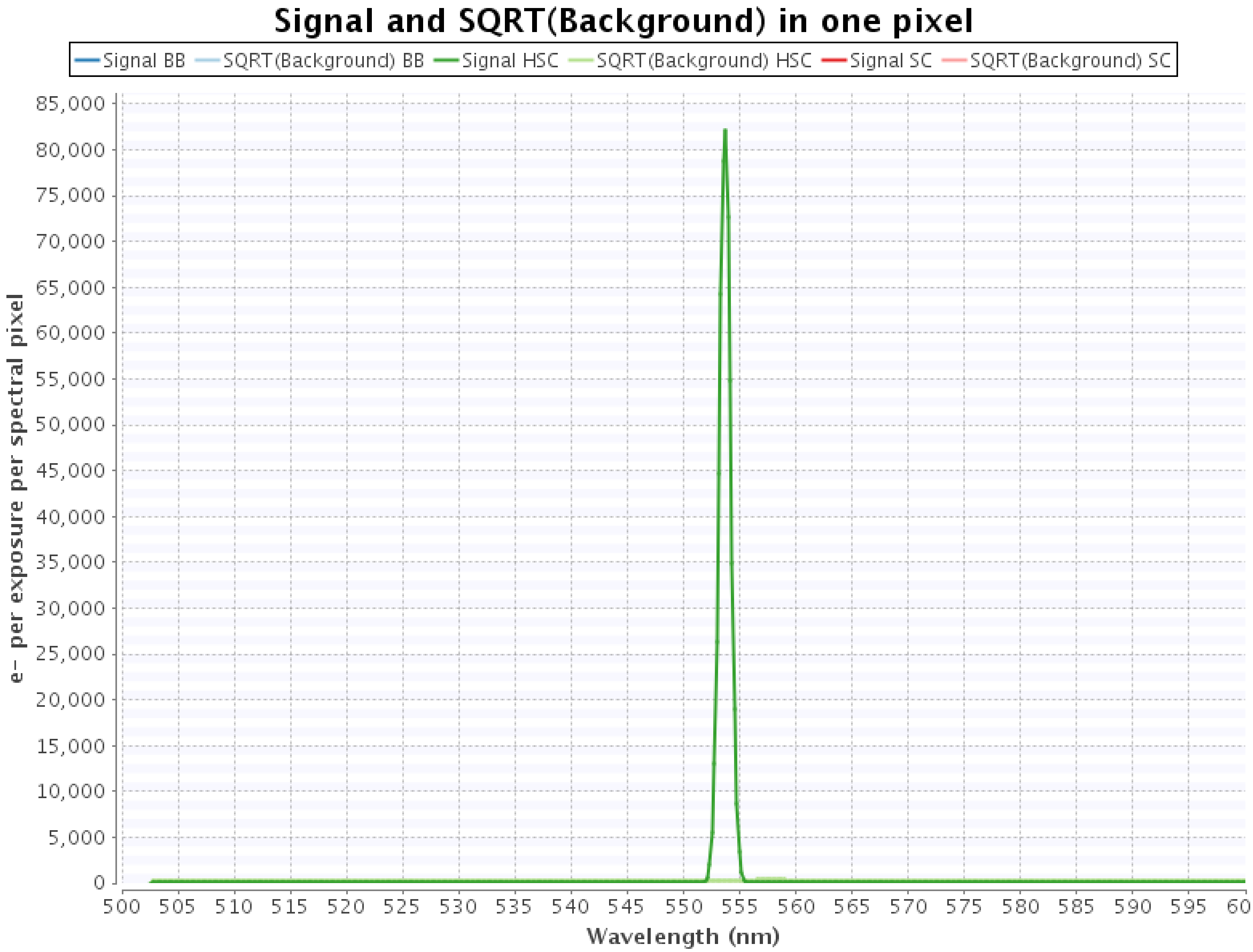
Sky subtraction aperture = 5.0 times the software aperture.

Requested total integration time = 7000.00 secs, of which 7000.00 secs is on source.

The peak pixel signal + background is 211181 e- (117322 ADU). This is 179% of the saturation limit of 117963 e-.

Observation Overheads	
Setup	960.0 s
Exposure	1 x 7000.0 s
Readout	1 x 4.4 s
DHS Write	1 x 10.0 s
Program time	**2 hours 12 mins 54 secs**

Click here for ASCII signal spectrum.
Click here for ASCII background spectrum.
Click here for Single Exposure S/N ASCII data.
Click here for Final S/N ASCII data.


Signal and SQRT(Background) in one pixel
Signal BB
SQRT(Background) BB
Signal HSC
SQRT(Background) HSC
Signal SC
SQRT(Background) SC
e- per exposure per spectral pixel
Wavelength (nm)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
55,000
60,000
65,000
70,000
75,000
80,000
85,000
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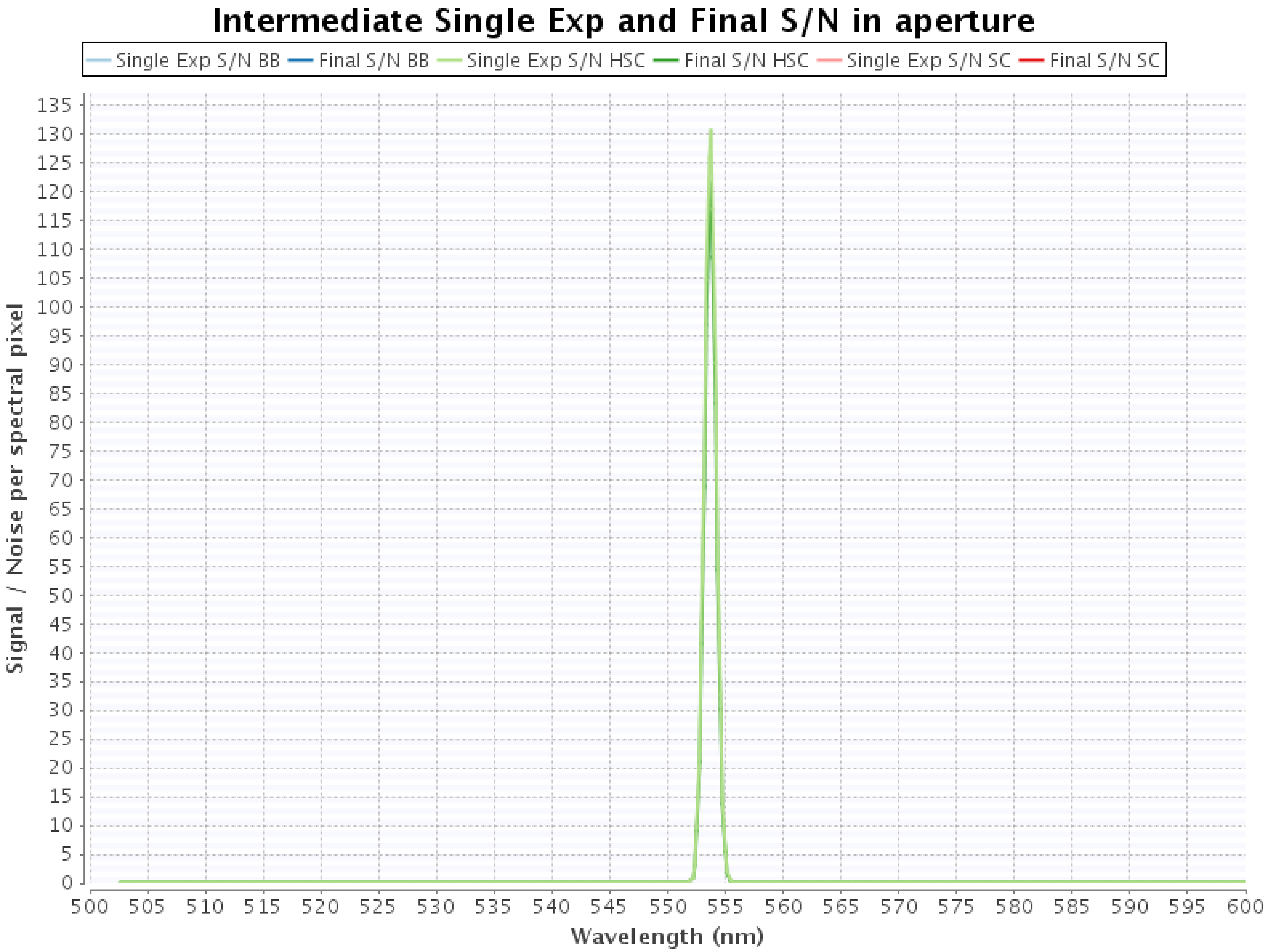

Output:
- Spectra plotted over range 500000.0 - 600000.0

Input Parameters:
Instrument: GMOS-S

Source spatial profile, brightness, and spectral distribution:
The z = 0.00000 Gaussian source with FWHM = 1.0 arcsec is an emission line at a wavelength of 0.5538 μm with a width of 550.0 km/s.
It's total flux is 2.6E-15 erg/s/cm² on a flat continuum of flux density 1.0E-19 erg/s/cm²/Å.

Instrument configuration:
Optical Components:
- Fixed Optics
- Grating Optics: B600_G5323
- Detector - Hamamatsu array

Amp gain: Low, Amp read mode: Slow
- Focal Plane Mask: Longslit 5.00 arcsec

Region of Interest: Central Spectrum

Central Wavelength: 553.8 nm
Spatial Binning (imaging mode: same in x and y, spectroscopy mode: y-binning): 4
Spectral Binning (x-binning): 4
Pixel Size in Spatial Direction: 0.323112arcsec
Pixel Size in Spectral Direction: 0.2nm

Telescope configuration:

- silver mirror coating.
- side looking port.
- wavefront sensor: oiwfs

Observing Conditions:

- Airmass: 1.50
- Image Quality: 100%   (≤ 0.78" at zenith, ≤ 1.00" on-source)
- Cloud cover: 70%
- Water Vapor: 100%
- Sky Background: 80%

Likelihood of execution: 56%

Calculation and analysis methods:

- Mode: spectroscopy
- Calculation of S/N ratio with 1 exposures of 7000.00 secs, and 100.00% of them on source.
- Analysis performed for aperture that gives 'optimum' S/N and a sky aperture that is 5.00 times the target aperture.