GEMINI OBSERVATORY

observing time request summary

Semester: 2015A **Observing Mode:** Fast Turnaround **Gemini Reference:**

Instruments: GMOS North

Time Awarded: NaN **Thesis:** Yes

Band 3 Acceptable: No

Title: **Late-Time Spectroscopy of the Extraordinary Superluminous Supernova PS1-14bj**

Principal Investigator: **Ragnhild Lunnan**
PI institution: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street Cambridge MA 02138, USA
PI status: Grad Thesis
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Co-Investigators: Ryan Chornock: Ohio University, chornock@ohio.edu
Edo Berger: Harvard University, eberger@cfa.harvard.edu
Reviewer: Ragnhild Lunnan
Mentor: Edo Berger

Partner Submission Details *(multiple entries for joint proposals)*

		PI Request		NTAC Recommendation			
Partner	**Lead**	**Time**	**Min**	**Reference**	**Time**	**Min**	**Rank**
	Total Time	*3.0 hr*	*3.0 hr*		*0.0 hr*	*0.0 hr*	

Abstract

The advent of wide-field optical time-domain surveys is providing an opportunity to discover and decipher new classes of astronomical transient phenomena. One of the most unexpected results from Pan-STARRS and other time-domain surveys is the discovery of superluminous supernovae (SLSNe), with bolometric luminosities up to 100 times higher than normal core-collapse and Type Ia supernovae (SNe), and with spectra that do not match known SN classes. These SLSNe represent a new challenge to our understanding of the deaths of massive stars, the standard core-collapse picture, and the mechanism for powering optical emission in SNe. In early 2014, Pan-STARRS discovered the unusally slowly evolving SLSN PS1-14bj at z=0.54, with a rise time > 100 days in the rest frame and generally similar properties to the claimed pair-instability supernova SN2007bi. Our follow-up shows that PS1-14bj has continued to evolve slowly, and at ~200 days past peak is still bright enough for spectroscopy. We propose to use Gemini's new Fast-Turnaround capabilities to obtain a late-time spectrum of PS1-14bj. Such a spectrum will greatly aid in distinguishing between potential explosion models for this unique object, including a possible pair-instability interpretation.

TAC Category / Keywords

GEMINI OBSERVATORY

observing time request summary

Extragalactic / Supernovae, Massive stars

Potential Problems

The submitted proposal has 1 observation with a low probability of suitable guide stars, and 1 observation with duplicate datasets in the GSA.

Scheduling Constraints

Observation Details (Band 1/2)

Observation	**RA**	**Dec**	**Brightness**	**Total Time** *(including overheads)*
PS1-14bj	10:02:08.433	03:39:19.020		3.0 hr

Potential problems: Some PAs do not have suitable guide stars (86%) ; 5 duplicate datasets in the GSA
Conditions: CC 50%/Clear, IQ 70%/Good, SB 50%/Dark, WV Any
Resources: GMOS-N LongSlit N+S None R400 OG515 (> 520 nm) 1.0 arcsec slit

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.*

The advent of wide-field optical time-domain surveys such as Pan-STARRS1 (PS1) is providing an opportunity to discover and decipher new classes of astronomical transient phenomena. One of the most exciting results from our Harvard-led PS1 transient program is the study of an emerging class of superluminous supernovae (SLSNe), with bolometric magnitudes in the range of -21 to -23 mag, i.e., 10-100 times more luminous than typical core-collapse and Type Ia SNe [1, 5, 20, 21]. These transients also exhibit spectra that are distinct from any of the known SN classes, dominated by rest-frame UV emission and broad absorption features ($\sim 10,000$ km/s) from intermediate-mass elements [5, 21, 14]. SLSNe radiate $\gtrsim 10^{51}$ erg in the optical, in excess of the kinetic energy of standard SNe, and thus represent a new challenge to our understanding of the deaths of massive stars and the mechanisms for powering optical emission in SNe.

Proposed explanations of the extreme luminosities include strong interaction with a dense circumstellar shell [4, 11, 18], or an engine-driven scenario, such as a magnetar-powered explosion [12, 24]. In general, ^{56}Ni decay can be ruled out as the main power source for SLSNe: the observed peak luminosities would require production of several solar masses of ^{56}Ni [5, 14], but this should then be accompanied by a correspondingly large ejecta mass leading to a very slowly-evolving light curve (due to the large diffusion time). Most SLSNe evolve more rapidly (Fig. 1), and a Ni-decay power source can therefore be ruled out as unphysical ($M_{\rm Ni} \gtrsim M_{\rm ej}$); [5, 21, 14]. An exception to this is the peculiar SLSN SN 2007bi [10, 25], which showed a slow decline over > 500 days consistent with the decay rate of radioactive ^{56}Co. SN 2007bi's spectrum was also distinct from most H-poor SLSNe, and consistent with a large amount of ^{56}Ni synthesized in the explosion. The implied ejecta mass, and in turn, progenitor mass, led to the claim of SN 2007bi being a pair-instability supernova (PISN) [10], but this interpretation is controversial, as other models for SLSNe can also fit the observed data [25, 3, 19]. The main problem is that SN 2007bi was discovered near peak and its rise time to maximum light was not well constrained. Other surveys have since found SLSNe with similar slow decline rates and spectroscopic properties, but with short rise times incompatible with a PISN interpretation, thus casting further doubts on the nature of SN 2007bi [19].

In the last months of the PS1 survey, we discovered another SLSN showing striking similarities to SN 2007bi: PS1-14bj. An early Gemini spectrum (Fig. 2) shows that PS1-14bj does not resemble either normal Type Ic SNe or "typical" H-poor SLSNe (which are bluer, and do not show strong features in this wavelength range) but matches an early-time spectrum of SN 2007bi very well. Unlike SN 2007bi, however, PS1-14bj was discovered on the rise, and showed an observed rise-time of $\gtrsim 100$ days in the rest frame (Figure 3), longer than any published SLSN and consistent with PISN predictions (Fig. 1; [9, 13]). Thus, PS1-14bj is unique amongst SLSNe discovered to date, and will provide an important test case for possible explosion models, including the ^{56}Ni decay / PISN scenario.

Here, we propose to use Gemini's new Fast-Turnaround capabilities to obtain a late-time spectrum of PS1-14bj. The observed decline rate shows that PS1-14bj has continued to evolve very slowly, and will still be bright enough for spectroscopy during the FT observing window (Fig. 3). Such a late-time spectrum will contribute crucial information about the interpretation of this event, including ejecta composition from nebular features in the spectrum, and placing limits on light curve contributions from circumstellar interaction by searching for Hα line emission. We note that SN 2007bi, the only similar object to PS1-14bj in the published literature, had highly unusual spectra showing a mix of photospheric and nebular features [10, 25].

The Gemini spectrum will be leveraged with our existing multiband light curve and early-time spectroscopic data from Gemini, PS1, Magellan, and MMT. These time-critical observations are an ideal match for the Fast-Turnaround program because at the regular 2015A deadline the object was still in solar conjuction, so we lacked confirmation of the continued high luminosity and slow late-time decline rate of the source. The Gemini program only requires a single epoch of observations, will add important information about a unique event, and will be rapidly analyzed and published along with our other data on this object.

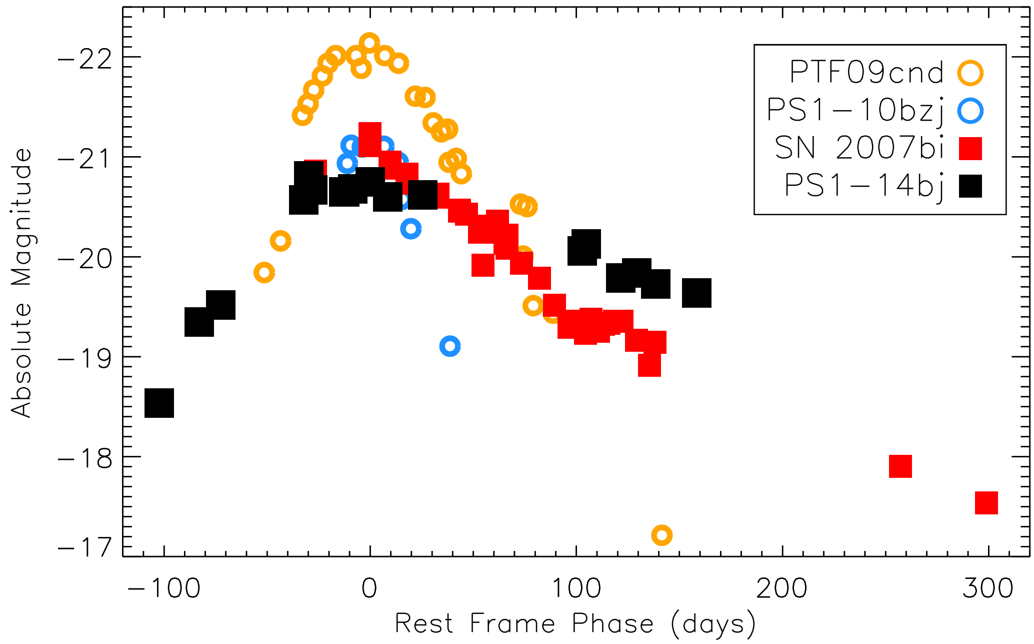


Figure 1: Observed r-band light curve of PS1-14bj to date (black), compared to the more typical H-poor SLSNe PTF09cnd (orange; [21]) and PS1-10bzj (blue; [14]), as well as to SN 2007bi (red; [10, 25]). Typical H-poor SLSNe show a range of peak luminosities, but generally evolve too fast for the light curves to be explained by ^{56}Ni decay. By contrast, PS1-14bj and SN 2007bi both evolve much more slowly, with a late-time slope consistent with ^{56}Co decay. PS1-14bj is currently the only SLSN where both a slow ($\gtrsim$ 100 day) rise-time and a slow late-time decay has been observed, as SN 2007bi lacked data on the rise.

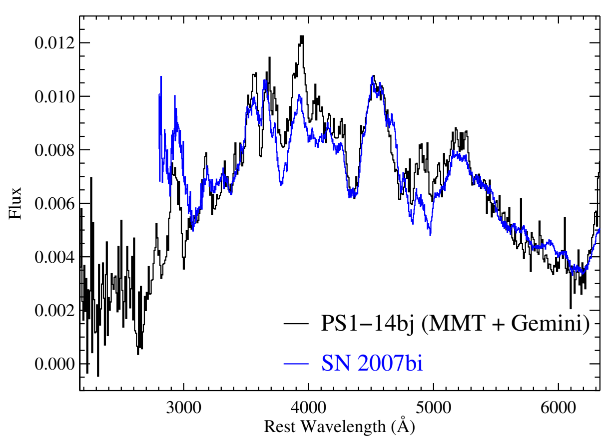


Figure 2: Classification spectrum of PS1-14bj at $z = 0.54$ (black), taken before maximum light, and one of the last to be observed as part of our Gemini PS1 follow-up program. The spectrum does not resemble the majority of H-poor SLSNe, which are characterized by a blue continuum with no strong features in this wavelength range other than oxygen [21]. Instead, the spectrum is strikingly similar to the unusual SLSN 2007bi (blue; [10]).

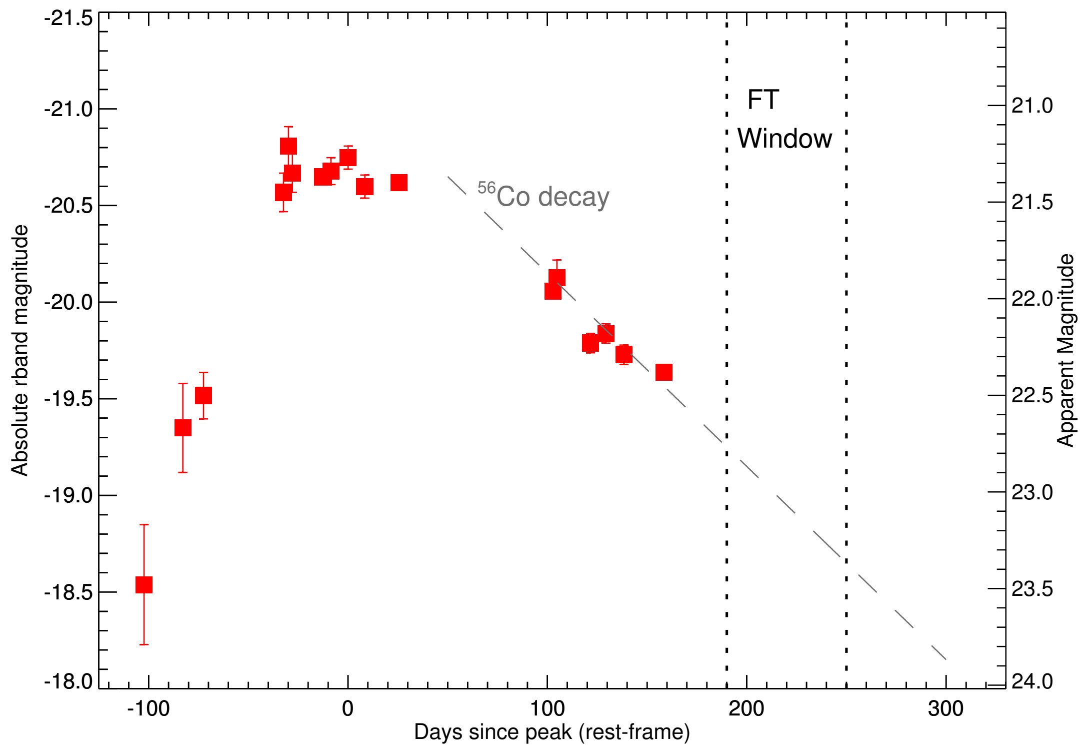


Figure 3: Observed r-band light curve of PS1-14bj to date, obtained as part of our multi-wavelength followup campaign. Note the extremely slow evolution of the light curve and the $\gtrsim 100$ day rise time, unique among SLSNe discovered to date and consistent with expectations from pair-instability SN models. The slow decline observed thus far is consistent with ^{56}Co (gray dashed line). The time period covered by this Fast Turnaround proposal cycle is indicated by the dotted lines.

References: [1] Barbary, K., et al. 2009, ApJ, 690, 1358 • [2] Berger, E., et al. 2012, ApJ, 755, L29 • [3] Chatzopoulos, E., et al. 2013, ApJ, 773, 76 • [4] Chevalier, R. A., & Irwin, C. M. 2011, ApJ, 729, L6 • [5] Chomiuk, L., et al. 2011, ApJ, 743, 114 • [6] Chornock, R., et al. 2013, ApJ, 767, 162 • [7] Chornock, R., et al. 2014, ApJ, 780, 44 • [8] Dessart, L., et al. 2012, MNRAS, 426, L76 • [9] Dessart, L., et al. 2013, MNRAS, 428, 3227 • [10] Gal-Yam, A., et al. 2009, Nature, 462, 624 • [11] Ginzburg, S., & Balberg, S. 2012, ApJ, 757, 178 • [12] Kasen, D., & Bildsten, L. 2010, ApJ, 717, 245 • [13] Kasen, D., Woosley, S. E., & Heger, A. 2011, ApJ, 734, 102 • [14] Lunnan, R., et al. 2013, ApJ, 771, 97 • [15] Lunnan, R., et al. 2014, ApJ, 787, 138 • [16] Lunnan, R., et al. 2015, ApJ, submitted, arXiv:1411.1060 • [17] McCrum, M., et al. 2014, MNRAS, 437, 656 • [18] Moriya, T. J., et al. 2013, MNRAS, 428, 1020 • [19] Nicholl, M., et al. 2013, Nature, 502, 346 • [20] Quimby, R. M., et al. 2007, ApJ, 668, L99 • [21] Quimby, R. M., et al. 2011, Nature, 474, 487 • [22] Smith, N., et al. 2007, ApJ, 666, 1116 • [23] Smith, N., et al. 2008, ApJ, 686, 467 • [24] Woosley, S. E. 2010, ApJ, 719, L204 • [25] Young, D. R., et al. 2010, A&A, 512, A70

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)*

The recently-concluded Pan-STARRS1 (PS1) survey used a dedicated 1.8 m survey telescope to provide the first deep multi-band all-sky time-domain optical survey, using two primary modes: the 3Pi and the medium-deep surveys (MDS). The depth of the MDS ($\sim$23.5 AB mag per visit) allowed us to discover SLSNe at higher redshifts (median $\langle z \rangle \approx 1$) than other contemporaneous surveys (e.g., PTF, CRTS), which has enabled our studies of the rest-frame ultraviolet emission of these objects (e.g., [5, 2, 14]) and the host galaxy demographics over a large range in redshift [15, 16].

PS1-14bj was discovered in the final months of the MDS in late 2013. The rolling nature of the PS1 survey allowed us to obtain multiband PS1 photometry at very early epochs, starting $\sim$100 days before maximum light. After the MDS survey ended, we have been collecting multicolor optical and near-infrared photometry of PS1-14bj using a suite of large optical telescopes (Magellan, MMT, and some Gemini spectroscopy acquisition images) to define both the shape of the bolometric light curve and the evolution of the spectral energy distribution over time.

We were able to obtain several epochs of optical spectroscopy in the months surrounding maximum light through our PS1 Gemini followup program (GN-2014A-Q-76; Fig. 2). These data document the close correspondence of PS1-14bj with SN 2007bi and the slow spectral evolution near maximum light. The early-time spectra demonstrate a lack of emission lines that would be expected from strong circumstellar interaction, as well as the distinction from the bluer spectra of normal hydrogen-poor SLSNe.

We have continued to follow the light curve of PS1-14bj to late times with our other available facilities. Determing the power source of the continued high luminosity of PS1-14bj at late times and the slow photometric decline rate is the main goal of these observations. *Late-time spectroscopy of PS1-14bj is necessary to distinguish between the various models proposed to power SLSNe.*

At the latest observed epochs, the spectra of SN 2007bi exhibited strong nebular emission lines from Mg I] λ4571, [Fe II] blends near 5200 Å and [O I] λ6300, all of which fall into the spectral range of our proposed observations. The unusually strong [Fe II] emission at late epochs was used as evidence that the ejecta of SN 2007bi contained large amounts of iron, presumably synthesized as ^{56}Ni in the explosion, which in turn was argued to favor the hypothesis of a pair-instability explosion [10]. The proposed observations of PS1-14bj will allow us to test whether the spectra are dominated by these nebular emission features at a phase of $\sim$220 days after maximum light.

Conversely, Dessart and collaborators have argued that explosions that synthesize large amounts of ^{56}Ni should experience large amounts of line blanketing in the near-UV from iron-peak elements [8, 9]. Even SN 2007bi was too blue for their pair-instability models and they favored a central engine like a magnetar to provide continued energy input and keep the spectra as hot and highly ionized as observed. We must use spectroscopy to compare to their models, as photometry alone does not distinguish the mechanisms.

One class of models proposed to explain the prolonged luminous emission from slowly-evolving SLSNe is ongoing strong circumstellar interaction with material lost by the progenitor star in the years prior to explosion. If this material is hydrogen rich, it should result in strong Hα emission, as has been seen in Type II SLSNe. At the redshift of PS1-14bj, Hα is near 10,100 Å, just outside the wavelength range of traditional CCD spectrographs. However, the superb red sensitivity of GMOS, coupled with the clear sky subtraction afforded by nod-and-shuffle observations will allow us to detect an Hα line as luminous as those seen in SNe 2006gy and 2006tf [22, 23], should it be present. If the circumstellar material is hydrogen poor but helium rich, the strongest expected line will be He I λ5876, which will also fall in our spectral window.

Proprietary Period: 6 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-Gemini facilities, including those available through NOAO. 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 a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?*

Our target, PS1-14bj, was discovered near the end of the Pan-STARRS Medium Deep Survey, and we have followed it with a number of facilities in order to obtain a multi-filter light curve and spectral sequence. The proposed Gemini Fast-Turnaround data will be analyzed in context of this already obtained data from Gemini, PS1, MMT, and Magellan, and rapidly published. The late-time spectra proposed here will provide unique information to complement the early-time spectra and late-time photometry. We have also observed PS1-14bj in the X-rays with XMM (PI: Margutti) as part of an effort to look for the proposed ionization breakout signature predicted by Metzger et al. for magnetar-powered models.

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.*

Ragnhild Lunnan is also the PI of programs GN-2014B-Q-62 and GN-2015A-Q-54, which aim to obtain imaging of the host galaxies of high-redshift SLSNe from Pan-STARRS. Some data were obtained for GN-2014B-Q-62 in January 2015 and reductions are underway; as 2015A has not yet started no data have been obtained.

This proposed program is complementary to our recently completed Gemini ToO program for spectroscopic followup of Pan-STARRS SLSNe, and early spectra of PS1-14bj were obtained through that program (GN-2014A-Q-76; Fig. 2). Data from these programs have been published by Lunnan et al., 2013 [14], Chornock et al., 2013, 2014 [6, 7], Berger et al., 2012 [2] and Chomiuk et al., 2011 [5].

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the exposure times, and the constraints requested (seeing, cloud cover, sky brightness, and, if appropriate, water vapor). If applying for instruments on both Gemini North and South, state the time request for each site. If a Band 3 allocation is acceptable, give the Band 3 time requested from each partner.*

At a redshift $z = 0.54$, important features like the nebular [OI]λ6300 line and Hα are redshifted out to $\sim$1μm, requiring a red setup and excellent sky subtraction in the near-infrared. We choose the GMOS R400 grism with the OG515 order-blocking filter. We plan to observe at two central wavelengths of 8100 and 8150 Å to cover the chip gaps, and also request nod-and-shuffle mode to ensure the most reliable sky subtraction.

We use the observed brightness and color evolution of PS1-14bj to guide our input to the Gemini ITC, and design the observations to reach a S/N $>$ 1–2 per spectral element. The supernova spectral features are broad ($\sim 10^4$ km/s) and so the spectra can be further binned in post-processing to achieve higher S/N for those features. For the expected brightness of PS1-14bj during the Fast-Turnaround observing window ($r \sim 23$ AB mag; Fig. 3) we find that at least 2 hours (4x1800s) of on-source exposure time is required to achieve this, with 2x2 binning, a 1″slit, and 80%-ile conditions. We propose to use a standard A=60s exposure time and 15 nod-and-shuffle cycles for each of the four 1800s exposures (shuffling by 1536 pixels), with one pair of exposures observed at each of the two requested central wavelengths. **Including nod-and-shuffle, calibration, and acquisition overheads, our total requested time is 3 hours.**

In addition to a blackbody input spectrum, we also ran the ITC with a single emission line as input, ensuring that this setup will also be sensitive enough to detect or place limits on potential Hα emission. This will again allow us to evaluate the contribution from strong circumstellar interaction to the SN luminosity. We use line luminosities and widths typical of previously observed superluminous Type IIn SNe (SN 2006tf, SN 2006gy [22, 23]), and find that our setup will detect such Hα emission at S/N $>$ 3 per spectral pixel at the peak (and higher S/N when integrated over the line profile).

Band 3 Plan *If applying for queue time and it is acceptable for the proposal to be scheduled in Band 3, describe the changes to be made to allow it to be successful in Band 3 (limit text to half a page). Band 3 observations are used to fill the queue when no Band 1 or 2 programs are available. Successful Band 3 programs generally use poorer than median observing conditions, have targets away from the most popular regions of the sky, do not require strict timing or other constraints, and do not require special instrument configurations.*

Classical Backup Program *If applying for classically scheduled time, describe the program you will pursue should the weather be worse than the requested observing conditions (limit text to half a page).*

Justify Target Duplications *If your targets have been previously observed by Gemini using similar or identical setups to those proposed here, justify the duplication below. Duplicate observations can be identified through a search of the Gemini Science Archive.*

PS1-14bj was observed in the spring of 2014 with GMOS as part of our overall ToO Pan-STARRS follow-up and classification program (GN-2014A-Q-76). The proposed observations here aim to obtain a late-time spectrum, and are thus complementary to the early spectra previously obtained, rather than a duplication.

ITC Examples *Attach representative Gemini ITC output for each instrument requested.*

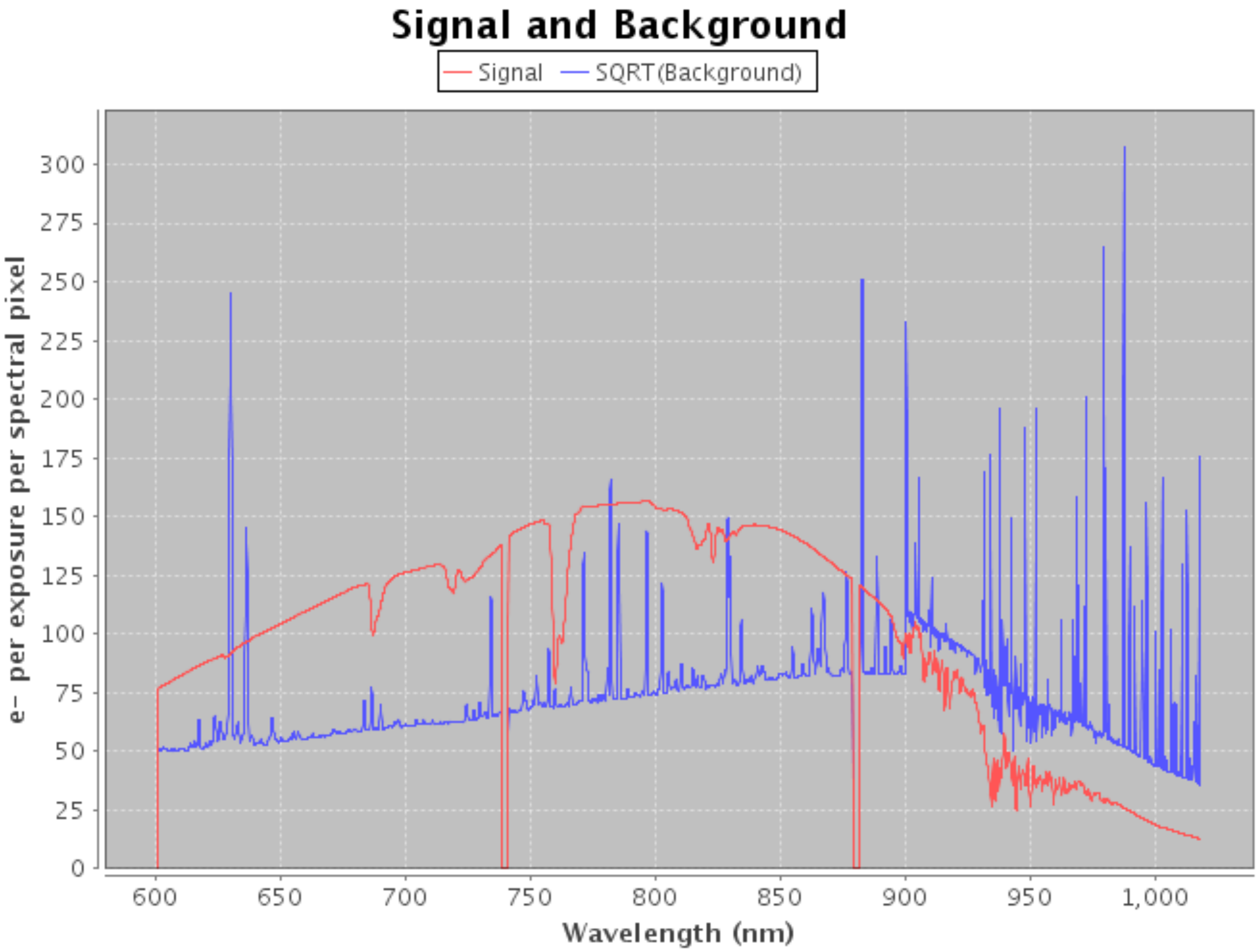
Gemini Integration Time Calculator GMOS version 5.0

Click here for help with the results page.
Read noise: 3.6
software aperture extent along slit = 1.32 arcsec
fraction of source flux in aperture = 0.69
derived image size(FWHM) for a point source = 0.94arcsec

Sky subtraction aperture = 5.0 times the software aperture.

Requested total integration time = 7200.00 secs, of which 7200.00 secs is on source.

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 Background
Signal
SQRT(Background)
e- per exposure per spectral pixel
0
25
50
75
100
125
150
175
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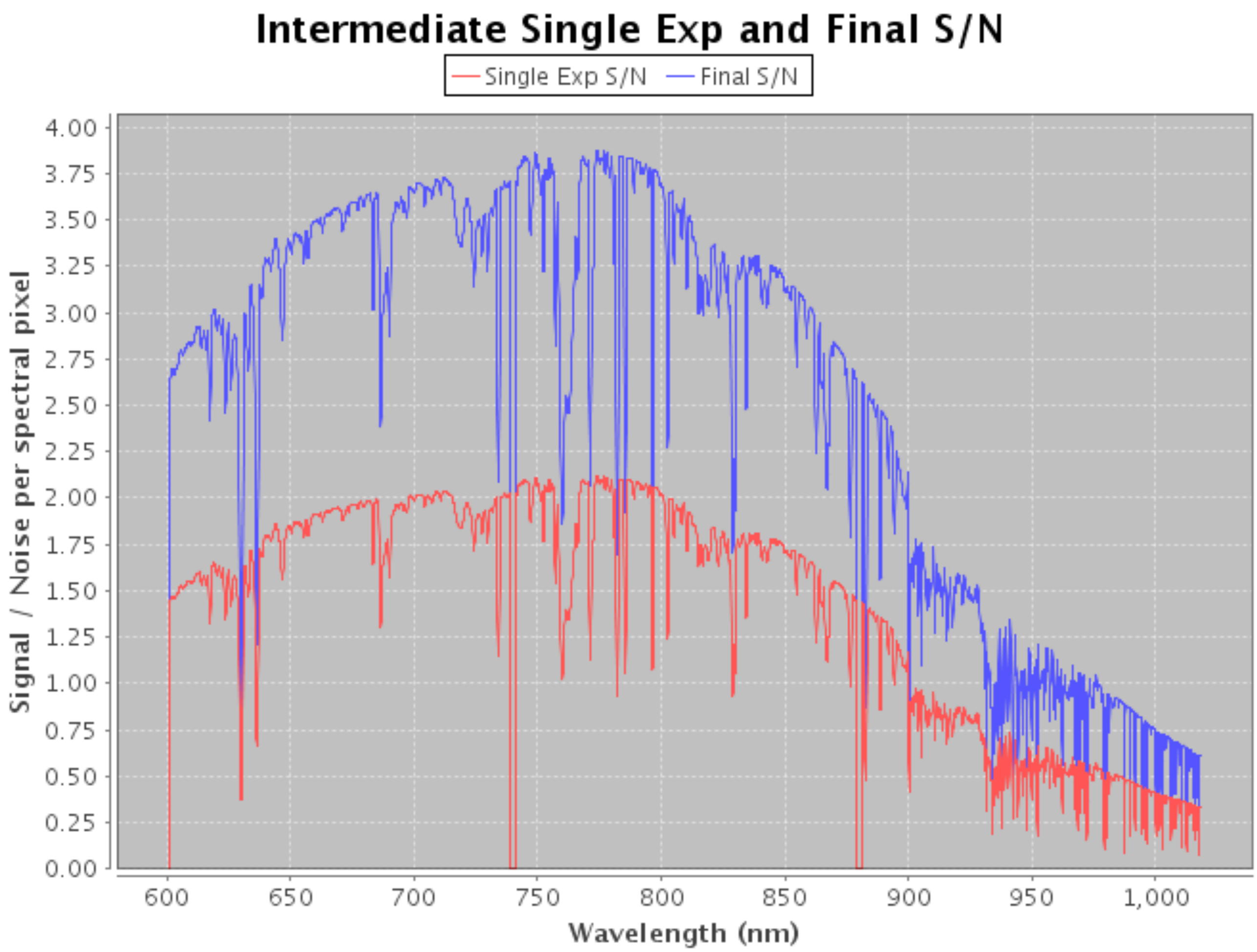
250
275
300
600
650
700
750
800
850
900
950
1,000
Wavelength (nm)



Output:

- Spectra autoscaled.

Input Parameters:

Instrument: GMOS-N

Source spatial profile, brightness, and spectral distribution:
The z = 0.54 point source is a 7000.0K Blackbody, at 23.0 ABmag in the R band.

Instrument configuration:
Optical Components:

- Filter: og515
- Fixed Optics
- Grating Optics: R400_G5305
- Detector - EEV DD array
- Focal Plane Mask: slit1.0

Central Wavelength: 810.0 nm
Spatial Binning: 2
Spectral Binning: 2
Pixel Size in Spatial Direction: 0.1454arcsec
Pixel Size in Spectral Direction: 0.1346nm

Telescope configuration:

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

Observing Conditions:

- Image Quality: 70.00%
- Sky Transparency (cloud cover): 50.00%
- Sky transparency (water vapour): 100.00%
- Sky background: 50.00%
- Airmass: 1.50

Frequency of occurrence of these conditions: 17.50%

Calculation and analysis methods:

- mode: spectroscopy
- Calculation of S/N ratio with 4 exposures of 1800.00 secs, and 100.00 % of them were on source.
- Analysis performed for aperture that gives 'optimum' S/N and a sky aperture that is 5.00 times the target aperture.

Gemini Integration Time Calculator
GMOS version 5.0

Click here for help with the results page.
Read noise: 3.6
software aperture extent along slit = 1.32 arcsec
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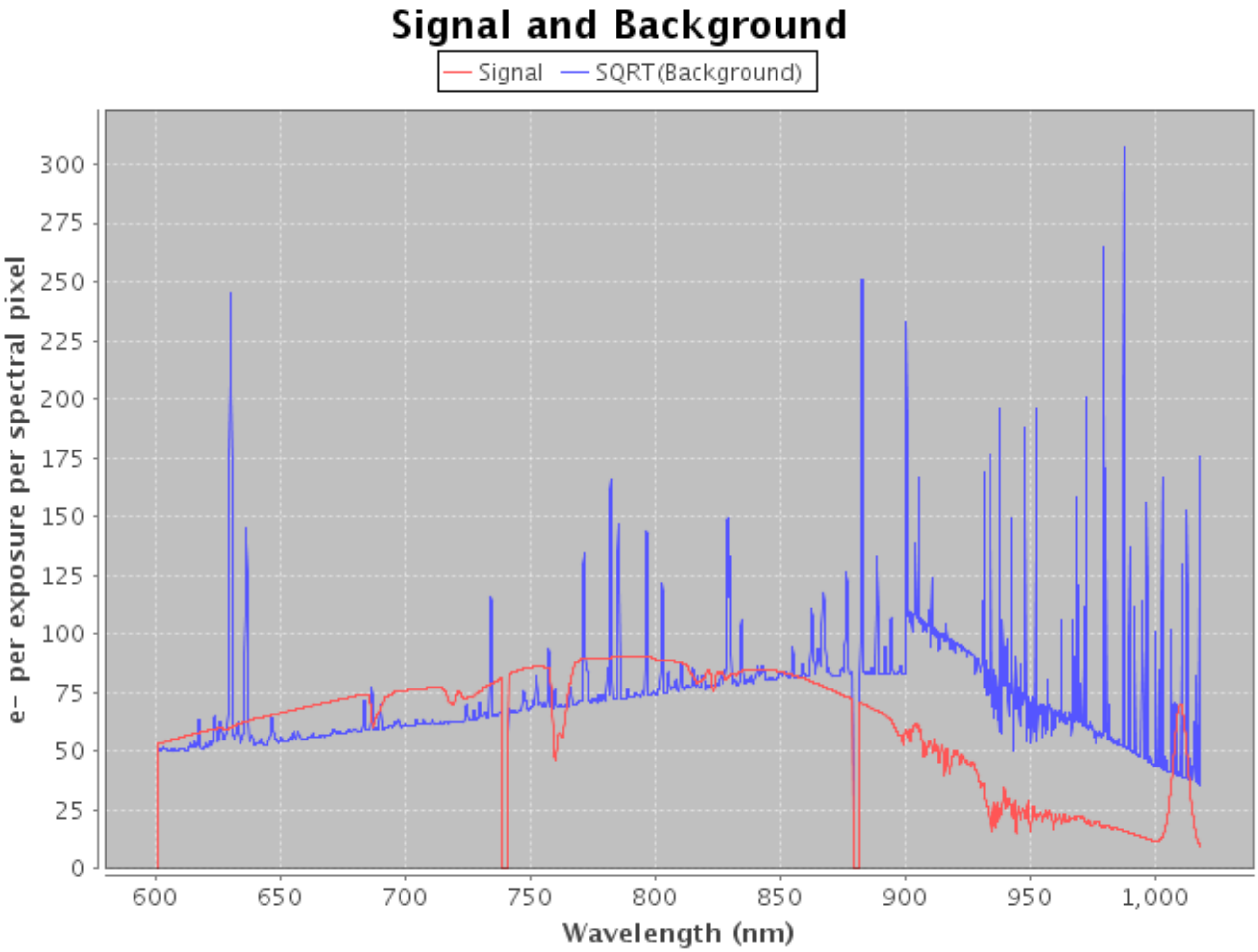
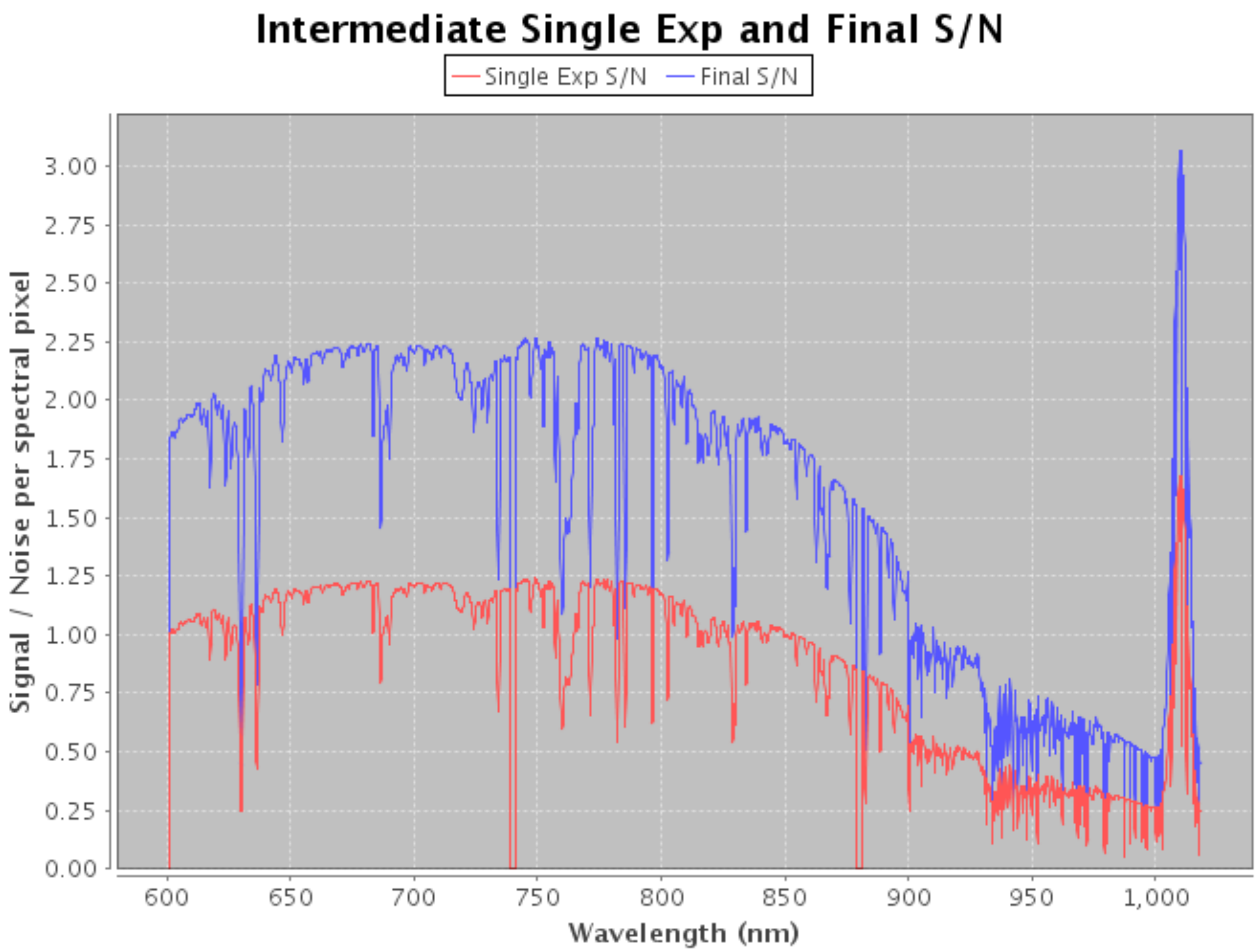

Signal and Background
Signal
SQRT(Background)
e- per exposure per spectral pixel
Wavelength (nm)
0
25
50
75
100
125
150
175
200
225
250
275
300
600
650
700
750
800
850
900
950
1,000



Output:

- Spectra autoscaled.

Input Parameters:
Instrument: GMOS-N

Source spatial profile, brightness, and spectral distribution:
The z = 0.54 point source is an emission line, at a wavelength of 0.6560 microns, and with a width of 2000.00 km/s.
It's total flux is 3.0E-16 ergs_flux on a flat continuum of flux density 1.0E-18 ergs_fd_wavelength.

Instrument configuration:
Optical Components:

- Filter: og515
- Fixed Optics
- Grating Optics: R400_G5305

- Detector - EEV DD array
- Focal Plane Mask: slit1.0

Central Wavelength: 810.0 nm
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Pixel Size in Spectral Direction: 0.1346nm

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- wavefront sensor: oiwfs

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- Sky background: 50.00%
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Frequency of occurrence of these conditions: 17.50%

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- mode: spectroscopy
- Calculation of S/N ratio with 4 exposures of 1800.00 secs, and 100.00 % of them were on source.
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