SNIFS Background Subtraction Requirements & Methods

G. Aldering
Institute for Nuclear and Particle Astrophysics,
E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720.

Abstract

The background-subtraction methodology for supernova studies with SNIFS is discussed, with the goal of providing sufficient background on the methodology to allow the SNfactory collaboration to make the best choice regarding the need for additional sky-subtraction optics for the red and/or blue spectroscopy channels. It is shown that, in the absence of unmodeled errors, supernova photometry requires only that a final reference observation be obtained with SNIFS, and that the relative shapes of the PSF's of the spectrograph and imager channels be determined. A solution to the later problem – based on reconstruction of the wavefront error using defocused stellar images – is outlined, but not explored in detail.

The sky subtraction needs for galaxy studies are also discussed. Minimal galaxy studies should be possible in the blue without sky-subtraction optics. However, detailed studies, especially in the red, require sky-subtraction optics. An alternative to implementation of sky-subtraction optics includes use of more suitable ancillary instrumentation. This loses the advanatage of parallel observations of the host galaxies which SNIFS provides, but may in any case be dictated by the high signal-to-noise required for the study of, e.g., the galaxy ages and abundances.

1 The Nature of the Background

The primary goal of the SNIFS instrument is to produce spectrophotometry for its target SNe. For each observation, SNIFS will produce a spectral image of a supernova (SN) superposed on its host galaxy and the foreground night sky. This requires the subtraction of the combined light of the host galaxy and the night sky.

The host galaxy component can range from smooth and faint to highly-structured and bright. This component is intrinsically stable, but will be blurred to varying extents by atmospheric seeing. The night sky is spatially smooth at optical wavelengths (over scales of arcminutes), but the spectral shape and amplitude can vary over a large range depending on auroral activity, the amount of moonlight, and ecliptic coordinates.

Leinert et al. (1998) describe the properties of the night sky in some detail. As shown in Fig. 1, the OH emission lines dominate the sky spectrum in the red. These lines are quite variable on timescales of minutes (Glazebrook & Bland-Hawthorn, 2001). There are also numerous atmospheric absorption features in the red due to O_2 and H_2O; the strength and structure of these features will vary with airmass and meteorological conditions. The blue spectral region is relatively free of strong emission lines at sites free of light pollution (Osterbrock & Martel, 1992; Osterbrock et al., 1996; Osterbrock, Fulbright, & Bida, 1997; Osterbrock et al., 2000), however, it will contain numerous absorption features due to scattered sunlight both at low ecliptic latitudes or when the moon is up. Sunlight reflected off the moon or interplanetary dust is reddened slightly, however, once it gets scattered in the atmosphere it is quite blue since Rayleigh scattering – and to some extent aerosal

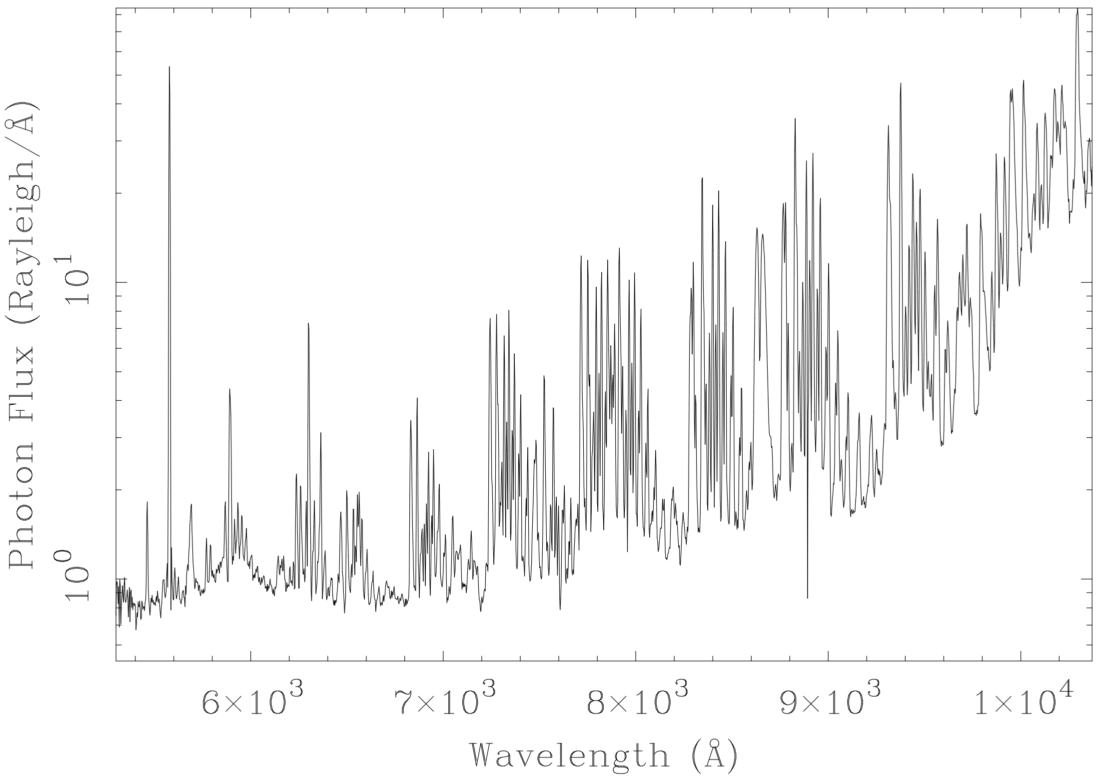

Figure 1: Spectrum of the dark night sky; note the logarithmic scaling

scattering – preferentially scatter blue light. The bottom line is that the sky spectrum for each SN observation will be different, and sky subtraction based on models or templates is insufficient.

2 Background subtraction techniques for SNe

2.1 Interpolation

A fairly standard technique for subtracting the background is based on using the background well away from the source to interpolate the background at the source location. For SNe located on a very smooth low-order background, this may be adequate. This would occur in the case of SNe situated far from their host galaxies. This method is unlikely to be adequate for SNe imbedded in the disk of a spiral galaxy or located in the very steep inner portion of an elliptical galaxy.

Interpolation techniques are well known, so implimentation details will not be discussed further other than to note that basis functions which have better physical motivation than polynomials (such as exponential, de Vacouleurs, or Sersic profiles with positivity constraints) might prove advantageous.

2.2 Final reference spectral image

In the case of broadband photometry of SNe a deep image of the host galaxy is obtained without the SN present and then for all the images of the SN it is scaled in flux and subtracted. In some cases a sufficiently good image of the host galaxy prior to the SN event exists. More often, an image is taken after the SN has faded; a waiting period of roughly one year after the SN explosion is sufficient. These images are referred to as "final reference images." The SNfactory will require final reference images for all its SNe since spectral imaging like that of SNIFS will not have been obtained prior to the SNe explosions.

A further complication in subtracting a final reference image is that the resolution of the SN image and the final reference image must be made to match via convolution. In the case of spectral imaging, this requires the same wavelength as well as spatial resolution. As long as the SN and final reference images are obtained with SNIFS, the wavelength resolution will be very nearly the same. However, atmospheric seeing and optical aberrations (due to Seidel aberrations as well as optical misalignment and focusing errors) will result in different spatial resolutions.

2.3 Methodology

Let us denote the optical point spread function at the location of the spectrograph microlens array as $P_s(x_s, y_s, \lambda, t_j)$. x_s, y_s indicate the image location on the microlens array, λ is the wavelength of observation, and t_j denotes a specific time interval in which the spectrograph and imager are simultaneously observing. (Spatial and wavelength resolution set by the spectrograph optics will not be considered here since these spatial and spectral resolution terms are not very time-dependent and are generally easy to measure from arc lines.) Let us further denote the optical point spread function for the $i \in \{1, ..., N\}$ filters of the photometry channel as $P_p(x_p, y_p, \lambda_i, t_j)$. Both PSF's will have a common component due to atmospheric seeing, $A(\lambda, t_j)$ as well as a components, $O_s(x_s, y_s, \lambda, t_j)$ and $O_p(x_p, y_p, \lambda_i, t_j)$ due to optical elements (telescope, filters, mirrors, lenses, etc.). That is, we can write

$$P_s(x_s, y_s, \lambda, t_j) = A(\lambda, t_j) \otimes O_s(x_s, y_s, \lambda, t_j)$$

and

$$P_p(x_p, y_p, \lambda_i, t_j) = A(\lambda_i, t_j) \otimes O_p(x_p, y_p, \lambda_i, t_j)$$

It is expected that the widths, W, of these terms will satisfy

$$W(O_s) \sim W(O_p) \ll W(A)$$

for all $x_s, y_s, x_p, y_p, \lambda$, and t_j, but this has yet to be demonstrated.

The host galaxy spectral image is assumed to be time independent, and will be denoted as $G(x, y, \lambda)$. The supernova itself is simply a delta function, $F_{SN}(\lambda, t_j)\delta(x_{SN}, y_{SN})$, spatially convolved with P_s. (Note that in the current configuration the supernovae cannot be observed simultaneously on both the spectrograph and imager.) The sky, $S(\lambda, t_j)$, is assumed to have no spatial structure.

The available data will be a set of M SN spectral images:

$$I_{s_j} = P_s(x_s, y_s, \lambda, t_j) \otimes [F_{SN}(\lambda, t_j)\delta(x_{SN}, y_{SN}) + G(x, y, \lambda) + S(\lambda, t_j)]$$

a set of photometry channel images filled with anonymous non-variable stars:

$$I_{p_j} = P_p(x_p, y_p, \lambda_i, t_j) \otimes \left[\sum_k F_{*_k}(\lambda)\delta(x_{*_k}, y_{*_k}) + S(\lambda_i, t_j) \right]$$

and a final reference spectral image:

$$I_{s_r} = P_s(x_s, y_s, \lambda, t_r) \otimes [G(x, y, \lambda) + S(\lambda, t_r)] \, .$$

If a separate sky channel is implemented, if will provide spectral images of blank sky:

$$I_{sso_j} = P_{sso}(x_{sso}, y_{sso}, \lambda, t_j) \otimes S(\lambda, t_j),$$

$$I_{sso_r} = P_{sso}(x_{sso}, y_{sso}, \lambda, t_r) \otimes S(\lambda, t_r).$$

The sky-subtraction optics (SSO) module may produce slightly difference wavelength resolution, but that can be treated separately. Using this dataset we wish to solve for the values of $F_{SN}(\lambda, t_j)$ for $j \in \{1, ..., M\}$.

Recalling that the convolution of a sum equals the sum of convolutions (i.e., convolution is distributive under addition), and that we have assumed that there is no spatial structure in the sky, the sky can be taken out of the spatial convolution. Enforcing normalization on the PSF-related spatial convolution kernals at each λ (which in practice must be accomplished using calibration) then gives:

$$I_{s_j} = P_s(x_s, y_s, \lambda, t_j) \otimes [F_{SN}(\lambda, t_j)\delta(x_{SN}, y_{SN}) + G(x, y, \lambda)] + S(\lambda, t_j)$$

$$I_{p_j} = P_p(x_p, y_p, \lambda_i, t_j) \otimes \sum_k F_{*_k}(\lambda)\delta(x_{*_k}, y_{*_k}) + S(\lambda_i, t_j),$$

$$I_{s_r} = P_s(x_s, y_s, \lambda, t_r) \otimes G(x, y, \lambda) + S(\lambda, t_r),$$

and

$$I_{sso_j} = S(\lambda, t_j),$$

$$I_{sso_r} = S(\lambda, t_r).$$

It is apparent that in the general case $F_{SN}(\lambda, t_j)$ cannot be measured from I_{s_j} alone. If $G = 0$, interpolative sky subtraction can be performed since S has no spatial structure.

The ideal general case will be established and treated first. In general one obtains

$$F_{SN}(\lambda, t_j)\delta(x_{SN}, y_{SN}) = \frac{1}{P_s(x_s, y_s, \lambda, t_j)} \otimes I_{s_j} - I_{sso_j} - G(x, y, \lambda).$$

The host galaxy is given by

$$G(x, y, \lambda) = \frac{1}{P_s(x_s, y_s, \lambda, t_r)} \otimes I_{s_r} - I_{sso_r},$$

which leads to

$$F_{SN}(\lambda, t_j)\delta(x_{SN}, y_{SN}) = \left[\frac{1}{P_s(x_s, y_s, \lambda, t_j)} \otimes I_{s_j} - \frac{1}{P_s(x_s, y_s, \lambda, t_r)} \otimes I_{s_r} \right] - \left[I_{sso_j} - I_{sso_r} \right]$$

upon substituion.

In practice deconvolution is ill-posed, and in this case it is unnecessary. Rather than performing a spatial deconvolution it is sufficient to spatially convolve the image with the best PSF to match the image with the worst PSF for each j, r pair. For simplicity, it will be assumed that the PSF for the final reference spectral image is as good as the best SN spectral image, that is, that

$$W(P_s(x_s, y_s, \lambda, t_r)) \leq W(P_s(x_s, y_s, \lambda, t_j)) \text{ for } j \in \{1, ..., M\}.$$

Then there will be a spatial convolution (as opposed to deconvolution) kernal,

$$K_s(x_s, y_s, \lambda, t_{j,r}) = P_s(x_s, y_s, \lambda, t_j) \otimes \frac{1}{P_s(x_s, y_s, \lambda, t_r)}$$

which can be used to blur the reference observations to the spatial resolution of the SN observations. This approach gives

$$F_{SN}(\lambda, t_j) P_s(x_{SN}, y_{SN}, \lambda, t_j) = \left[I_{s_j} - K_s(x_s, y_s, \lambda, t_{j,r}) \otimes I_{s_r}\right] - \left[I_{sso_j} - I_{sso_r}\right].$$

Note again that, under the assumption that the sky has no spatial structure, spatial convolutions can be performed on images which have not been sky-subtracted. The image resulting from executing only the first half of the above equation is expected to be spatially flat except for the presence of the SN, therefore the SN alone can be measured by interpolative subtraction of structureless background. That is,

$$F_{SN}(\lambda, t_j) P_s(x_{SN}, y_{SN}, \lambda, t_j) = \left[I_{s_j} - K_s(x_s, y_s, \lambda, t_{j,r}) \otimes I_{s_r}\right] - \mathcal{F}(\lambda),$$

where $\mathcal{F}(\lambda) \equiv S(\lambda, t_j) - S(\lambda, t_r)$ is a function of wavelength but has no spatial dependence. This is a critical point since it means that — technically speaking — sky-subtraction optics are not required for the purposes of SN spectro-photometry. Note also that the quality of the result can be judged by whether all structure other than the SN has been eliminated after the first half of the above equation is calculated. Such evaluation is necessary since $P_s(x_s, y_s, \lambda, t_j)$ and $P_s(x_s, y_s, \lambda, t_r)$ are not known quantities; they must be estimated from the SN or other point sources in the $6'' \times 6''$ spectrograph field of view or from the $P_p(x_{p_k}, y_{p_k}, \lambda_i, t_j)$ and $P_p(x_{p_k}, y_{p_k}, \lambda_i, t_r)$ measured in the photometry channel. This latter approach is discussed in the Appendix.

3 Sky Subtraction Needs for Galaxy Studies

Supernova host-galaxy redshifts are required as part of the main SNfactory science program. In addition, there is scientific interest in the study of the intrinsic properties of these host galaxies. Finally, University of Hawaii observers may have their own interests in studying extended sources. Without subtraction of the night sky, the range of possible studies becomes limited.

In the blue, where the sky is not highly structured, it will be possible to measure absorption- and emission-line redshifts, as well as velocity dispersions, without sky subtraction. Emission line luminosities and ratios (but not equivalent widths) can also be measured by interpolating in wavelength around features of interest. However, absorption-line abundance and age studies will be at the mercy of sky subtraction errors. A correct estimate of the sky level will be possible only if the outer lenses of the IFU are free of galaxy light.

In the red (see Fig. 1) it may be difficult to perform any meaningful analysis of the host galaxy without sky subtraction due to the highly structured and variable nature of the OH emission. Key lines such as Hα and the Ca II triplet would be difficult to work with for all but the brightest or most compact galaxies. Since galaxies are centrally-concentrated, one could eliminate the sky contribution while retaining some of the galaxy contribution by subtracting the spectra of the outer lenses of the IFU. The amount by which the galaxy signal is erroneously suppressed will depend on how much galaxy light is in the periphery of the IFU field compared to the center. With this approach, galaxy redshifts probably could be measured in the red for most SN host galaxies.

As redshifts are the only SNfactory *requirement* for host galaxies, and because it is plausible that redshifts can be measured without proper sky subtraction, the SNfactory could consider a separate sky-subtraction optical channel unnecessary. Indeed, for more detailed host-galaxies studies it might prove more effective to use other instrumentation better suited to these tasks. For instance, experience with long-slit spectrographic observations of SN host galaxies from the SCP's Spring 1999 Nearby Campaign indicates that for the spectra of typical SN host galaxies taken near the SN location integration times of many hours on 4-m class telescopes are necessary to begin to undertake meaningful age and abundance studies. For the sake of discussion, assume 20 SNIFS observations of 10 minutes each per SN; this gives a total integration on the host galaxy equivalent to one hour on a 4-m class telescope. For measurement of the bulk galaxy properties, all the pupil spectra with galaxy light can be included, perhaps quadrupling the effective integration compared to those from a long-slit spectrograph. These rough calculations suggest that for typical host galaxies the SNfactory observations are not going to provide detailed measurements of the host galaxy at the SN location, and may be barely sufficient to provide information on the intrinsic bulk properties of the SN hosts.

4 Conclusion on Sky-Subtraction Optics

In summary, for the study of the SNe themselves, sky-subtraction optics are not needed as long as final reference observations with SNIFS are available to subtract from the SNIFS SN observations. This conclusion must be tempered by the possibility that calibration errors may result in sky-subtraction errors which have not been modeled here.

Furthermore, age and abundance studies of SN host galaxies require that SNIFS have sky-subtraction optics or that the SNfactory should employ other instrumentation (e.g. VIMOS) more suited to this task. Without sky-subtraction optics redshift determination, velocity dispersion studies, and emission-line luminosity studies in the blue should still be possible. In the red, even these – more limited – studies will be difficult without sky-subtraction optics.

References

Glazebrook, K. & Bland-Hawthorn, J. 2001, PASP, 113, 197

Leinert, C. et al. 1998, A&ApS, 127, 1

Osterbrock, D. E. & Martel, A. 1992, PASP, 104, 76

Osterbrock, D. E., Fulbright, J. P., Martel, A. R., Keane, M. J., Trager, S. C., & Basri, G. 1996, PASP, 108, 277

Osterbrock, D. E., Fulbright, J. P., & Bida, T. A. 1997, PASP, 109, 614

Osterbrock, D. E., Waters, R. T., Barlow, T. A., Slanger, T. G., & Cosby, P. C. 2000, PASP, 112, 733

Roddier, C. & Roddier, F. ;. 1993, Optical Society of America Journal, 10, 2277

A Determining relative spatial convolution kernals

From the previous discussion, recall that spectro-photometry of each SN requires that the quantity $K_s(x_s, y_s, \lambda, t_{j,r})$ be determined for all $t_j \in \{1, ..., M\}$. Although it is relatively straightforward to assess whether the correct $K_{s_{j,r}}$ have been chosen when high S/N data are available, finding the correct $K_{s_{j,r}}$ to start with is not trivial, and for low S/N data feedback on the quality of the result will be weak. Here the groundwork is laid for a more general approach to determining $K_{s_{j,r}}$.

A.1 Using the imager PSF to estimate the spectrograph PSF

One possible approach would be to measure anonymous stars before and after the SN observation taken at t_j and the final reference observation taken at t_r. The difficultly here is that the atmospheric seeing component, A, of the PSF will not be sufficiently stable to guarantee that the calibration PSF matches the SN or final reference PSF.

The SNIFS imager will observe a field of anonymous field star while the spectrograph is observing the SN. Thus, an estimate of $K_{s_{j,r}}$ over specific wavelength ranges can be formulated as:

$$
\begin{aligned}
K_s(x_s, y_s, \lambda, t_{j,r}) &= P_s(x_s, y_s, \lambda, t_j) \otimes \frac{1}{P_s(x_s, y_s, \lambda, t_r)} \\
&= A(\lambda_i, t_j) \otimes O_s(x_s, y_s, \lambda_i, t_j) \otimes \frac{1}{A(\lambda_i, t_r) \otimes O_s(x_s, y_s, \lambda_i, t_r)}
\end{aligned}
$$

Rewriting this in terms of Fourier transforms gives

$$
\widetilde{K}_{s_{j,r}} = \frac{\widetilde{P}_{s_j}}{\widetilde{P}_{s_r}} = \frac{\widetilde{A}_j\ \widetilde{O}_{s_j}}{\widetilde{A}_r\ \widetilde{O}_{s_r}} = \frac{\left[\widetilde{P}_{p_j}/\widetilde{O}_{p_j}\right]\ \widetilde{O}_{s_j}}{\left[\widetilde{P}_{p_r}/\widetilde{O}_{p_r}\right]\ \widetilde{O}_{s_r}} = \left[\frac{\widetilde{P}_{p_j}}{\widetilde{P}_{p_r}}\right]\left[\frac{\widetilde{O}_{s_j}}{\widetilde{O}_{s_r}}\right]\left[\frac{\widetilde{O}_{p_r}}{\widetilde{O}_{p_j}}\right]
$$

where the function parameters and their Fourier counterparts have been suppressed for ease of notation. $\widetilde{P}_{p_j}/\widetilde{P}_{p_r}$ can be measured from the photometry channel. So, if the ratio of the spectrograph and photometer $\widetilde{O}$'s are known at the time of observation (t_j or t_r), or if the ratio of $\widetilde{O}$'s at two different times (t_j and t_r) for each instrument are known, then a measurement of $K_{s_{j,r}}$ needed for SN spectro-photometry can be made for descrete wavelength ranges, λ_i. All P's and O's also must be interpolated to the focal-plane location of the SN, x_{SN}, y_{SN}. The PSF is expected to be a slowly and smoothly varying function of λ, interpolation should provide $K_{s_{j,r}}$ over the full wavelength range of the spectro-photometric observations.

It is possible that the ratios of the O's will be fairly stable over time. Also, the widths, $W(O)$, are expected to be narrow, so their Fourier transforms should be very wide. The error made by simply ignoring changes in the O's is given by:

$$
\epsilon = T^{-1}\left(\left[\widetilde{G}\ \frac{\widetilde{P}_{p_j}}{\widetilde{P}_{p_r}}\right]\left(\frac{\widetilde{O}_{s_j}}{\widetilde{O}_{s_r}}\frac{\widetilde{O}_{p_r}}{\widetilde{O}_{p_j}} - 1\right)\right)
$$

where T^{-1} denotes the inverse Fourier transform.

A.2 Measurement of optical transfer function from defocused phase maps

If it turns out that the optical transfer functions, O_s and O_p, are not negligable relative to the atmospheric transfer function, A, *and* that O_s and/or O_p are not stable, then they will have to measured as part of the calibration procedure. One method of measuring the O's is using the phase map method of (Roddier & Roddier, 1993). In this method an image of a star is obtained on either side of focus. The image (or spectral image) is that of the illumination beam pattern before and after the optical pupil, and the intensity variations reveal changes in the total curvature of the wavefront. The wavefront phase map which is the Fourier transform of the desired optics PSF, O, can then be reconstructed. The size of the defocused image will be limited to $6''$for the spectrograph — some experimentation will be needed to determine whether this is sufficient.