Correcting the Contamination of Second-order Spectra: Improving Hα Measurements in Reverberation Mapping Campaigns postprint

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Abstract

Long-term spectroscopic monitoring campaigns on active galactic nuclei (AGNs) provide a wealth of information about its interior structure and kinematics. However, a number of the observations suffer from the contamination of second-order spectra (SOS) which will introduce some undesirable uncertainties at the red side of the spectra. In this paper, we test the effect of SOS and propose a method to correct it in the time domain spectroscopic data using the simultaneously observed comparison stars. Based on the reverberation mapping (RM) data of NGC 5548 in 2019, one of the most intensively monitored AGNs by the Lijiang 2.4 m telescope, we find that the scientific object, comparison star, and spectrophotometric standard star can jointly introduce up to 30% SOS for Grism 14. This irregular but smooth SOS significantly affects the flux density and profile of the emission line, while having little effect on the light curve. After applying our method to each spectrum, we find that the SOS can be corrected effectively. The deviation between corrected and intrinsic spectra is 2%, and the impact of SOS on time lag is very minor. This method makes it possible to obtain the Hα RM measurements from archival data provided that the spectral shape of the AGN under investigation does not have a large change.

Full Text

Preamble

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Abstract

Long-term spectroscopic monitoring campaigns on active galactic nuclei (AGNs) provide a wealth of information about their interior structure and kinematics. However, many observations suffer from contamination by second-order spectra (SOS), which introduces undesirable uncertainties on the red side of the spectra. In this paper, we test the effect of SOS and propose a method to correct it in time-domain spectroscopic data using simultaneously observed comparison stars. Based on reverberation mapping (RM) data of NGC 5548 from 2019—one of the most intensively monitored AGNs by the Lijiang 2.4 m telescope—we find that the target object, comparison star, and spectrophotometric standard star can jointly introduce up to 30% SOS contamination for Grism 14.

This irregular but smooth SOS significantly affects the flux density and profile of emission lines, while having little effect on light curves. After applying our method to each spectrum, we find that the SOS can be effectively corrected. The deviation between corrected and intrinsic spectra is 2%, and the impact of SOS on time lag is very minor. This method makes it possible to obtain Hα RM measurements from archival data, provided that the spectral shape of the AGN under investigation does not change dramatically.

Key words: techniques: spectroscopic – methods: data analysis – galaxies: individual (NGC 5548) – (galaxies:) quasars: emission lines

1. Introduction

Active galactic nuclei (AGNs), among the most luminous objects in the universe, are powered by gas accretion onto supermassive black holes (SMBHs). Broad emission lines are the most prominent features of AGNs, providing crucial information for studying the physical properties of SMBHs and their surroundings. In the context of the unified model (Antonucci 1993), the broad emission lines originate from the broad line region (BLR) located thousands of gravitational radii from the central SMBH and are broadened by the Doppler motions of BLR clouds under the strong gravitational field of the SMBH. According to the photoionization model, broad emission lines are driven by the central ionizing source.

Analyzing the delayed response (or time lag, τ) of broad emission lines to continuum variations provides information on the scale and structure of the BLR. The mass of the SMBH can be derived using the virial theorem: M_{BH} = f × R_{BLR} × v^{2} / G, where f is a virial factor determined by the geometry and kinematics of the BLR gas, R_{BLR} = cτ is the responsivity-weighted radius of the BLR (with c being the speed of light), and v is a measurement of cloud velocity (e.g., FWHM or the "line dispersion" σ_{line}; see Peterson et al. 2004, and references therein). This technique is called reverberation mapping (RM; Blandford & McKee 1982; Peterson 1993), and further details about the parameters are well introduced by Du et al. (2014).

As the number of RM experiments increased, it was gradually found that R_{BLR} typically shows a tight correlation with continuum luminosity (L), where R_{BLR} and L are usually measured from the Hβ emission line and monochromatic luminosity at 5100 Å, respectively (Kaspi et al. 2000; Denney et al. 2010; Bentz et al. 2013). Consequently, the mass of the SMBH can be estimated using a single-epoch spectrum, which is convenient for large spectral surveys such as the Sloan Digital Sky Survey (SDSS; e.g., Shen et al. 2014). For high-quality RM data, it is possible to reconstruct the kinematics and geometry of the BLR via velocity-resolved time lags (De Rosa et al. 2018; Feng et al. 2021a; Li et al. 2022; Villafaña et al al. 2022) because the velocity and lag of a cloud are determined by its position in the BLR.

While the RM technique is simple and widely used in the literature, it is based on two fundamental assumptions: that BLR clouds are photoionized by the central ionizing source and that their motions are dominated by the gravity of the central SMBH (Peterson 1993). These assumptions need to be verified by observational evidence. The photoionization model also predicts a stratified radial structure of the BLR due to ionization energy and optical depth, indicating that we can compare the lags and velocities of different emission lines to validate these assumptions (e.g., the τ v_{FWHM}$^{-2}$ relationship; Fausnaugh et al. 2017). Multi-line RM is therefore an alternative avenue for studying ionization and virialization properties in the BLR.

So far, the masses of SMBHs have been successfully measured in about 100 AGNs using the RM method (e.g., Bentz et al. 2010; Hu et al. 2021), but most studies have focused on Hβ, making it difficult to investigate multi-line properties. Moreover, the Hβ emission line fails in some cases, such as type 1.8/1.9 AGNs (Osterbrock 1981) or infrared spectra of high-redshift sources. Hα is the strongest optical emission line at low redshift and is less blended with optical Fe II, resulting in higher signal-to-noise ratio and more reliable profile measurements. In some AGNs with weak broad emission features, Hα is usually the only detectable optical broad line (e.g., type 1.9 AGNs), making it essential for investigating the properties of Hα-emitting regions. Unfortunately, Hα RM results have been reported for fewer than 20 AGNs (e.g., Bentz et al. 2010), and only a handful have velocity-resolved measurements (Bentz et al. 2010; Feng et al. 2021a). Thus, new spectroscopic monitoring programs are necessary to expand the Hα RM sample, though this is challenging because RM observations are very time-consuming.

Considering that most previous reverberation experiments focused on local (z < 0.3) AGNs, it is possible to observe Hα in some sources (e.g., the SEAMBH project; Du et al. 2014). We might utilize these data to obtain Hα lags and even analyze velocity-resolved lags. However, since previous observation strategies were primarily designed to optimize for Hβ, Hα might suffer from observational effects. For example, telluric absorption at wavelengths longer than 6800 Å, which would significantly contaminate the Hα emission line, was often ignored. Furthermore, most Hβ-based observations used relatively bluer spectrographs (e.g., Lu et al. 2019), which might cause the second-order spectrum (hereafter SOS) to superimpose around the Hα wavelength. Telluric absorption can be corrected using theoretical telluric absorption spectra (Kausch et al. 2015) or supplementary observations of a telluric standard star, though both methods can be affected by changing weather conditions. SOS contamination is usually solved via a dichroic filter that divides red and blue light into separate channels (e.g., Oke & Gunn 1982) or an order-blocking filter that blocks UV/blue photons (e.g., Feng et al. 2020). However, previous Hβ-based RM campaigns rarely adopted either scheme.

If we can precisely obtain atmospheric profiles in real time, both telluric absorption and SOS can be accurately corrected. Although most observatories do not provide this information, we can still correct Hα data when simultaneously observed comparison stars are available, as the object and comparison star experience identical weather conditions (e.g., airmass, seeing, clouds). Indeed, some previous RM campaigns used comparison stars for flux calibration (e.g., Maoz et al. 1990; Kaspi et al. 2000; Du et al. 2014; Feng et al. 2021b; Hu et al. 2021). Therefore, it is possible to extract Hα RM results from archival data. It has been demonstrated that telluric absorption can be well corrected using a comparison star (Feng et al. 2020; Lu et al. 2021), while SOS correction still requires effort.

Starting in October 2012, a large RM project (Du et al. 2014) was carried out on the 2.4 m telescope at Lijiang, aimed at increasing the number of RM AGNs with high Eddington ratios. The project monitored 50 AGNs, most of which also had Hα emission line observations. The varying degrees of SOS contamination in these spectral data motivated us to investigate this effect.

This paper is organized as follows. In Section 2, we present our SOS correction method. Application to NGC 5548 is presented in Section 3. Discussion is in Section 4, and we summarize our results in Section 5.

2. Method

Flux calibration strategies based on comparison stars are commonly used for spectroscopic monitoring projects (e.g., Maoz et al. 1990; Kaspi et al. 2000; Feng et al. 2021a). In some RM campaigns, several nearby comparison stars within 1° of the target are observed simultaneously using multi-slit (Williams et al. 2021) or fiber (Shen et al. 2016) modes, while others can only obtain a single comparison star (Du et al. 2014; Lu et al. 2022). Due to the identical observation conditions for target and comparison star, this approach can achieve high-accuracy relative flux calibration even in poor weather. For most previous Hβ-focused spectra, flux calibration generally consisted of three steps: (1) absolute flux calibration of each comparison star using a spectrophotometric standard star; (2) generation of a fiducial spectrum of the comparison star by combining spectra observed on clear nights; and (3) comparison of each comparison spectrum to the fiducial spectrum to derive sensitivity functions for direct flux calibration of the target.

However, this process cannot correct SOS contributions because the standard star, comparison star, and target each introduce different contamination.

[Figure 1: see original paper] shows the fiducial spectrum of the comparison star for NGC 5548. The orange line is the contaminated spectrum generated from 81 days of observation with contamination starting from 6300 Å. The blue line is the uncontaminated fiducial spectrum generated from 7 days of observation with a UV-blocking filter.

To correct SOS contamination, we start with the calibrated flux of the target, where O_{cou} and C_{cou} are the observed spectra (in counts) of the target and comparison star, respectively, C_{fid} is the fiducial spectrum of the comparison star that can be expressed as C_{fid} = (C_{cou}/E(λ)^(A_C - A_S)) · (S_{int}/S_{cou}), where E(λ) is the extinction curve of the observatory, A_C and A_S are the airmass of the comparison star and standard star, respectively, S_{int} and S_{cou} are the intrinsic and observed spectra of the standard star. If the spectrum is not affected by SOS, C_{fid} is equal to its intrinsic spectrum (C_{int}).

Combining Equations (2) and (3), we find that SOS contamination of the target is a mixture of contributions from the comparison star, standard star, and the target itself. Moreover, atmospheric extinction varies with wavelength and weather, further complicating the final SOS. [Figure 1: see original paper] shows fiducial spectra of the comparison star produced from spectra with (orange) and without (blue) SOS. Wavelengths in all figures are in observed frame, which facilitates estimation of SOS influences on other targets. There is a clear irregular shape on the red side of the spectrum that propagates to the target during relative flux calibration. We note that this effect only exists in the C_{int} term of Equation (2). Thus, we can avoid the SOS from the standard star if we already have C_{int}, which can be easily obtained from a single observation on a clear night. After that, only O_{cou} and C_{cou} still contribute SOS contamination in Equation (2). In principle, correcting for this effect requires detailed knowledge of instrument information and exact weather conditions, which would be very complicated and nearly impossible to achieve.

A plausible approach is to assume that the spectral shape of the AGN remains constant during the monitoring period. Although many observations show a "bluer-when-brighter" phenomenon in radio-loud AGNs (e.g., Dai et al. 2021; Fang et al. 2022; Negi et al. 2022), this assumption is still reasonable because (1) RM projects usually focus on radio-quiet sources, and (2) the spectral index generally varies within a narrow range. Under this assumption, we can derive that the ratio of the comparison star and target intrinsic spectra should be constant at any two wavelengths (i.e., λ_1 and λ_2). Furthermore, the SOS efficiencies ( ) of the comparison star and target should be consistent due to identical weather conditions and instrument configuration, i.e., _C(λ) = _O(λ). Combining these relationships, we obtain that the ratio of the superimposed SOS to the intrinsic flux density of the comparison star should be proportional to that of the target. This means the SOS of the target can be derived from the comparison star.

To measure the SOS of the comparison star in each epoch, we decompose the spectrum into first- and second-order components (i.e., C_{cou1} and C_{cou2}) and calculate a sensitivity function using two windows of line-free regions around the Hα absorption line. In principle, if the SOS is smooth, the flux of the continuum-subtracted absorption line should not be contaminated by SOS. However, dividing by C_{cou1} introduces a fraction of SOS to the calibrated Hα absorption flux. After rewriting the components, we obtain F_{cal} = F_{int} × (1 + C_{sos}(λ)/C_{int}(λ)), where F_{int} is the intrinsic flux of the Hα absorption line measured from a non-SOS spectrum. Note this pertains only to SOS under the assumption of a smooth SOS profile.

C_{sos}(λ)/C_{int}(λ) represents the ratio of superimposed SOS of the comparison star, from which we can derive O_{sos}(λ)/O_{int}(λ) and consequently obtain the corrected spectra of the scientific target. [Figure 2: see original paper] illustrates our correction scheme. Although the equations suggest relative changes in SOS at different wavelengths should be consistent, this requires observational confirmation, and we also need to examine the shape of the SOS.

In general, to apply this method to existing time-domain observational data, we need to re-observe the uncontaminated standard, comparison, and target objects on a photometric night. This yields a reliable fiducial spectrum of the comparison star and a response function representing the SOS contamination of the target/comparison pair for each day, taking advantage of the strategy of observing a nearby comparison star simultaneously.

3. Application to NGC 5548

The Yunnan Faint Object Spectrograph and Camera (YFOSC), equipped with a series of grisms, long slits, and filters, is a versatile instrument for spectroscopy and photometry mounted on the 2.4 m telescope. Before 2018, YFOSC was not equipped with an ultraviolet-blocking (UV-blocking) filter that was typically used to block SOS overlapping the scientific spectrum, so SOS contamination in archival spectra was not well considered. For example, NGC 5548 was well monitored by a long-term RM campaign using the Lijiang 2.4 m telescope to probe BLR evolution. Lu et al. (2022) performed a five-season observation and published RM results for broad Hγ, Hβ, and Helium lines, while the broad Hα line was not considered because the Hα region was contaminated by SOS. In this section, we apply the above method to eliminate the overlapped SOS from NGC 5548 data observed in 2019, enabling us to obtain the intrinsic spectrum and compare the resulting broad Hα line light curves before and after SOS elimination to estimate the impact of SOS on the time series.

3.1. Observation and Data Reduction

As described in Section 2, constructing the uncontaminated fiducial spectrum is the core step for eliminating overlapping SOS from scientific data. During the RM spectroscopic monitoring of NGC 5548 in 2019, we selected a photometric night (JD = 2458465) and performed spectroscopic observations with a UV-blocking filter to obtain UV cut-off spectra of NGC 5548 and its comparison star. Because the filter cuts off at approximately 4150 Å, the spectra at wavelengths below 8300 Å were not affected by SOS. We also observed a spectrophotometric standard star (G191-B2B) with the UV-blocking filter in the nearby sky to generate the UV-blocking fiducial spectrum. In addition, we carried out six spectroscopic observations after the RM campaign on six nights and obtained extra UV cut-off spectra of NGC 5548 and its comparison star to check the validity of our method.

Following Lu et al. (2022), we reduced the UV cut-off spectra using standard IRAF version 2.16 routines. The primary reduction steps included bias subtraction, flat-field correction, wavelength calibration, and cosmic-ray elimination. Standard neon and helium lamps were used for wavelength calibration. One-dimensional spectra were extracted with an aperture of 5.66. Varying seeing and mis-centering usually led to wavelength shifts, which we corrected using the [O III] $ $5007 line as a wavelength reference with the interpolated cross-correlation function (ICCF).

3.2. Eliminating the Contamination of SOS

From the UV-blocking spectroscopic observation on the photometric night, we generated the UV-blocking fiducial spectrum through spectral flux calibration using the UV cut-off spectra of the standard star. Meanwhile, we obtained a contaminated fiducial spectrum from the contaminated spectra observed during the 2019 RM campaign. The term "contaminated" means that the spectra are overlapped by SOS due to the lack of a UV-blocking filter. [Figure 1: see original paper] clearly shows that spectra at wavelengths longer than 6300 Å are contaminated by SOS. This means that if the scientific spectrum is calibrated using the contaminated fiducial spectrum, we cannot obtain the intrinsic spectrum in the SOS-overlapped regions. In this section, we use the method described in Section 2 to construct the intrinsic spectrum for the contaminated NGC 5548 spectra observed during the 2019 season (Lu et al. 2022).

Following the method described in Section 2, we first obtained the contaminated sensitivity function by comparing the observed spectrum of the comparison star in each exposure to the UV-blocking fiducial spectrum. This sensitivity function was then applied to calibrate the contaminated spectrum of NGC 5548 observed on nights when we conducted UV-blocking spectroscopic observations. Simultaneously, we generated a UV cut-off sensitivity function and used it to calibrate the UV cut-off spectrum of NGC 5548, resulting in the UV-blocking spectrum. This step helped eliminate contamination from the standard star, and the UV-blocking spectrum contains no SOS at all. To obtain F_{cal} in Equation (9), we used a compound model consisting of a linear and a Gaussian component to fit the spectra of the comparison star near the Hα absorption band. From Equations (7) to (9), we derived O_{sos} and C_{sos} and computed a response factor for each night representing the ratio of that night to the photometric night in terms of SOS response functions. The response function for contamination from the target/comparison pair on the photometric night was generated from the two calibrated spectra obtained in the previous step. Then, together with this factor, the corrected spectra of NGC 5548 for the six days were finally derived.

Panel (a) of [Figure 3: see original paper] shows the spectra of NGC 5548 for one day, with the UV-blocking and corrected spectra shown in blue and green, respectively. The contaminated spectrum, calibrated while ignoring SOS, is shown in orange. Panel (b) shows the 2% deviations between the corrected spectrum and the UV-blocking spectrum, demonstrating that the contaminated spectrum is well corrected by our method. Results for the five days are presented in [Figure 4: see original paper], where the deviations are also negligible (note there were clouds on Julian date 2458635). These results indicate that our method successfully processes contaminated data, producing results nearly identical to UV-blocking spectra. Therefore, we proceeded to apply this correction method to all 81 contaminated spectra.

3.3. Comparison

We generated the mean contaminated and corrected spectra from the 81 spectra and display them in [Figure 5: see original paper]. Panel (a) of [Figure 3: see original paper] also presents the contaminated spectrum and its deviation from the UV-blocking spectrum shown in panel (c). These figures reveal that the impact of SOS on absolute spectral flux can be up to 30%.

We generated Hα light curves using both contaminated and corrected spectra to assess the impact of SOS. Light curves of the continuum (rest-frame 5100 Å) and the Hβ emission line are also presented as references because they are not affected by SOS. However, the contaminated Hα line does not exhibit a typical spectral shape. Therefore, we measured the light curve using integration rather than spectral decomposition. This approach was also employed for the other two light curves for consistency.

To measure the continuum light curve, we calculated the median value between 5090 and 5110 Å. For the Hα emission line, we inspected the mean spectra and defined the red, blue, and integral windows as 6180–6250 Å, 6880–6850 Å, and 6400–6700 Å, respectively. We used the red and blue windows for continuum fitting, then integrated the emission line flux in the integral window after subtracting the fitted continuum. For Hβ, the windows were 4500–4520 Å, 5090–5100 Å, and 4700–4920 Å, respectively. The light curves are presented in [Figure 6: see original paper]. It is evident that the two Hα light curves exhibit similar shapes, indicating that the impact on time lag is negligible.

4. Discussion

In most RM campaigns that do not specifically focus on the Hα line, there are often overlaps between the Hα line and the SOS from the UV/blue band. The practical impact of SOS depends on the relative blueness of the standard star and the target/comparison star pair. Based on our analysis of NGC 5548, we deduce that the standard star (G191-B2B) was much bluer than the target/comparison star pair, while NGC 5548 was slightly bluer than J1417. As a result, the flux of contaminated spectra (with SOS ignored in the flux calibration process) was significantly lower than that of corrected spectra around the Hα band. This was primarily due to division by a larger sensitivity function generated from the comparison star, while the SOS effect of the target/comparison pair tends to reduce the effect caused by the contaminated fiducial spectrum. The overall impact is about 30%, indicating that Grism 14—used for monitoring NGC 5548 and most other objects in the LJT (Lijiang 2.4 m telescope) RM campaign—has a significant impact on absolute flux calibration, as shown in [Figure 5: see original paper]. As mentioned above, the factor representing systematic bias is mainly caused by G191-B2B and depends on the spectral slopes of the target, comparison star, and standard star.

As demonstrated in [Figure 6: see original paper], light curves show less susceptibility to SOS, except in integrated absolute flux. First, this could be attributed to the higher sensitivity of light curves to relative flux variations compared to nearly proportional changes in absolute flux that are contaminated by almost the same ratio every day in the Hα band. Second, the partial SOS effect was eliminated by subtracting the linear-fitting continuum before integrating the emission-line flux. However, the broadness of the Hα integral interval renders absolute flux highly sensitive to changes in spectral shape caused by SOS, in contrast to the Hα absorption line of the comparison star, where this impact is relatively small compared to proportional changes from SOS. The contamination of the target/comparison pair changes under different observation conditions, leading to slight variations in the contaminated Hα light curves. This effect causes the light curve contaminated by SOS to closely resemble the continuum light curve, as SOS originates primarily from the continuum in the UV/blue band. The lack of spectral decomposition and host galaxy contamination elimination (done for consistency with contaminated results) makes the continuum light curve not as good as in previous work (Lu et al. 2022), but it is sufficient to observe the trend of changes in the Hα light curve caused by SOS contamination. Multi-line RM observations indicate that the Hα line is emitted from a much larger region than the Hβ line (Bentz et al. 2010; Feng et al. 2021b), and its light curve should be smoother. However, as shown in [Figure 6: see original paper], the opposite was observed with SOS overlapping. The reason may be the different presence of components within the integral range. It is evident that the correction consistently decreases the normalized flux when the light curve is trending downward, and conversely increases it when trending upward. This implies that the correction method slightly shifts the light curve to the left.

The basically proportional variation caused by SOS on the absolute flux of the Hα line is approximately 30%. Furthermore, emission line width and spectral shape significantly impact RM measurements, such as the determination of SMBH masses and velocity-resolved time lags. We can see that our method significantly corrected the line profile. Correcting the spectral shape enables exploration of the structure of the Hα-emitting BLR through velocity-resolved time lags. Therefore, further research on Hα RM measurements using this correction method will be conducted in a subsequent paper.

The corrected spectra show only about 2% deviation compared to UV-blocking spectra obtained with an order-blocking filter. We anticipate we can achieve even smaller deviation by correcting the telluric absorption of the comparison star using the method proposed by Lu et al. (2021). It is worth mentioning that when applying this method to specific archival data, a minority of AGNs might undergo significant variation in spectral shape, rendering the basic assumption of constant spectral shape invalid. Therefore, we suggest quantifying the variation if a long time has elapsed since the archival observations. By applying this method to contaminated data, we can carry out expensive RM experiments without consuming excessive telescope time, as theoretically only one day of optimal weather conditions is required for each object. We plan to apply this method to archival RM data, particularly from the LJT, which has the potential to increase the current sample of Hα RM measurements.

5. Summary

In this paper, we present a method to correct SOS contamination using a simultaneously observed comparison star. Our application successfully corrects the spectral shape, as evidenced by comparison with UV-blocking results. To derive corrected spectra from SOS-contaminated data, we implemented a two-step procedure. First, we eliminate the SOS from the spectrophotometric standard star by generating an uncontaminated fiducial spectrum, which is then used to calculate the sensitivity function for the target and comparison star. Second, we eliminate the SOS from the target/comparison pair using the Hα absorption feature of the comparison star.

We tested this method on NGC 5548 by obtaining seven additional spectra with a UV-blocking filter. An uncontaminated fiducial spectrum and SOS response function were derived from observations on a photometric night. The remaining six UV-blocking spectroscopic observations were used to obtain uncontaminated UV-blocking spectra, along with corrected ones, to verify the validity of the correction method, resulting in approximately 2% deviation.

This method was applied to RM spectra obtained during the 2019 observation season, producing 81 corrected spectra and 81 contaminated spectra that were calibrated ignoring SOS contamination. The corrected spectra were compared to the contaminated spectra to assess the influence of SOS. The major impacts of SOS are manifested in three aspects:

1. For absolute flux near Hα, the contaminated spectra are about 30% lower than the UV-blocking spectra.
2. The spectral shape changes significantly, making line width and velocity-resolved time-lag measurements unreliable for further investigation if we directly use contaminated spectra.
3. The contaminated Hα light curve is less smooth than Hβ, and the timing of changes in the corrected Hα light curve is slightly advanced.

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Note: Figure translations are in progress. See original paper for figures.