The Single-Object Slitless Spectroscopy Mode of *Webb*'s NIRISS Instrument

Paul Goudfrooij, *goudfroo@stsci.edu*, **Loïc Albert**, *albert@astro.umontreal.ca*,
& **René Doyon**, *doyon@astro.umontreal.ca*

The *James Webb Space Telescope*'s Near Infrared Imager and Slitless Spectrograph (NIRISS) will offer a number of innovative observing modes, including single-object slitless spectroscopy (SOSS). This mode is optimized for spectroscopy of transiting exoplanet systems around nearby (and thus often bright) stars. It operates in the wavelength range between 600 and 2800 nm, which includes strategic spectral features from molecules such as O_2, H_2O, CO_2, and CH_4, which are either common or expected in the atmospheres of exoplanets.

The SOSS mode is enabled by a grism that generates two usable orders of cross-dispersed spectra of a single target. A third order is also present, albeit at a low signal level. Order 1 covers the wavelength range ~850–2800 nm at a resolving power $R = 700$, while the usable part of order 2 covers ~600–1300 nm at $R = 1400$. Figure 1 illustrates the location and shape of point source spectra created by the SOSS grism.

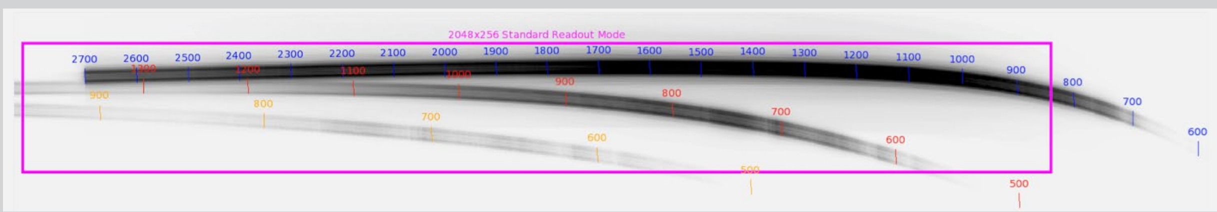

Figure 1: Simulation of the appearance of a SOSS spectrum of a M3V star. Grayscales indicate intensities in logarithmic units. Wavelengths in nm are indicated in blue, red, and orange for spectral orders 1, 2, and 3, respectively. The magenta box outlines the portion of the spectrum read out by the default SOSS detector window.

A unique feature of the SOSS mode is the wide shape of the radial distribution of its light in the direction perpendicular to the dispersion. This is commonly called "the cross-dispersion point spread function" (cdPSF). For most spectroscopy modes on the *Webb* telescope, the aim is to provide a good spatial sampling of the sky, in which case a typical full width at half maximum (FWHM) of cdPSFs is 2–3 detector pixels. In contrast, the width of the SOSS cdPSF is ≈35 pixels, with FWHM ≈ 25 pixels(!). The appearance of the SOSS cdPSF is illustrated in Figure 2.

The shape of the SOSS cdPSF is caused by a weak defocussing lens built into the SOSS grism. It produces two important benefits to spectroscopic studies of exoplanet systems, which typically require data with very high signal-to-noise ratio (S/N)—of order 10^4–10^5! First, the wide cdPSF allows observations of bright targets whose spectra would be saturated on the detector in the absence of the lens. Second, it mitigates the need to dither[1] the telescope during SOSS observations. For most observing modes on *Webb*, the small PSFs of telescope dictate a need for dithering, to circumvent the effects of bad detector pixels. However, the combination and calibration of dithered data requires an adequate knowledge of the relative sensitivities of every individual detector pixel. Achieving this is impractical for the S/N required for the science cases that motivate the SOSS mode. Thus, the wide cdPSF of the SOSS grism

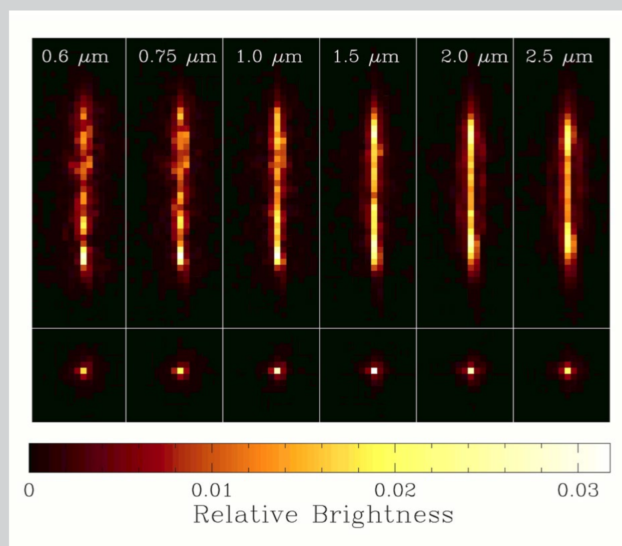

Figure 2: Simulation of the SOSS cdPSF (the PSF in the direction perpendicular to the dispersion). The top panels depict simulations at the wavelengths indicated with the weak lens in place, while the bottom panels do so *without* the weak lens. The features shown in these simulations have been confirmed by actual observations taken during the cryogenic vacuum tests at Goddard Space Flight Center. (Figure courtesy of David Lafrenière, Université de Montréal).

[1]"Dithers" are small-angle maneuvers of the telescope between individual exposures. Their main purposes are to eliminate the effect of bad detector pixels and/or to improve the effective spatial resolution of the resulting data.

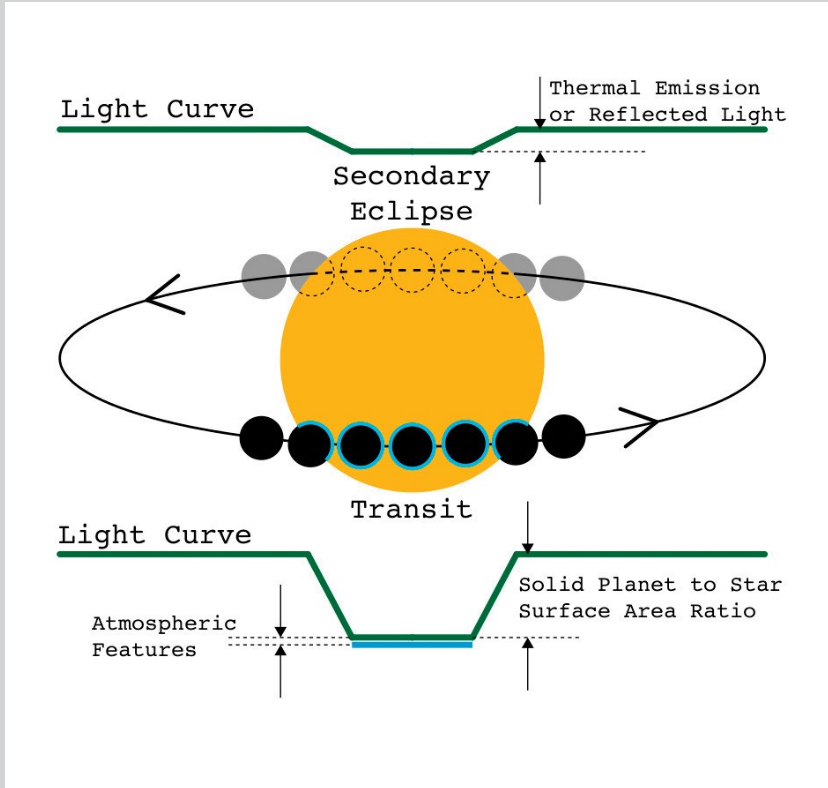

Figure 3: Illustration of star-planet configurations that cause transits and secondary eclipses. The star is represented by a yellow circle, while the planet is shown in black when in front of the star and in gray when on the far side of the star. The planet's atmosphere is shown in light blue, when the planet is in front of the star. Light curves for transits and secondary eclipses are illustrated in green at the bottom and top, respectively.

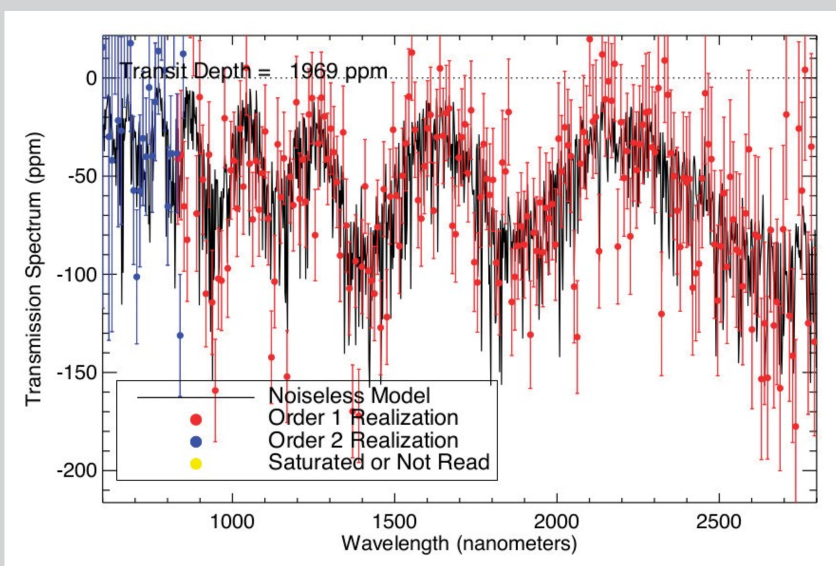

Figure 4: Simulation of an Earth-size "water world" planet with half the Earth's density, observed with NIRISS/SOSS. We stack five transits and assume $J = 8.0$ mag for a late M star with a temperature of 3200 K and a radius of 0.2 Sun radii orbiting in the habitable zone. This target requires 32 hours of clock time under the assumptions of an overhead of 45 minutes (for the telescope slew, target acquisition, and detector stabilization) and spending twice as much exposure time out of transit as in-transit. (Planet atmosphere model courtesy of Eliza Kempton, Grinnell College).

avoids dithering and allows dwelling on the same detector pixels during long exposures. The result is uniquely high relative photometric accuracy.

Characterization of exoplanet atmospheres with SOSS

We envision that the SOSS mode will advance the study of three main types of exoplanets: Jupiter-like planets, super-earths, and possibly earth-like planets. Super-earths are planets with masses between that of the earth and about eight times that, with a density indicative of a rocky body.

The choice of targets will mainly be limited by observational factors. One condition is that planets pass directly in front of their stellar host—a transit event—and/or that planets be completely eclipsed by their host—a secondary eclipse (see Figure 3). Both conditions require that the orbit of the exoplanet be almost edge-on as seen from Earth, which, for a randomly distributed population of planetary systems, occurs less than 5% of the time.

The physics achieved in transit events will differ slightly from that in secondary eclipses. For transits, only planets with a significant atmosphere can leave an observational spectral imprint: the starlight grazing through the small crescent of the atmosphere is transmitted with varying strengths, depending on the chemical composition of the upper planet's atmosphere. For secondary eclipses, light is incident at 90 degrees, which allows a deeper probe into the atmosphere of a planet. In the case of rocky planets, the light then actually reaches the solid surface before being reflected back at us, thus allowing a measurement of the planet's albedo.

Another important limitation on transit events is the scale height of the exoplanet atmosphere: large scale heights are synonymous with large effective-radius changes as a function of wavelength, and hence larger, more observable, signals. The atmospheric scale height is proportional to temperature and inversely proportional to surface gravity and molecular weight. For example, an atmosphere of hydrogen has a larger scale height than that of nitrogen, by the ratio of the molecular weights, 28/2 = 14. Another example is that a massive planet with high surface gravity—say $\log g = 4.0$—has a smaller scale height than Earth—$\log g = 3.0$—by a factor of 10. Thus, the exoplanets with the strongest expected spectral signatures are low-density, hydrogen-rich, high-temperature planets.

The final limitation is photon statistics. For hot Jupiters, with the largest signal, the strength of spectral features expected in transmission spectra are less than 1000 parts per million (ppm). Detecting these features at S/N = 10 requires spectra of the stellar host with a S/N > 10,000. These constraints mean that targets need to be rather bright, ideally $J < 10$ mag.

The wealth of new exoplanets found by the transit method has made the study of their atmospheres a reality. The likely most numerous type of exoplanets that *Webb* will observe are gas giants. Observing such Jupiter-like exoplanets at a variety of distances and around various types of star hosts will allow the discovery of trends that may exist between the chemistry of a planet's atmosphere and the planet's temperature or the host-star type. The effect of the metal abundance will also be studied.

Super Earths are another type of high-profile targets. These are currently the closest observable analogs to Earth and are at the characterization limit with *Hubble*. Two good examples are GJ 1214b and HD 97658b. Models showed that hydrogen-rich or even water atmospheres would be detectable with *Hubble*, using the grism mode of the near-infrared channel of the Wide Field Camera 3 (WFC3). While the WFC3 observations were successful, both of these super Earths unfortunately turned out to exhibit relatively featureless transmission spectra, likely because of high-altitude haze or dust in their atmospheres (Kreidberg et al. 2014; Van Grootel et al. 2014; Knutson et al. 2014).

The upcoming all-sky photometric survey by the *Transiting Exoplanet Survey Satellite*, slated for launch in 2017, will likely find new super Earth targets of sufficient brightness to be observed with *Webb* (see **tess.gsfc.nasa.gov**). It may even identify Earth-like hosts. If such targets are sufficiently bright ($J <$ 8 mag), then it will be possible to characterize the compositions of their atmospheres with the SOSS mode of NIRISS. A simulation of a SOSS observation of an Earth-size "water-world" planet is illustrated in Figure 4. To be successful, such observations will require uninterrupted observations of several transit events, as well as a deep understanding of the instrumental systematic noise.

The SOSS mode of NIRISS promises to be a big leap forward in the quest for spectra of Earth analogs. It may possibly detect water, methane, and/or CO_2 absorption bands, if such properties exist among planets around nearby sufficiently bright stars.

References

Knutson, H. A., Dragomir, D., Kreidberg, L., et al. 2014, ApJ, 794, 155
Kreidberg, L., Bean, J. L., Désert, J.-M., et al. 2014, Nature, 505, 69
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