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# Europa's Optical Aurora: Update from Four New *Hubble* Eclipse Observations

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Atomic emissions from the tenuous atmosphere of Jupiter's moon Europa provide information on the composition, column density, and variability of gas species, which inform our understanding of the atmosphere's origins. The strength and ratios of the UV and optical oxygen emission lines indicate that Europa's atmosphere is composed primarily of $O_2$ and has a column density of ~1–15 × $10^{14}$ $cm^{-2}$ (Hall et al. 1998; Roth et al. 2014, 2016; de Kleer & Brown 2018). The auroral emissions show variability on timescales from minutes to days, some of which can be attributed to Europa's position relative to Jupiter's plasma sheet (Roth et al. 2016; de Kleer & Brown 2018). The atmosphere is sourced from Europa's surface, from which material is liberated via sputtering and/or thermal processes (Johnson 1990; Oza et al. 2018).

Observations of Europa's aurora at optical wavelengths must be made while Europa is in eclipse by Jupiter so that the faint atmospheric signatures are not overwhelmed by reflected sunlight off the disk. In 2018 we observed Europa in eclipse by Jupiter on ten occasions with the Space Telescope Imaging Spectrograph (STIS) on the *Hubble Space Telescope* (*HST*). Data from the first five eclipses are published in de Kleer & Brown (2018), and include the first detection of Europa's aurora at optical wavelengths. Of the remaining five observations, the guide satellite acquisition failed on 2018 July 24 and no data were acquired. The four successful eclipse observations took place on 2018 July 14 and 28, and August 8 and 15. All four observations were made while Europa was in shadow and 7''–22'' from Jupiter's limb. The central meridian longitude of Europa was 10–14°W, which differs slightly from the 350 to 354°W of the previous five observations. The instrument settings, data reduction, and analysis methods are identical to those described in de Kleer & Brown (2018). Here we present results from these four new *HST* observations, and show the full data set together.

The images of Europa's 6300 Å oxygen aurora, and the disk-integrated auroral brightnesses, are shown in Figure 1. The aurora were detected on seven out of nine observing dates, and were >1 kR in brightness on February 18, April 5, and August 15. The total auroral strength roughly follows the trend with Europa's position in Jupiter's System III longitude seen in previous optical and UV observations (Roth et al. 2016; de Kleer & Brown 2018), although significant variability is also seen beyond this trend. There is one statistically significant hydrogen detection, on July 14. The hydrogen brightness was enhanced in only one of two dithers separated by only a few minutes, and is not accompanied by enhanced or colocated oxygen emission. The detection is at the $2\sigma$ level, and a single $2\sigma$ detection out of 18 unique observations is consistent with random noise.

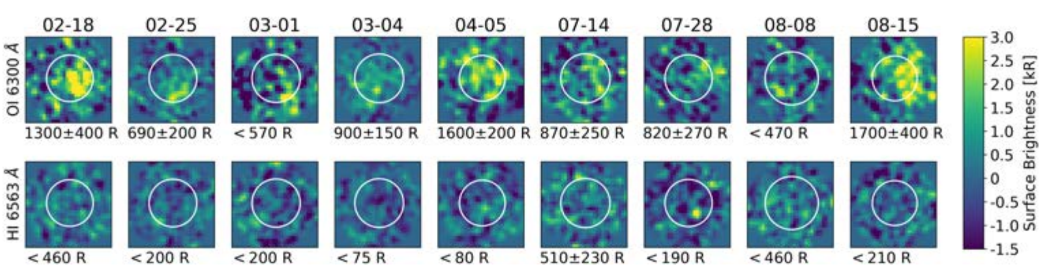


**Figure 1.** *HST*/STIS images on nine dates in 2018 of the region centered on Europa's location and the O I 6300 and H$\alpha$ 6563 Å lines. Europa's size and expected location is indicated with a circle, Europa's north pole is up, and all images have been lightly smoothed to bring out extended structures. Most small-scale bright features in the images are comparable in intensity to the noise and should be interpreted with caution. The disk-averaged brightness is printed below each panel.

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The oxygen aurora are typically brighter on the dusk hemisphere; averaged across all nine observations, the dusk/dawn hemisphere emission ratio is 1.8 ± 0.6. The greatest source of uncertainty on this ratio is the pointing; to derive the quoted uncertainty, we assume that the centering of Europa on each image varies from the nominal centering by an unknown amount up to 0.″25 and generate a distribution of dusk/dawn ratios by repeated drawings of pointing offsets. The quoted ratio and uncertainty represent the median and standard deviation of the resultant distribution. The ratio of 1.8 ± 0.6 matches the ratios of 1.5–2.0 measured from UV observations (Roth et al. 2016), consistent with a common source for the UV and optical emissions and supporting the claim that the dusk/dawn ratio does not change significantly during Europa's orbit. This latter property has been shown in recent work to be more consistent with thermal processes than sputtering as a source of Europa's oxygen atmosphere (Oza et al. 2018).

The factor of ~5 variability seen in the disk-integrated brightness of the optical aurora, from <500 to nearly 2000 R, matches the level of variability (~30–160 R) seen in the UV aurora (Roth et al. 2016). However, the peak optical brightnesses are 50% brighter than predicted from the peak UV brightnesses for an O or $O_2$ atmosphere (de Kleer & Brown 2018). Given that such high optical brightnesses were measured in three of our nine observations, while the UV data set spans 19 visits, random variations in the aurora strength are unlikely to be responsible. Electron energies and densities that are poorly estimated or varying on months–years timescales, or the presence of a substantial amount of an additional species such as $CO_2$ or $H_2O$, could enhance the optical emissions relative to the UV in this way.

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