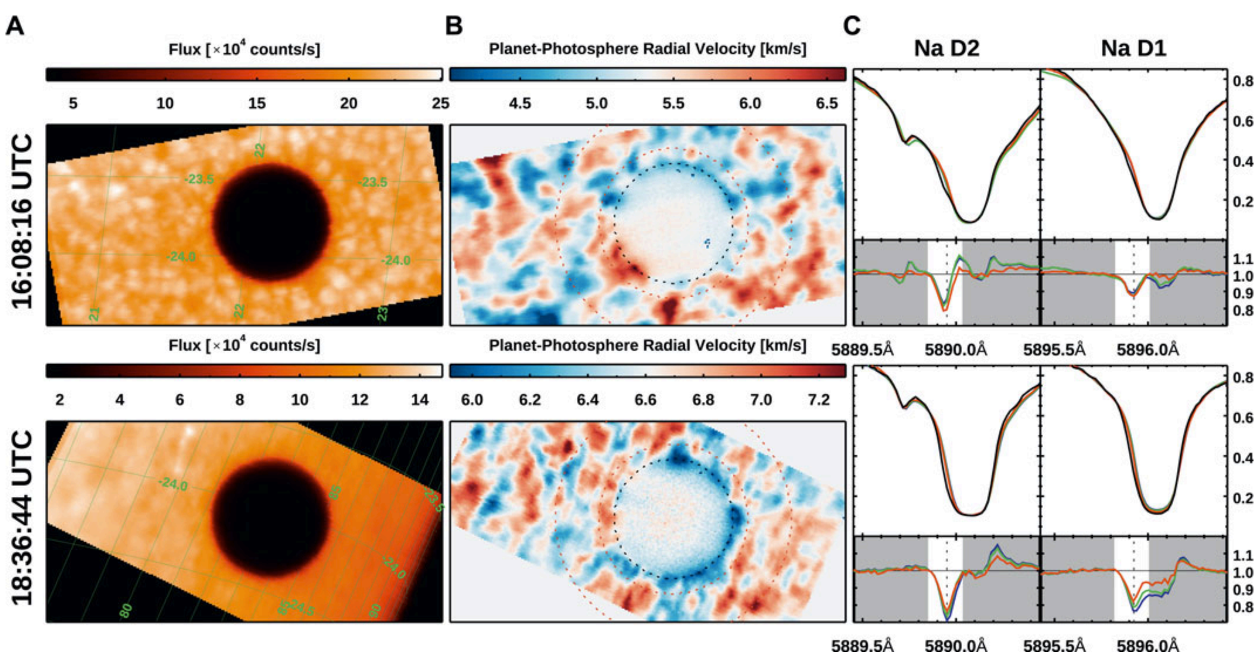
Na and K Absorption in Solar System Transit Spectroscopy. C. A. Schmidt[1], [1]Center for Space Physics, Boston University.

Introduction: Nearly 30 exoplanets and counting have been reported to have optical Na and/or K absorption lines in their transit spectra. Differences in instrumentation and analysis methods complicates the comparison between these systems and results are often overturned. Such signatures can be challenging to isolate from the stellar absorption lines. Our own Solar System offers a valuable benchmark for this formidable problem.

Solar System Analogs: Satellite eclipses offer us an opportunity: sunlight that passes through a planet's atmosphere measurable as the bright reflectance spectrum off of the eclipsed moon's surface. Na absorption has been reported in the terrestrial and jovian atmospheres using this technique, but many complicating factors must be accounted for. The penumbral spectrum is strongly time-dependent and the reflectance spectrum is not simply an integrated spectrum of the solar disk as we're accustomed to, but rather the emergent spectrum from the unocculted portion of the solar disk, which is non-trivial to model. Moreover, stray light and emission from the satellite's own atmosphere can contaminate this signal. Consequently, telluric and jovian sodium signatures using this methodology have been contested [1].

Io and Mercury are the only unambiguous examples of sodium absorption in the solar system. Potassium absorption has not been measured at either body, despite dedicated experiments. Light passing though Io's atmosphere can be measured in reflectance off another satellite like Ganymede or Europa during brief mutual events [2]. Measurements of Mercury's Na absorption are possible during solar transits [3,4] and this is the most direct Solar System analog for transiting exoplanet atmospheres. These Io and Mercury measurements have each sampled a light path through the collisionless exospheres. In each case, the column density and temperature of the absorption in-transit have been validated via comparison with the well-known emission characteristics.

Even where planetary geometry and the solar spectrum are known precisely, Solar System absorption data can be complex to interpret. The figure below shows Mercury's 2016 transit near mid-transit and the near solar limb in the top and bottom rows, respectively (A), as seen from Big Bear Solar Observatory [1]. The Doppler shift between the planet and the local photosphere changes (B), as does the shape of the Fraunhofer lines in the local solar spectrum (C). Mercury's sodium signal is strong; a 10 to 20% depth is evident at the planet's Doppler shift (dotted line). Yet, different recovery methods for the local solar spectrum in a given pixel, seen in the red/green/blue colored lines produces different artifacts and Na column abundances. With such challenges readily evident in our Solar System, the much more difficult task of interpreting spatially-unresolved and faint exoplanet signatures, wherein the planetary



geometry is not fully known, is indeed a formidable challenge that is a barrier towards our better understanding of exoplanetary atmospheres.

Importance for Exoplanet Study: Radiation pressure is important for alkali gas dynamics in close-orbiting exoplanets since the alkali D lines are so efficient at resonant scattering. When the star-planet velocity is ≳10 km/s, eccentric exoplanets experience more than an order of magnitude higher radiation pressures, aiding atmospheric escape and producing a larger effective cross-section for absorbing starlight at the phase of transit. The Doppler shift also aids in isolating the planetary signature from the stellar photosphere's absorption. Thus, high Doppler shift makes Na and K absorptions in eccentric exoplanets easier to study and so these few instances warrant close attention.

Radiation pressure on a planetary exosphere naturally produces blue-shifted absorption. Up to -1.2 km/s blueshift is evident at Mercury, and both radiation pressure and photoionization scale as inverse squares. Gravitationally bound Na and K exhibit no Doppler shifts at their line cores, whereas these elements absorbing with blueshifts of few km/s is indicative of atmospheric escape.

Alkali line cores with high blueshifts, or some measurable redshift cannot be attributed to any physical mechanism other than an exomoon [1]. The line of sight velocity of the exomoon may not be the only contribution—the Io-Jupiter system teaches us that moon-magnetosphere interactions can produce atmospheric jets with very high Doppler shifts thanks to ion chemistry (>100 km/s is measurable at Io). At present, observable metrics for both exomoons and exoplanet magnetospheres are few, and so it is important that this community recognizes velocity structure in the alkali transit spectroscopy is a valuable tool.

References: [1] Schmidt, C. A. (2022) *Front. Astron. Space Sci.,* 9, 801873. [2] Burger, M. et al. (2001) *ApJ*, 563, 1063-1074. [3] Schleicher, H., et al. (2004) *A&A* 425, 1119–1124 [4] Potter, A. E. et al. (2013). *Icarus* 226, 172–185.