The Hubble OPAL Program: 10 years of time-variable phenomena on Jupiter and the other giant planets (invited)

Supplementary Materials

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Introduction

The Outer Planet Atmospheres Legacy (OPAL) program began in 2014 as part of the Hubble 2020 legacy initiative (Simon et al. 2015). These observations were meant to cement long-term legacy of the Hubble Space Telescope (HST) by ensuring a regular cadence of giant planet observations to fill temporal gaps between individual programs (Fig. 1). The giant planets have highly dynamic atmospheres, so long-term trends tied to seasonal or other evolutionary cycles require regular data collected using the same instruments and filters.

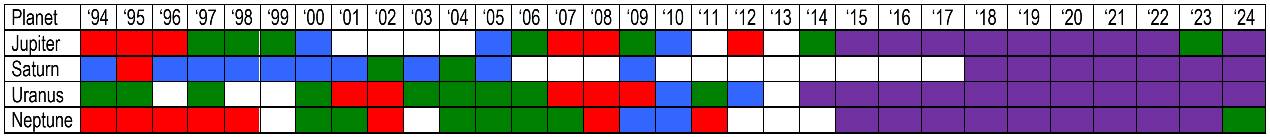
In addition to building up a long data base of consistent observations on an annual cadence, serendipitous discoveries have been made along the way. Filters extend from the near-UV (F225W at 225 nm) to the near-IR (FQ889N at 889 nm), and each planet is imaged to cover all longitudes over a period of two planetary rotations. All raw data are immediately available to the public, and the team also hosts high level science products in the form of global maps at the MAST Archive (Simon 2015).

In the References section, we list 64 publications based on OPAL data that were compiled using the official MAST bibliographic search tool, plus 6 recent additional publications not yet indexed by MAST. An automated search result list is maintained by the lead author on a UCB-SSL page.

A review paper on this topic is currently in preparation, so the OPAL team encourages any authors not included in the references below to provide citations to their work using OPAL data.

OPAL at Jupiter

Figure 2 provides some examples of studies enabled by Hubble's exquisite spatial resolution and OPAL's global and temporal coverage. OPAL data have been central to detailed studies of Jupiter's



Planet	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24
Jupiter	🟥	🟥	🟥	🟩	🟩	🟩	🟦	⬜	⬜	⬜	⬜	🟦	🟩	🟥	🟥	🟩	🟦	⬜	🟥	⬜	🟩	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟩	🟪
Saturn	🟦	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟦	🟩	🟦	⬜	⬜	⬜	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Uranus	🟩	🟩	⬜	🟩	⬜	⬜	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟦	🟩	🟦	⬜	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Neptune	🟥	🟥	🟥	🟥	🟥	⬜	🟩	🟩	🟥	⬜	🟩	🟩	🟩	🟩	🟥	🟦	🟦	🟥	⬜	⬜	⬜	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟩

Color code: white: no data, blue: individual images, green: wind pairs, red: single maps, purple: two global/near-global maps

Figure 1. Temporal coverage in high-resolution UV/visible-wavelength coverage of the outer planets had significant gaps prior to the start of OPAL in late 2014 (with Saturn starting in 2018 after the end of the Cassini mission).

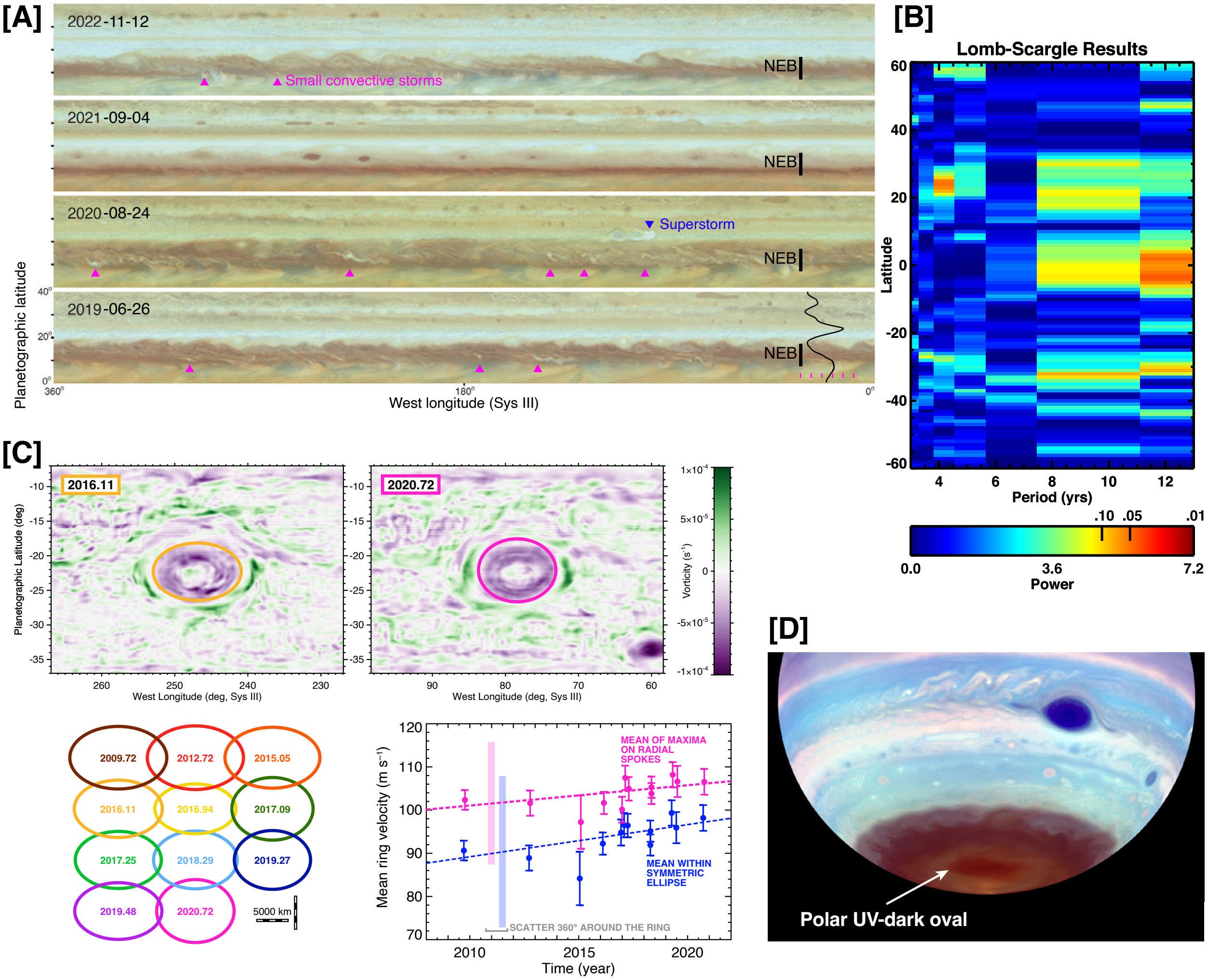


Figure 2. HST's high spatial resolution and stable photometry are central to OPAL investigations of time-variable phenomena on Jupiter. **[A]** OPAL observed simultaneous changes in storm activity and the widths and colors of belts and zones, with anomalous conditions in 2021 (Simon and Wong 2024). **[B]** A strong 4.5-year periodicity in the 395-nm brightness near 23 °N shows up in periodogram analysis, associated with superstorm eruptions like the 2020 event seen in panel A (Simon and Wong 2024). **[C]** The 2D wind field of the Great Red Spot (GRS) shows a dynamically "hollow" core (top two frames), irregular changes in shape and gradual decrease in size (lower left), and a slight increase in mean wind speeds (lower right; Wong et al. 2021). **[D]** UV-dark ovals in the polar hoods of stratospheric aerosols (like the northern dark oval seen in Cassini data, Porco et al. 2003) are more common in the south (Tsubota et al. 2025).

vortices including the Great Red Spot (Simon et al. 2015/2018/2024, Loeffler et al. 2016, Carlson et al. 2016, Bjoraker et al. 2018, Sánchez-Lavega et al. 2018/2021b, Iñurrigarro et al. 2020, Barrado-Izagirre et al. 2021, Wong et al. 2021, Morales-Juberías et al. 2022, Anguiano-Arteaga t al. 2023, Sankar et al. 2024, Harkett et al. 2024), high speed narrow wind jets (Simon et al. 2015/2022, Hueso et al. 2017, Tollefson et al. 2017, Johnson et al. 2018, Marcus et al. 2019, Wong et al. 2020, Rogers et al. 2022), small atmospheric waves and turbulence (Simon et al. 2015/2018/2022, Cosentino et al. 2017/2019, Tollefson et al. 2017, Fletcher et al. 2018, Giles et al. 2019), long-term color trends and aerosol layer variability (Medikoa et al. 2017, Tollefson et al. 2017, Braude et al. 2020, Pérez-Hoyos et al. 2020, Dahl et al. 2021, Fry and Sromovsky 2023, Simon and Wong 2024), and UV-dark ovals in the polar hoods (Tsubota et al. 2025).

Space missions

OPAL data have extended the science return of several space missions, with Jupiter observations commencing one year before Juno arrived at Jupiter. OPAL wind and cloud structure measurements have been used in diverse analyses of phenomena, from deep zonal atmospheric structure revealed by microwave emission (Oyafuso et al. 2020, Fletcher et al. 2021), to convective cycles in cyclonic vortices (Iñurrigarro et al. 2020/2022, Hueso et al. 2022). Wave, jet, and vortex features previously observed by Voyager, Galileo, and Cassini have also been studied in greater detail with the long-term OPAL program (Simon et al. 2015, Wong et al. 2021, Tsubota et al. 2025).

A selection of comparative studies using OPAL data and data from spacecraft and Earth-based observatories is shown in Fig. 3.

Earth-based observatories

High-resolution visible-wavelength observations from OPAL target the planets near solar opposition to maximize spatial resolution, as do many Earth-based programs. Multi-observatory studies include correlations between cloud color from OPAL and microwave brightness from the VLA (Costentino et al. 2017, de Pater et al. 2019), comparisons between Doppler velocimetry from the ground and time-series imaging from OPAL (Gonçalves et al. 2019, Schmider et al. 2024), calibration, validation, and context for spectral measurements (Mendikoa et al. 2017, Bjoraker et al. 2018, Braude et al. 2020, Dahl et al. 2021), and deep context for stratospheric winds and aerosol anomalies observed with JWST and Gemini (Hueso et al. 2023, Giles et al. 2019, Tsubota et al. 2025).

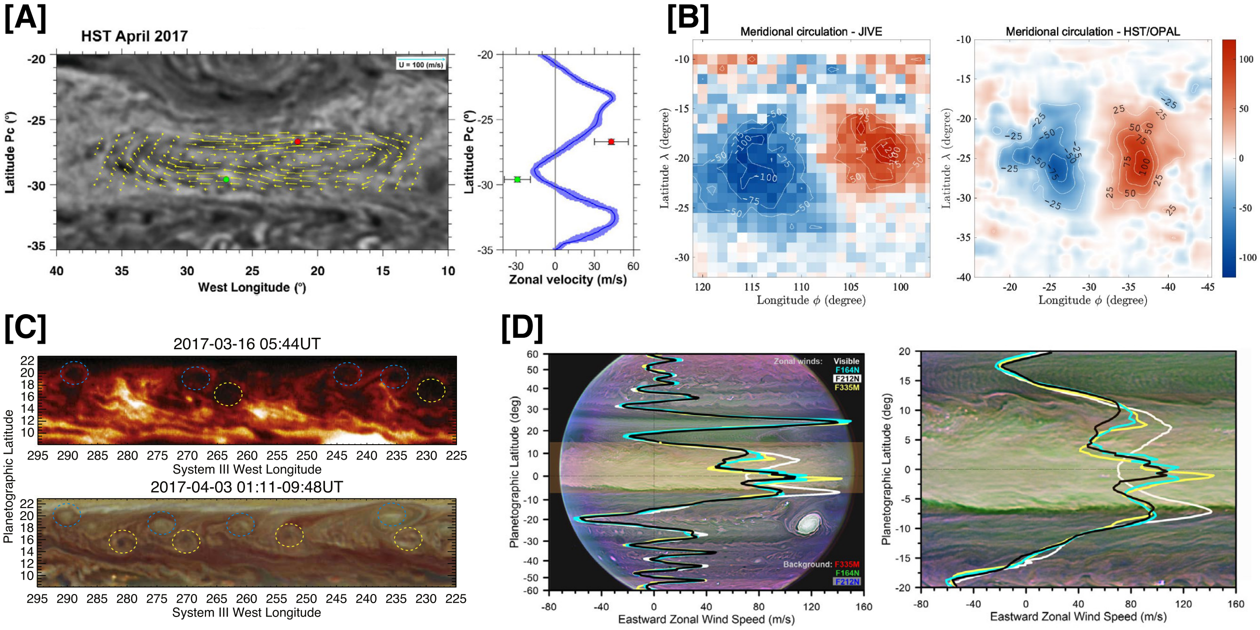


Figure 3. OPAL data provide comparisons, validation, and supplementation to other Earth-based and spacecraft datasets. **[A]** OPAL data enabled measurement of internal wind speeds in a cyclonic vortex, in images predating a convective outburst detected by JunoCam (Iñurrigarro et al. 2020). **[B]** Remarkable measurements of north-south velocities (red and blue respectively) within the GRS were performed using Doppler imaging, with OPAL data on the right used to validate the results (Schmider et al. 2024). **[C]** Transient mesoscale waves were detected in 2018 in OPAL data, as well as in thermal imaging by the VLT and Juno JIRAM. The maps here show an epoch when the mesoscale waves were detected in visible light, but were not visible in the infrared (Fletcher et al. 2018). Mesoscale wave comparisons were also made between OPAL data and images from amateur observers and the Voyager spacecraft (Simon et al. 2015/2018). **[D]** JWST imaging data revealed a narrow, high-speed upper tropospheric jet very close to the equator; OPAL data demonstrate that this high-altitude feature is completely undetected in visible-wavelength cloud-top wind tracking (Hueso et al. 2023).

Other planets, other observatories

The results cited here are a small subset of the Jupiter results achieved with the OPAL monitoring of the outer planets, with additional discoveries at Saturn, Uranus, and Neptune (some examples in Fig. 4). With more than 10 years of data in hand, and continuing for the life of Hubble, we expect the scientific return to increase geometrically. OPAL serves as a model for future long-term programs at other observatories (Wong et al. 2019, Jha et al. 2024) and guides the definition of mission science objectives (Palumbo et al. 2025).

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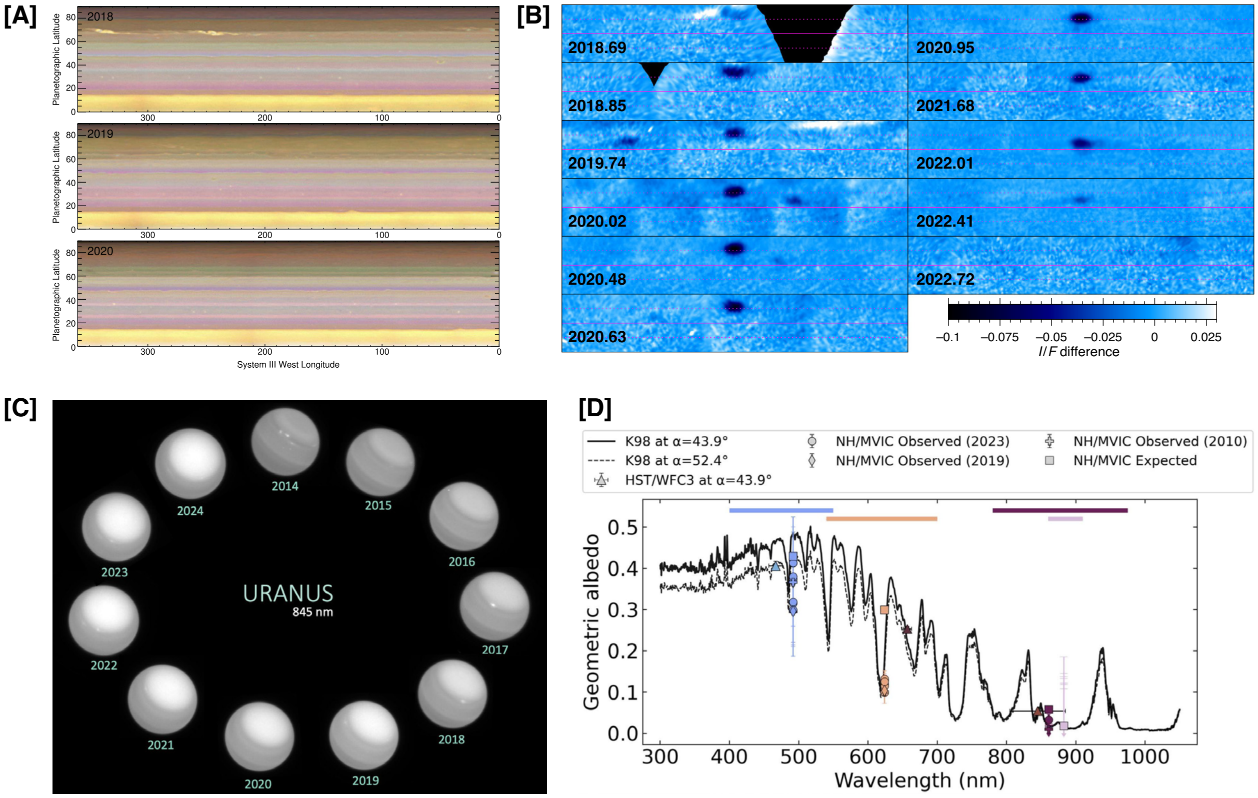

Figure 4. Many other OPAL results from Saturn, Uranus, and Neptune are beyond the scope of this Jupiter-focused report. **[A]** OPAL revealed numerous color changes in narrow banded structures at Saturn, with some potentially related to a convective outburst (Simon et al. 2021). OPAL also made new observations of Saturn ring spokes, tying to phenomena first observed by Voyager (Simon et al. 2023). **[B]** OPAL data enabled the full life cycle of a dark spot on Neptune to be observed for the first time (Simon et al. 2019, Hsu et al. 2019, Wong et al. 2022, Wong et al. 2024). **[C]** OPAL captured dramatic changes in the polar atmosphere of Uranus following solstice (Sromovsky et al. 2015, Toledo et al. 2019, James et al. 2023, Irwin et al. 2024). **[D]** Simultaneous OPAL and New Horizons observations of Uranus were used to quantify the dependence of disk-averaged brightness on solar phase angle, with the goal of providing local ground truth for interpreting directly-imaged exoplanet observations (Hasler et al. 2024).

References

Anguiano-Arteaga, A., S. Pérez-Hoyos, A. Sánchez-Lavega, J. F. Sanz-Requena, and P. G. J. Irwin (2023) Temporal Variations in Vertical Cloud Structure of Jupiter's Great Red Spot, Its Surroundings and Oval BA From HST/WFC3 Imaging. Journal of Geophysical Research (Planets) 128, e2022JE007427. DOI: 10.1029/2022JE007427

Barrado-Izagirre, N., J. Legarreta, A. Sánchez-Lavega, S. Pérez-Hoyos, R. Hueso, P. Iñurrigarro, J. F. Rojas, I. Mendikoa, I. Ordoñez-Etxeberria, and IOPW Team (2021) Jupiter's third largest and longest-lived oval: Color changes and dynamics. Icarus 361, 114394. DOI: 10.1016/j.icarus.2021.114394

Bjoraker, G. L., M. H. Wong, I. de Pater, T. Hewagama, M. Ádámkovics, and G. S. Orton (2018) The Gas Composition and Deep Cloud Structure of Jupiter's Great Red Spot. The Astronomical Journal 156, 101. DOI: 10.3847/1538-3881/aad186

Braude, A. S., P. G. J. Irwin, G. S. Orton, and L. N. Fletcher (2020) Colour and tropospheric cloud structure of Jupiter from MUSE/VLT: Retrieving a universal chromophore. Icarus 338, 113589. DOI: 10.1016/j.icarus.2019.113589

Carlson, R. W., K. H. Baines, M. S. Anderson, G. Filacchione, and A. A. Simon (2016) Chromophores from photolyzed ammonia reacting with acetylene: Application to Jupiter's Great Red Spot. Icarus 274, 106–115. DOI: 10.1016/j.icarus.2016.03.008

Chavez, E., E. Redwing, I. de Pater, R. Hueso, E. M. Molter, M. H. Wong, C. Alvarez, E. Gates, K. de Kleer, J. Aycock, J. Mcilroy, J. Pelletier, A. Ridenour, A. Sánchez-Lavega, J. F. Rojas, and T. Stickel (2023) Drift rates of major Neptunian features between 2018 and 2021. Icarus 401, 115604. DOI: 10.1016/j.icarus.2023.115604

Chavez, E., I. de Pater, E. Redwing, E. M. Molter, M. T. Roman, A. Zorzi, C. Alvarez, R. Campbell, K. de Kleer, R. Hueso, M. H. Wong, E. Gates, P. D. Lynam, A. G. Davies, J. Aycock, J. Mcilroy, J. Pelletier, A. Ridenour, and T. Stickel (2023) Evolution of Neptune at near-infrared wavelengths from 1994 through 2022. Icarus 404, 115667. DOI: 10.1016/j.icarus.2023.115667

Cosentino, R. G., A. Simon, and R. Morales-Juberías (2019) Jupiter's Turbulent Power Spectra From Hubble Space Telescope. Journal of Geophysical Research (Planets) 124, 1204–1225. DOI: 10.1029/2018JE005762

Cosentino, R. G., B. Butler, B. Sault, R. Morales-Juberías, A. Simon, and I. de Pater (2017) Atmospheric waves and dynamics beneath Jupiter's clouds from radio wavelength observations. Icarus 292, 168–181. DOI: 10.1016/j.icarus.2017.01.006

Dahl, E. K., N. J. Chanover, G. S. Orton, K. H. Baines, J. A. Sinclair, D. G. Voelz, E. A. Wijerathna, P. D. Strycker, and P. G. J. Irwin (2021) Vertical Structure and Color of Jovian Latitudinal Cloud Bands during the Juno Era. The Planetary Science Journal 2, 16. DOI: 10.3847/PSJ/abd400

de Pater, I., R. J. Sault, M. H. Wong, L. N. Fletcher, D. DeBoer, and B. Butler (2019) Jupiter's ammonia distribution derived from VLA maps at 3-37 GHz. Icarus 322, 168–191. DOI: 10.1016/j.icarus.2018.11.024

Fletcher, L. N., F. A. Oyafuso, M. Allison, A. Ingersoll, L. Li, Y. Kaspi, E. Galanti, M. H. Wong, G. S. Orton, K. Duer, Z. Zhang, C. Li, T. Guillot, S. M. Levin, and S. Bolton (2021) Jupiter's Temperate Belt/Zone Contrasts Revealed at Depth by Juno Microwave Observations. Journal of Geophysical Research (Planets) 126, e06858. DOI: 10.1029/2021JE006858

Fletcher, L. N., H. Melin, A. Adriani, A. A. Simon, A. Sanchez-Lavega, P. T. Donnelly, A. Antuñano, G. S. Orton, R. Hueso, E. Kraaikamp, M. H. Wong, M. Barnett, M. L. Moriconi, F. Altieri, and G. Sindoni (2018) Jupiter's Mesoscale Waves Observed at 5 μm by Ground-based Observations and Juno JIRAM. The Astronomical Journal 156, 67. DOI: 10.3847/1538-3881/aace02

Fletcher, L. N., O. R. T. King, J. Harkett, H. B. Hammel, M. T. Roman, H. Melin, M. M. Hedman, J. I. Moses, S. Guerlet, S. N. Milam, and M. S. Tiscareno (2023) Saturn's Atmosphere in Northern Summer Revealed by JWST/MIRI. Journal of Geophysical Research (Planets) 128, e2023JE007924. DOI: 10.1029/2023JE007924

Fry, P. M. and L. A. Sromovsky (2023) Investigating temporal changes in Jupiter's aerosol structure with rotationally-averaged 2015-2020 HST WFC3 images. Icarus 389, 115224. DOI: 10.1016/j.icarus.2022.115224

Ge, H., X. Zhang, L. N. Fletcher, G. S. Orton, J. Sinclair, J. Fernandes, T. Momary, Y. Kasaba, T. M. Sato, and T. Fujiyoshi (2019) Rotational Light Curves of Jupiter from Ultraviolet to Mid-infrared and Implications for Brown Dwarfs and Exoplanets. The Astronomical Journal 157, 89. DOI: 10.3847/1538-3881/aafba7

Giles, R. S., G. S. Orton, A. W. Stephens, M. H. Wong, P. G. J. Irwin, J. A. Sinclair, and F. Tabataba-Vakili (2019) Wave Activity in Jupiter's North Equatorial Belt From Near-Infrared Reflectivity Observations. Geophysical Research Letters 46, 1232–1241. DOI: 10.1029/2018GL081858

Gonçalves, I., F. X. Schmider, P. Gaulme, R. Morales-Juberías, T. Guillot, J.-P. Rivet, T. Appourchaux, P. Boumier, J. Jackiewicz, B. Sato, S. Ida, M. Ikoma, D. Mékarnia, T. A. Underwood, and D. Voelz (2019) First measurements of Jupiter's zonal winds with visible imaging spectroscopy. Icarus 319, 795–811. DOI: 10.1016/j.icarus.2018.10.019

Harkett, J., L. N. Fletcher, O. R. T. King, M. T. Roman, H. Melin, H. B. Hammel, R. Hueso, A. Sánchez-Lavega, M. H. Wong, S. N. Milam, G. S. Orton, K. de Kleer, P. G. J. Irwin, I. de Pater, T. Fouchet, P. Rodríguez-Ovalle, P. M. Fry, and M. R. Showalter (2024) The Thermal Structure and Composition of Jupiter's Great Red Spot From JWST/MIRI. Journal of Geophysical Research (Planets) 129, e2024JE008415. DOI: 10.1029/2024JE008415

Hasler, S. N., L. C. Mayorga, W. M. Grundy, A. A. Simon, S. D. Benecchi, C. J. A. Howett, S. Protopapa, H. B. Hammel, D. D. Wenkert, S. A. Stern, K. N. Singer, S. B. Porter, P. C. Brandt, J. W. Parker, A. J. Verbiscer, J. R. Spencer, and The New Horizons Planetary Science Theme Team (2024) Observations of Uranus at High Phase Angle as Seen by New Horizons. The Planetary Science Journal 5, 267. DOI: 10.3847/PSJ/ad8cdb

Hsu, A. I., M. H. Wong, and A. A. Simon (2019) Lifetimes and Occurrence Rates of Dark Vortices on Neptune from 25 Years of Hubble Space Telescope Images. The Astronomical Journal 157, 152. DOI: 10.3847/1538-3881/ab0747

Hueso, R., A. Sánchez-Lavega, J. F. Rojas, A. A. Simon, T. Barry, T. del . Río-Gaztelurrutia, A. Antuñano, K. M. Sayanagi, M. Delcroix, L. N. Fletcher, E. García-Melendo, S. Pérez-Hoyos, J. Blalock, F. Colas, J. M. Gómez-Forrellad, J. L. Gunnarson, D. Peach, and M. H. Wong (2020) Saturn atmospheric dynamics one year after Cassini: Long-lived features and time variations in the drift of the Hexagon. Icarus 336, 113429. DOI: 10.1016/j.icarus.2019.113429

Hueso, R. and A. Sánchez-Lavega (2019) Atmospheric Dynamics and Vertical Structure of Uranus and Neptune's Weather Layers. Space Science Reviews 215, 52. DOI: 10.1007/s11214-019-0618-6

Hueso, R., A. Sánchez-Lavega, P. Iñurrigarro, J. F. Rojas, S. Pérez-Hoyos, I. Mendikoa, J. M. Gómez-Forrellad, C. Go, D. Peach, F. Colas, and M. Vedovato (2017) Jupiter cloud morphology and zonal winds from ground-based observations before and during Juno's first perijove. Geophysical Research Letters 44, 4669–4678. DOI: 10.1002/2017GL073444

Hueso, R., I. de Pater, A. Simon, A. Sánchez-Lavega, M. Delcroix, M. H. Wong, J. W. Tollefson, C. Baranec, K. de Kleer, S. H. Luszcz-Cook, G. S. Orton, H. B. Hammel, J. M. Gómez-Forrellad, I. Ordonez-Etxeberria, L. Sromovsky, P. Fry, F. Colas, J. F. Rojas, S. Pérez-Hoyos, P. Gorczynski, J. Guarro, W. Kivits, P. Miles, D. Millika, P. Nicholas, J. Sussenbach, A. Wesley, K. Sayanagi, S. M. Ammons, E. L. Gates, D. Gavel, E. Victor Garcia, N. M. Law, I. Mendikoa, and R. Riddle (2017) Neptune long-lived atmospheric features in 2013-2015 from small (28-cm) to large (10-m) telescopes. Icarus 295, 89–109. DOI: 10.1016/j.icarus.2017.06.009

Hueso, R., P. Iñurrigarro, A. Sánchez-Lavega, C. R. Foster, J. H. Rogers, G. S. Orton, C. Hansen, G. Eichstädt, I. Ordonez-Etxeberria, J. F. Rojas, S. R. Brueshaber, J. F. Sanz-Requena, S. Pérez-Hoyos, M. H. Wong, T. W. Momary, B. Jónsson, A. Antuñano, K. H. Baines, E. K. Dahl, S. Mizumoto, C. Go, and A. Anguiano-Arteaga (2022) Convective storms in closed cyclones in Jupiter's South Temperate Belt: (I) observations. Icarus 380, 114994. DOI: 10.1016/j.icarus.2022.114994

Hueso, R., A. Sánchez-Lavega, T. Fouchet, I. de Pater, A. Antuñano, L. N. Fletcher, M. H. Wong, P. Rodríguez-Ovalle, L. A. Sromovsky, P. M. Fry, G. S. Orton, S. Guerlet, P. G. J. Irwin, E. Lellouch, J. Harkett, K. de Kleer, H. Melin, V. Hue, A. A. Simon, S. Luszcz-Cook, and K. M. Sayanagi (2023) An intense narrow equatorial jet in Jupiter's lower stratosphere observed by JWST. Nature Astronomy 7, 1454–1462. DOI: 10.1038/s41550-023-02099-2

Iñurrigarro, P., R. Hueso, A. Sánchez-Lavega, and J. Legarreta (2022) Convective storms in closed cyclones in Jupiter: (II) numerical modeling. Icarus 386, 115169. DOI: 10.1016/j.icarus.2022.115169

Iñurrigarro, P., R. Hueso, J. Legarreta, A. Sánchez-Lavega, G. Eichstädt, J. H. Rogers, G. S. Orton, C. J. Hansen, S. Pérez-Hoyos, J. F. Rojas, and J. M. Gómez-Forrellad (2020) Observations and numerical modelling of a convective disturbance in a large-scale cyclone in Jupiter's South Temperate Belt. Icarus 336, 113475. DOI: 10.1016/j.icarus.2019.113475

Irwin, P. G. J., J. Dobinson, A. James, N. A. Teanby, A. A. Simon, L. N. Fletcher, M. T. Roman, G. S. Orton, M. H. Wong, D. Toledo, S. Pérez-Hoyos, and J. Beck (2024) Modelling the seasonal cycle of Uranus's colour and magnitude, and comparison with Neptune. Monthly Notices of the Royal Astronomical Society 527, 11521–11538. DOI: 10.1093/mnras/stad3761

Irwin, P. G. J., M. H. Wong, A. A. Simon, G. S. Orton, and D. Toledo (2017) HST/WFC3 observations of Uranus' 2014 storm clouds and comparison with VLT/SINFONI and IRTF/Spex observations. Icarus 288, 99–119. DOI: 10.1016/j.icarus.2017.01.031

James, A., P. G. J. Irwin, J. Dobinson, M. H. Wong, T. K. Tsubota, A. A. Simon, L. N. Fletcher, M. T. Roman, N. A. Teanby, D. Toledo, and G. S. Orton (2023) The Temporal Brightening of Uranus' Northern Polar Hood From HST/WFC3 and HST/STIS Observations. Journal of Geophysical Research (Planets) 128, e2023JE007904. DOI: 10.1029/2023JE00790410.22541/essoar.168500322.24767923/v1

Jha, S. W., D. I. Casetti-Dinescu, G. M. Bernstein, M. J. Hayes, L. M. Oskinova, A. B. Pace, R. M. Quimby, M. Reiter, A. Rest, A. G. Riess, D. J. Sand, and D. R. Weisz (2024) HST/JWST Long-Term Monitoring Working Group Final Report. DOI: 10.48550/arXiv.2405.12297

Johnson, P. E., R. Morales-Juberías, A. Simon, P. Gaulme, M. H. Wong, and R. G. Cosentino (2018) Longitudinal variability in Jupiter's zonal winds derived from multi-wavelength HST observations. Planetary and Space Science 155, 2–11. DOI: 10.1016/j.pss.2018.01.004

Loeffler, M. J. and R. L. Hudson (2018) Coloring Jupiter's clouds: Radiolysis of ammonium hydrosulfide (NH4SH). Icarus 302, 418–425. DOI: 10.1016/j.icarus.2017.10.041

Loeffler, M. J., R. L. Hudson, N. J. Chanover, and A. A. Simon (2016) The spectrum of Jupiter's Great Red Spot: The case for ammonium hydrosulfide (NH4SH). Icarus 271, 265–268. DOI: 10.1016/j.icarus.2016.02.010

Mapaye, R. and M. H. Wong (2022) Unveiling Uranus: A Difference in Dark Spots Compared to Neptune. Compendium of Undergraduate Research in Astronomy and Space Science 525, 93. DOI: 10.26624/QSAX2925

Marcus, P. S., J. Tollefson, M. H. Wong, and I. de . Pater (2019) An equatorial thermal wind equation: Applications to Jupiter. Icarus 324, 198–223. DOI: 10.1016/j.icarus.2018.09.037

Mendikoa, I., A. Sánchez-Lavega, S. Pérez-Hoyos, R. Hueso, J. F. Rojas, and J. López-Santiago (2017) Temporal and spatial variations of the absolute reflectivity of Jupiter and Saturn from 0.38 to 1.7 μm with PlanetCam-UPV/EHU. Astronomy and Astrophysics 607, A72. DOI: 10.1051/0004-6361/201731109

Molter, E., I. de Pater, S. Luszcz-Cook, R. Hueso, J. Tollefson, C. Alvarez, A. Sánchez-Lavega, M. H. Wong, A. I. Hsu, L. A. Sromovsky, P. M. Fry, M. Delcroix, R. Campbell, K. de Kleer, E. Gates, P. D. Lynam, S. M. Ammons, B. P. Coy, G. Duchene, E. J. Gonzales, L. Hirsch, E. A. Magnier, S. Ragland, R. M. Rich, and F. Wang (2019) Analysis of Neptune's 2017 bright equatorial storm. Icarus 321, 324–345. DOI: 10.1016/j.icarus.2018.11.018

Morales-Juberías, R., A. A. Simon, and R. G. Cosentino (2022) Analysis of the long-term drift rates and oscillations of Jupiter's largest vortices. Icarus 372, 114732. DOI: 10.1016/j.icarus.2021.114732

Oyafuso, F., S. Levin, G. Orton, S. T. Brown, V. Adumitroaie, M. Janssen, M. H. Wong, L. N. Fletcher, P. Steffes, C. Li, S. Gulkis, S. Atreya, S. Misra, and S. Bolton (2020) Angular Dependence and Spatial Distribution of Jupiter's Centimeter-Wave Thermal Emission From Juno's Microwave Radiometer. Earth and Space Science 7, e01254. DOI: 10.1029/2020EA001254

Palumbo, P., and 133 colleagues (2025) The JANUS (Jovis Amorum ac Natorum Undique Scrutator) VIS-NIR Multi-Band Imager for the JUICE Mission. Space Science Reviews 221, 32. DOI: 10.1007/s11214-025-01158-6

Pérez-Hoyos, S., A. Sánchez-Lavega, J. F. Sanz-Requena, N. Barrado-Izagirre, Ó. Carrión-González, A. Anguiano-Arteaga, P. G. J. Irwin, and A. S. Braude (2020) Color and aerosol changes in Jupiter after a North Temperate Belt disturbance. Icarus 352, 114031. DOI: 10.1016/j.icarus.2020.114031

Porco, C. C., R. A. West, A. McEwen, A. D. Del Genio, A. P. Ingersoll, P. Thomas, S. Squyres, L. Dones, C. D. Murray, T. V. Johnson, J. A. Burns, A. Brahic, G. Neukum, J. Veverka, J. M. Barbara, T. Denk, M. Evans, J. J. Ferrier, P. Geissler, P. Helfenstein, T. Roatsch, H. Throop, M. Tiscareno, and A. R. Vasavada (2003) Cassini Imaging of Jupiter's Atmosphere, Satellites, and Rings. Science 299, 1541–1547. DOI: 10.1126/science.1079462

Rogers, J. H., G. Eichstädt, C. J. Hansen, G. S. Orton, T. Momary, A. Casely, G. Adamoli, M. Jacquesson, R. Bullen, D. Peach, T. Olivetti, S. Brueshaber, M. Ravine, and S. Bolton (2022) Flow patterns of Jupiter's south polar region. Icarus 372, 114742. DOI: 10.1016/j.icarus.2021.114742

Roman, M. T., L. N. Fletcher, G. S. Orton, N. Rowe-Gurney, and P. G. J. Irwin (2020) Uranus in Northern Midspring: Persistent Atmospheric Temperatures and Circulations Inferred from Thermal Imaging. The Astronomical Journal 159, 45. DOI: 10.3847/1538-3881/ab5dc7

Sánchez-Lavega, A., A. Anguiano-Arteaga, P. Iñurrigarro, E. Garcia-Melendo, J. Legarreta, R. Hueso, J. F. Sanz-Requena, S. Pérez-Hoyos, I. Mendikoa, M. Soria, J. F. Rojas, M. Andrés-Carcasona, A. Prat-Gasull, I. Ordoñez-Extebarria, J. H. Rogers, C. Foster, S. Mizumoto, A. Casely, C. J. Hansen, G. S. Orton, T. Momary, and G. Eichstädt (2021) Jupiter's Great Red Spot: Strong Interactions With Incoming Anticyclones in 2019. Journal of Geophysical Research (Planets) 126, e06686. DOI: 10.1029/2020JE006686

Sánchez-Lavega, A., E. García-Melendo, J. Legarreta, R. Hueso, T. del Río-Gaztelurrutia, J. F. Sanz-Requena, S. Pérez-Hoyos, A. A. Simon, M. H. Wong, M. Soria, J. M. Gómez-Forrellad, T. Barry, M. Delcroix, K. M. Sayanagi, J. J. Blalock, J. L. Gunnarson, U. Dyudina, and S. Ewald (2020) A complex storm system in Saturn's north polar atmosphere in 2018. Nature Astronomy 4, 180–187. DOI: 10.1038/s41550-019-0914-9

Sánchez-Lavega, A., E. García-Melendo, T. del Río-Gaztelurrutia, R. Hueso, A. Simon, M. H. Wong, K. Ahrens-Velásquez, M. Soria, T. Barry, C. Go, and C. Foster (2021) Interaction of Saturn's Hexagon With Convective Storms. Geophysical Research Letters 48, e92461. DOI: 10.1029/2021GL092461

Sánchez-Lavega, A., P. Irwin, and A. García Muñoz (2023) Dynamics and clouds in planetary atmospheres from telescopic observations. Astronomy and Astrophysics Review 31, 5. DOI: 10.1007/s00159-023-00150-9

Sánchez-Lavega, A., R. Hueso, G. Eichstädt, G. Orton, J. Rogers, C. J. Hansen, T. Momary, F. Tabataba-Vakili, and S. Bolton (2018) The Rich Dynamics of Jupiter's Great Red Spot from JunoCam: Juno Images. The Astronomical Journal 156, 162. DOI: 10.3847/1538-3881/aada81

Sankar, R., S. Brueshaber, L. Fortson, C. Hansen-Koharcheck, C. Lintott, K. Mantha, C. Nesmith, and G. S. Orton (2024) Jovian Vortex Hunter: A Citizen Science Project to Study Jupiter's Vortices. The Planetary Science Journal 5, 203. DOI: 10.3847/PSJ/ad6e75

Schmider, F.-X., P. Gaulme, R. Morales-Juberías, J. Jackiewicz, I. Gonçalves, T. Guillot, A. A. Simon, M. H. Wong, T. Underwood, D. Voelz, C. Sanchez, R. DeColibus, S. A. Kovac, S. Sellers, D. Gilliam, P. Boumier, T. Appourchaux, J. Dejonghe, J. P. Rivet, S. Markham, S. Howard, L. Abe, D. Mekarnia, M. Ikoma, H. Hanayama, B. Sato, M. Kunitomo, and H. Izumiura (2024) Three-dimensional Atmospheric Dynamics of Jupiter from Ground-based Doppler Imaging Spectroscopy in the Visible. The Planetary Science Journal 5, 100. DOI: 10.3847/PSJ/ad3066

Simon, A.A (2015) Outer Planet Atmospheres Legacy ("OPAL") [dataset]. MAST archive at Space Telescope Science Institute. DOI: 10.17909/T9G593

Simon, A. A. and M. H. Wong (2024) Zonal and Regional Jupiter Brightness Trends from the Hubble Outer Planet Atmospheres Legacy Program. The Planetary Science Journal 5, 259. DOI: 10.3847/PSJ/ad8c23

Simon, A. A., M. H. Wong, P. S. Marcus, and P. G. J. Irwin (2024) A Detailed Study of Jupiter's Great Red Spot over a 90-day Oscillation Cycle. The Planetary Science Journal 5, 223. DOI: 10.3847/PSJ/ad71d1

Simon, A. A., M. M. Hedman, P. D. Nicholson, M. S. Tiscareno, M. R. Showalter, T. McDonald, and S. Callos (2023) Hubble Detects the Start of a New Saturn Ring Spoke Season. Geophysical Research Letters 50, e2022GL101904. DOI: 10.1029/2022GL101904

Simon, A. A., M. H. Wong, L. A. Sromovsky, L. N. Fletcher, and P. M. Fry (2022) Giant Planet Atmospheres: Dynamics and Variability from UV to Near-IR Hubble and Adaptive Optics Imaging. Remote Sensing 14, 1518. DOI: 10.3390/rs14061518

Simon, A. A., R. Hueso, A. Sánchez-Lavega, and M. H. Wong (2021) Midsummer Atmospheric Changes in Saturn's Northern Hemisphere from the Hubble OPAL Program. The Planetary Science Journal 2, 47. DOI: 10.3847/PSJ/abe40f

Simon, A. A., M. H. Wong, and A. I. Hsu (2019) Formation of a New Great Dark Spot on Neptune in 2018. Geophysical Research Letters 46, 3108–3113. DOI: 10.1029/2019GL081961

Simon, A. A., R. Hueso, P. Iñurrigarro, A. Sánchez-Lavega, R. Morales-Juberías, R. Cosentino, L. N. Fletcher, M. H. Wong, A. I. Hsu, I. de Pater, G. S. Orton, F. Colas, M. Delcroix, D. Peach, and J.-M. Gómez-Forrellad (2018) A New, Long-lived, Jupiter Mesoscale Wave Observed at Visible Wavelengths. The Astronomical Journal 156, 79. DOI: 10.3847/1538-3881/aacaf5

Simon, A. A., F. Tabataba-Vakili, R. Cosentino, R. F. Beebe, M. H. Wong, and G. S. Orton (2018) Historical and Contemporary Trends in the Size, Drift, and Color of Jupiter's Great Red Spot. The Astronomical Journal 155, 151. DOI: 10.3847/1538-3881/aaae01

Simon, A. A., J. F. Rowe, P. Gaulme, H. B. Hammel, S. L. Casewell, J. J. Fortney, J. E. Gizis, J. J. Lissauer, R. Morales-Juberias, G. S. Orton, M. H. Wong, and M. S. Marley (2016) Neptune's Dynamic Atmosphere from Kepler K2 Observations: Implications for Brown Dwarf Light Curve Analyses. The Astrophysical Journal 817, 162. DOI: 10.3847/0004-637X/817/2/162

Simon, A. A., M. H. Wong, and G. S. Orton (2015) First Results from the Hubble OPAL Program: Jupiter in 2015. The Astrophysical Journal 812, 55. DOI: 10.1088/0004-637X/812/1/55

Sromovsky, L. A., I. de Pater, P. M. Fry, H. B. Hammel, and P. Marcus (2015) High S/N Keck and Gemini AO imaging of Uranus during 2012-2014: New cloud patterns, increasing activity, and improved wind measurements. Icarus 258, 192–223. DOI: 10.1016/j.icarus.2015.05.029

Stauffer, J., M. S. Marley, J. E. Gizis, L. Rebull, S. J. Carey, J. Krick, J. G. Ingalls, P. Lowrance, W. Glaccum, J. D. Kirkpatrick, A. A. Simon, and M. H. Wong (2016) Spitzer Space Telescope Mid-IR Light Curves of Neptune. The Astronomical Journal 152, 142. DOI: 10.3847/0004-6256/152/5/142

Toledo, D., P. G. J. Irwin, P. Rannou, N. A. Teanby, A. A. Simon, M. H. Wong, and G. S. Orton (2019) Constraints on Uranus's haze structure, formation and transport. Icarus 333, 1–11. DOI: 10.1016/j.icarus.2019.05.018

Tollefson, J., M. H. Wong, I. de . Pater, A. A. Simon, G. S. Orton, J. H. Rogers, S. K. Atreya, R. G. Cosentino, W. Januszewski, R. Morales-Juberías, and P. S. Marcus (2017) Changes in Jupiter's Zonal Wind Profile preceding and during the Juno mission. Icarus 296, 163–178. DOI: 10.1016/j.icarus.2017.06.007

Tsubota, T. K., M. H. Wong, T. Stallard, X. Zhang, and A. A. Simon (2025) UV-dark polar ovals on Jupiter as tracers of magnetosphere-atmosphere connections. Nature Astronomy 9, 221–229. DOI: 10.1038/s41550-024-02419-0

Wong, M.H., L. Sromovsky, A.A. Simon, P. Irwin, P.M. Fry, R. Morales-Juberias, A. Sanchez-Lavega, J. Legarreta, R. Hueso, and I. de Pater (2024) The dissipation phase of dark spot NDS-2018 on Neptune. AAS/Division for Planetary Sciences Meeting Abstracts 56, 210.03, 8 October, Boise ID. DOI: 10.3847/25c2cfeb.64cecc52

Wong, M. H., L. A. Sromovsky, P. M. Fry, A. Sánchez-Lavega, R. Hueso, J. Legarreta, A. A. Simon, R. Morales-Juberías, J. Tollefson, I. de Pater, and P. G. J. Irwin (2022) Evolution of a dark vortex on Neptune with transient secondary features. Icarus 387, 115123. DOI: 10.1016/j.icarus.2022.115123

Wong, M. H., P. S. Marcus, A. A. Simon, I. de Pater, J. W. Tollefson, and X. Asay-Davis (2021) Evolution of the Horizontal Winds in Jupiter's Great Red Spot From One Jovian Year of HST/WFC3 Maps. Geophysical Research Letters 48, e93982. DOI: 10.1029/2021GL093982

Wong, M. H., A. A. Simon, J. W. Tollefson, I. de Pater, M. N. Barnett, A. I. Hsu, A. W. Stephens, G. S. Orton, S. W. Fleming, C. Goullaud, W. Januszewski, A. Roman, G. L. Bjoraker, S. K. Atreya, A. Adriani, and L. N. Fletcher (2020) High-resolution UV/Optical/IR Imaging of Jupiter in 2016-2019. The Astrophysical Journal Supplement Series 247, 58. DOI: 10.3847/1538-4365/ab775f

Wong, M. H., A. Otarola, K. R. de Kleer, S. H. Cook, A. Hendrix, K. Sayanagi, A. Simon, T. Greathouse, B. Holler, I. de Pater, M. Lucas, D. Trilling, R. Cartwright, N. Chanover, M. Tiscareno, G. Orton, C. Nixon, S. N. Milam, P. M. Fry, R. Giles, J. Sinclair, and M. Adamkovics (2019) Solar system Deep Time-Surveys of atmospheres, surfaces, and rings. Bulletin of the American Astronomical Society 51, 541. DOI: 10.48550/arXiv.1903.06321

Wong, M. H., J. Tollefson, A. I. Hsu, I. de Pater, A. A. Simon, R. Hueso, A. Sánchez-Lavega, L. Sromovsky, P. Fry, S. Luszcz-Cook, H. Hammel, M. Delcroix, K. de Kleer, G. S. Orton, and C. Baranec (2018) A New Dark Vortex on Neptune. The Astronomical Journal 155, 117. DOI: 10.3847/1538-3881/aaa6d6