Hubble Detects the Start of a New Saturn Ring Spoke Season

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Key Points:

- The start of a new Saturn spoke season was confirmed by Hubble observations in 2021 and 2022, with spokes tracked over an 11-hour period
- The spokes occurred near 1.8 Saturn radii and are spectrally red, but slightly bluer than the rings
- Spoke activity and contrast is expected to increase as ring opening angle decreases in advance of Saturn's next equinox in May 2025

Abstract

Saturn's ring spokes typically appear over an 8-year duration centered on equinox. Hubble Space Telescope observations in 2021 indicate the beginning of a new spoke season as Saturn approaches equinox in 2025. The spokes show increased contrast and longevity in 2022, persisting for up to eleven hours. The spokes are visible from UV to near-IR and are slightly bluer (i.e., less red) than the rings, but we find no significant wavelength dependence in the spectral contrast, which approximates their optical depth). Spoke rotation rates are between 606 and 626 minutes, consistent with either Keplerian rotation or possibly the variable rotation rate of Saturn's kilometric radiation (SKR). Spoke activity is expected to increase over the next several years.

Plain Language Summary

Saturn is known for its iconic, pristine rings. However, the main B ring can have have splotches and streaks of darker or lighter material, known as spokes, that may be tied to dust interactions with the planet's magnetic field. These spokes appear periodically, lasting around 8 years, centered around Saturn spring or fall equinox. Hubble Space Telescope observations in 2021 and 2022 revealed the start of a new ring spoke season in advance of the next equinox in 2025. Multi-color observations reveal a reddish color, and that the spokes circle the planet at about the same rate as the ring particles, though perhaps influenced by the variable rotation rate of Saturn's magnetosphere. Spoke activity should continue to increase for the next several years, becoming more visible to ground-based telescopes over time.

1 Introduction

Streaks and patches in Saturn's B ring were first observed during the Voyager 1 (1980) and Voyager 2 (1981) flybys (Collins et al. 1980; Smith et al. 1981). Dubbed spokes, they typically appear as radial streaks near the ring ansae, and are usually, but not exclusively, dark in back scattered light and bright in forward scattered light. Spokes are observed slightly more often on the morning ring ansa (Smith et al. 1981, 1982; Grun 1983). Scattering properties suggest that the spokes are formed by levitating dust particles, and statistical analyses have tied their appearance to locations in Saturn's magnetic field, and suggest that they form from electrostatic discharges across the rings (Smith et al. 1982; Porco & Danielson 1982).

An extensive search for spokes in Hubble data from 1996 to 2004 found many examples over the years 1996 to 1998, but none after, suggesting that, in addition to the influence of the magnetic field, proper solar illumination and observing conditions were required (McGhee et al. 2005). However, despite better imaging capability, spokes were not present when Cassini first arrived at Saturn in 2004 (Mitchell et al. 2013). Rather, Cassini first observed spokes in 2005, and they were seen through at least 2013 with decreasing frequency (Mitchell et al. 2006; 2013). With these statistics, it was expected the spokes should not appear again until the sun-ring opening angle next dropped below 20°, for an 8-year period centered on equinox (Mitchell et al. 2013).

Saturn's next equinox occurs 6 May 2025, implying that spokes would begin to appear in ~2021. We report on first detections of new ring spokes since the end of the Cassini mission, using data from the Hubble Outer Planet Atmospheres Legacy (OPAL) program in 2021 and 2022. Using the extended filter and time coverage in our data sets we examined the spectral shape and motion of the spokes. We also conducted an extensive search of the later years of Cassini imaging data, and prior OPAL data, to determine if there were any unreported instances of spokes at high sun-ring opening angle. Lastly, the Hubble detections were then placed into context with prior spoke detections.

2 Materials and Methods

The OPAL program was designed to provide high resolution imaging of each of the outer planets every Earth year in multiple Wide Field Camera 3 (WFC3) filters, primarily for atmospheric studies (Simon et al. 2015). As Cassini was still operating when the program began in late 2014, Saturn was not observed by OPAL until 2018. The program observes over two planetary rotations, allowing mapping of the atmosphere at all longitudes, but also providing full coverage of Saturn's rings. All data are processed through the WFC3 calibration pipeline followed by filter fringe correction, which primarily affects the narrowband long wavelength filters by a few percent (Wong 2011). Images are then navigated for planet center using an iterative limb fitting process and the calibrated radiances (I) are converted to reflectance (I/F) by dividing by F, where the solar flux (π F) is taken from Colina et al. (1996), integrated over each filter's bandpass (Simon et al. 2015).

During this routine processing of 12 September 2021 Saturn data, it was noted that a low contrast feature was apparent on the B ring in at least one Hubble orbit. With contrast enhancement, the feature was observed to rotate in subsequent images confirming the detection of a ring spoke, Figure 1. A search of all Hubble 2021 images found the features were present throughout the Hubble orbit (~45 minutes), Table S1, centered around System III west longitudes 307° to 315° and ~1.76 Saturn radii (R_S). The spoke complex was detectable in all filters. Spokes were not noted in any subsequent data from September 2021 and spokes were not present at these longitudes one Saturn rotation later.

Data next acquired on 22 September 2022 showed new spokes in three Hubble orbits with time separations up to eleven hours, Figure 2. The 2022 spoke complex was observed near 1.8 R_S, centered on subplanet longitude 270° W. All ring longitudes were not imaged twice due to data loss, however, the spoke longitudes were recovered on both Saturn rotations. The relevant longitudes are behind the planet at the beginning of the next Hubble orbit, but features become visible almost immediately when these longitudes are illuminated by the sun. At emergence, a dark linear streak is seen extending from ~261.9° W at 1.78 R_S and extending to 266.4° W at 1.83 R_S.

With such coarse temporal spacing, it is impossible to say if the same exact feature persists over eleven hours, but it does indicate continued activity in the 260° W longitude region. These orbits also showed other unconfirmed features on both morning and evening ansae, but they were generally too indistinct for further study. In the three Hubble 2022 orbits, the spokes were visible at all wavelengths from the UV to the near-IR and with greater contrast than observed in 2021, though fading by the end of the third Hubble orbit, Fig. 2 (bottom right).

3 Results

Spoke detections are most tenuous at UV wavelengths due to the faintness of the rings, but despite the low signal, the contrast is not much different than at other wavelengths, Figure 3.

Because the temporal coverage and number of spokes detected are very limited, and because the OPAL observations cycle between filters, the exact relationship between contrast and spoke location in Fig. 3A is not clear cut. However, the abrupt drop in spoke contrast over contiguous Hubble orbits in 2022, followed by fading out in ~20 minutes, is consistent with measurements of spoke decay on timescales of 500-3500 seconds (Grun et al. 1992).

The OPAL program's comprehensive wavelength coverage also allows for spectral comparisons between the individual spoke detections. Despite temporal variations in contrast, all of the spokes have nearly identical spectral characteristics with absorption at blue and UV wavelengths, Figure 4. The spoke spectra, Fig. 4A, which include ring background signal, generally match that of the rings with but are slightly less red, in good agreement with Cassini VIMS spoke spectra (D'Aversa et al. 2010). The spoke spectral contrast, Fig. 4B, equals its optical depth in the absence of scattering and if the spokes are optically thin (D'Aversa et al. 2010). The spoke particles can scatter both sunlight and reflected ring light, affecting the absolute magnitude of the measured spoke extinction, but more data are required over a range of lighting conditions to constrain the scattering properties (e.g., McGhee et al 2005). The spectral contrast shows little variation with wavelength except in the narrow 889-nm filter, where the spoke contrast is lower.

In addition to contrast changes, the spoke azimuthal location also noticeably migrates eastward relative to System III longitude over time. In 2021, the larger, more diffuse, feature at 1.75 R_S cannot be tracked accurately, but the 1.78 R_S feature migrates from ~307.3° W to 306.3° W longitude over the 33.2 minutes between F631N exposures. This corresponds to a rotation period of 606 ± 15 minutes, which is close to the Keplerian rate at this radius and is within the error bars of previously reported spoke rotation rates (Porco & Danielson 1982; Grun et al. 1983, 1992; Mitchell et al. 2013); we adopted large error bars due to the low contrast and spatial resolution when compared with Voyager or Cassini. Tracking the higher contrast 2022 spoke over a full Saturn rotation, Fig. 3B, yields a rotation rate of 626 minutes, while using the consecutive Hubble orbits where the spoke identification is conclusive, the 53-minute image separation yields a rotation rate of 608 minutes.

4 Discussion

The spokes have long been thought to have a connection to the magnetic field, as specific ring longitudes, perhaps tied to a magnetic anomaly, tend to be preferred (Porco & Danielson 1982). However, the magnetic rotation rate is not well-defined, with the SKR period varying with time and hemisphere (e.g., Kurth et al. 2008, Ye et al. 2018). Unfortunately, the prediction of magnetic longitude does not extend past the Cassini mission but extrapolating using the SLS3 system (Kurth et al. 2008), places the spokes at 160° in both 2021 and 2022. This was a region of high spoke activity in the Voyager 1 and 2 data (Porco & Danielson 1982), though the significance is unclear after such a long lapse given the variations in the SKR rotation rate (Ye et al. 2018).

Additionally, spoke appearance has a seasonal component (e.g., McGhee et al. 2005; Mitchell et al. 2006 and references therein). In particular, the plasma environment that allows dust to be lifted above the rings is strongly controlled by the sun-ring opening angle, β. From analyses of prior observations, McGhee et al. (2005) inferred that spoke inferred that spoke formation only occurs when $|\beta| < 15°$. After Cassini's early observations of spokes, refined plasma-dust levitation models suggested β <20° as a more accurate boundary (Mitchell et al. 2006); the new Hubble observations all occur at β <20°, Table S1.

To place the 2021 and 2022 data further in context, we searched prior years of Hubble data, as well as the last few years of Cassini data to determine if any spokes were present at higher ring angles. No further evidence of spokes was found in OPAL data from 2018 through 2020. From Cassini, spokes were previously noted through late 2013, and imaging continued until the spacecraft's final plunge into the atmosphere in 2017. We found several images, Table S2, that showed spokes from late 2013 through mid 2014, predominately in forward scattering. The detected spokes are faint, Figure 5, and our search was undoubtedly incomplete. Callos et al. (2022) presented a more thorough search, but this detection provides an approximate timescale of final spoke appearance, which did occur beyond β =20°.

Figure 6 plots the sun-ring opening angle vs time with blue shading indicating when detections have occurred, including the new detections in Cassini images in mid-2014 and a ground-based detection at Pic du Midi in 1992 (Sheehan & O'Meara 1993). In the pre-Cassini era, Hubble observations happened every few months from 1998-2005, with no noted spoke detections (McGhee et al. 2005). Cassini detections began when β dipped below ~ -21° and continued until about β = 22°. Since 2018, Saturn has only been observed sparsely at Hubble resolution, once per year with the OPAL program. The 2021 Hubble detection occurred at β ~18°, in family with previous detections; the 2020 observations, with no spokes detected, were at β ~21.5°. The increased spoke contrast, and multiple sightings, in 2022 (at β ~13°) may indicate an increase in spoke activity as the ring opening angle continues to decrease.

5 Conclusions

Hubble observations of Saturn in 2021 and 2022 yielded serendipitous detections of Saturn ring spokes. On both dates they appear as dark features occurring on the morning ring ansa and are detectable from UV through near-IR wavelengths. The 2022 spokes had higher contrast against the rings (up to ~9%) and were observed at multiple times at similar longitudes. Spoke activity continued over one Saturn rotation, but coverage is too sparse to determine if this singular feature persisted over the ten-hour gap or if new spokes formed in the interim. The second 2022 spoke detection occurred as soon as the affected ring longitudes were visible past Saturn's shadow and remained visible, but with fading contrast, over a period of ~90 minutes. Because the spokes were visible over many tens of minutes (and possibly eleven hours), rotational periods could be measured and ranged from ~606 to 626 minutes. This range is roughly consistent with the Keplerian or magnetic rotation periods, in good agreement with prior studies.

Lastly, the Hubble filter coverage allowed for spectral characterization and comparison among the spokes. The spokes show similar spectral shape to each other and to the rings, and their spectral contrast is essentially neutral, consistent with previous observations. The contrast and spoke persistence were higher in 2022, perhaps heralding an era of increased activity as Saturn approaches its next equinox in 2025. The Hubble OPAL program will continue its annual Saturn observational cadence for as long as the facility is operational, and the spokes should soon be readily visible to ground based telescopes, as well.

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Open Research

Data Availability Statement

The data analyzed in this work were acquired with the NASA/ESA Hubble Space Telescope under programs GO16266 and GO16790 and are available in the Barbara A. Mikulski Archive for Space Telescopes. The 2021 and 2022 Hubble spoke detection images may be retrieved directly from http://dx.doi.org/10.17909/42rj-vm82. The Cassini data shown are available using the NASA Planetary Data System (PDS) Ring-Moon Systems Node's Outer Planets Unified Search (OPUS) service (https://pds-rings.seti.org/search/). Saturn ring ephemeris data were generated using the PDS Rings Node Saturn Ephemeris Generator Verion 3.0 (https://pds-rings.seti.org/tools/ephem3_sat.shtml). All figures were created using IDL Version 8.5.

Figure captions:

Figure 1. Hubble 2021 spoke detection. Images acquired on 12 September 2021 show a faint dark feature that rotates with the rings over 30 minutes. Contrast has been enhanced, but the features are only a few percent darker than the rings themselves.

Figure 2. Hubble 2022 spoke detection. Images acquired on 22 September 2022 showed similar coherent dark features as in Fig. 1, but over a longer time period of one Saturn rotation.

Figure 3. Azimuthal ring brightness scans (averaged over 1.80±0.01 R_S and normalized by the mean brightness away from the spokes), from the 2022 spoke detection. A) Ring scans in multiple filters from the first 2022 Hubble orbit, shifted down with time for clarity. B) The same longitudes scanned over multiple Hubble orbits, spanning more than eleven hours.

Figure 4. Hubble ring spoke reflectance (I/F) spectra for 2021 and 2022. A) Spoke spectra for both 2021 locations and for the 2022 spoke at three different times; also shown is the 2022 mean ring brightness (yellow points). Error bars are estimated using the square root of the sum of the squared standard deviation of the non-spoke mean and the photometric accuracy of the filters (Calamida et al. 2021). B) Spoke spectral contrast of the same spokes as in A), defined as 1 – $(I/F_{Spoke})/(I/F_{Ring})$ following McGhee et al. (2005).

Figure 5. Cassini spoke detections in 2014. Sparse spokes appear as faint bright features in Cassini images of the unlit side of the rings.

Figure 6. Variation in sun-ring opening angle, β, over time. Blue shaded areas indicate spoke detections, while grey indicates no detections. White indicates a lack of high spatial resolution data, not necessarily a lack of spokes.

References

Calamida, A., Mack, J. Medina, J., Shahanan, C., Bajaj, V., Deustua S. (2021). WFC3 Instrument Science Report 2021-04: New time-dependent WFC3 UVIS inverse sensitivities (Baltimore: STScI) https://www.stsci.edu/files/live/sites/www/files/home/hst/instrumentation/wfc3/documentation/instrument-science-reports-isrs/_documents/2021/WFC3_ISR_2021-04.pdf

Callos, S., Hedman, M., Hamilton, D. (2022). A Comprehensive Survey of Spokes in Cassini Images of Saturn's B Ring. Division of Planetary Sciences 54th meeting, abstract 301.02

Colina, L., Bohlin, R.C., Castelli, F. (1996). The 0.12–2.5 microns absolute flux distribution of the Sun for comparison with solar analog stars. *Astronomical Journal* 112, 307–31

Collins, S.A., Cook II, A.F., Cuzzi, J.N., Danielsen, G.E., Hunt, G.E., Johnson, T.V., et al. (1980). First Voyager view of the rings of Saturn. *Nature* 288, 439-442

D'Aversa E., Bellucci, G., Nicholson, P.D., Hedman, M.M., Brown, R.H., Showalter, M.R., et al. (2010). The spectrum of a Saturn ring spoke from Cassini/VIMS. *Geophysical Research Letters* 37, L01203. doi:10.1029/2009GL041427.

Grun, E., Morfill, G.E., Terrile, R.J., Johnson, T.V., Schwehm, G. (1983) The evolution of spokes in Saturn's B ring. *Icarus* 54, 227-252. doi: 10.1016/0019-1035(83)90194-X.

Grun, E., Goertz, C.K., Morfill, G.E., Havnes, O. (1992). Statistics of Saturn's spokes. *Icarus* 99, 191-201. doi: 10.1016/0019-1035(92)90182-7.

Kurth, W.S., Averkamp, T.F., Gurnett, D.A., Groene, J.B., Lecacheux, A. (2008). An update to a Saturnian longitude system based on kilometric radio emissions. *J. Geophys. Res*. 113, A05222. doi:10.1029/2007JA012861

McGhee, C.A., French, R.G., Dones, L., Cuzzi, J.N., Salo, H.J., Danos, R. (2005). HST observations of the spokes in Saturn's B ring. *Icarus* 173, 508.

Mitchell, C.J., Horanyi, M., Havnes, O., Porco, C.C.. (2006). Saturn's Spokes: Lost and Found. *Science* 311, 1587-1589. doi: 10.1126/science.1123783

Mitchell, C.J., Porco, C.C. Dones, H.L., Spitale, J.N. (2013). The behavior of spokes in Saturn's B ring. *Icarus* 225, 446-474. doi: 10.1016/j.icarus.2013.02.011

Porco, C.C., & Danielson, G.E. (1982). The periodic variation of spokes in Saturn's rings. *Astronomical. J.* 87, 826-833

Sheehan, W. & O'Meara, S.J. (1993). Exotic worlds. *Sky & Telescope* 85, 20–24.

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

Smith, B.A., Soderblom, L., Beebe, R., Boyce, J., Briggs, G., Bunker, A., et al. (1981). Encounter with Saturn: Voyager 1 imaging science results. *Science* 212, 163-191

Smith, B.A., Soderblom, L., Batson, R., Bridges, P., Inge, J., Masursky, H., et al. (1982). A new look at the saturnian system: the Voyager 2 images. *Science* 215, 504-537

Wong, M. H. (2011). "Fringing in the WFC3/UVIS detector" in Proc. 2010 STScI Calibration Workshop, ed. S. Deustua & C. Oliveira (Baltimore, MD: STScI), 189-200.

Ye, S.-Y., Fischer, G., Kurth, W.S., Menietti, J.D., Gurnett, D.A. (2018). An SLS5 longitude system based on the rotational modulation of Saturn radio emissions. *Geophysical Research Letters* 45, 7297– 7305. Doi:10.1029/2018GL077976

Figure 1.

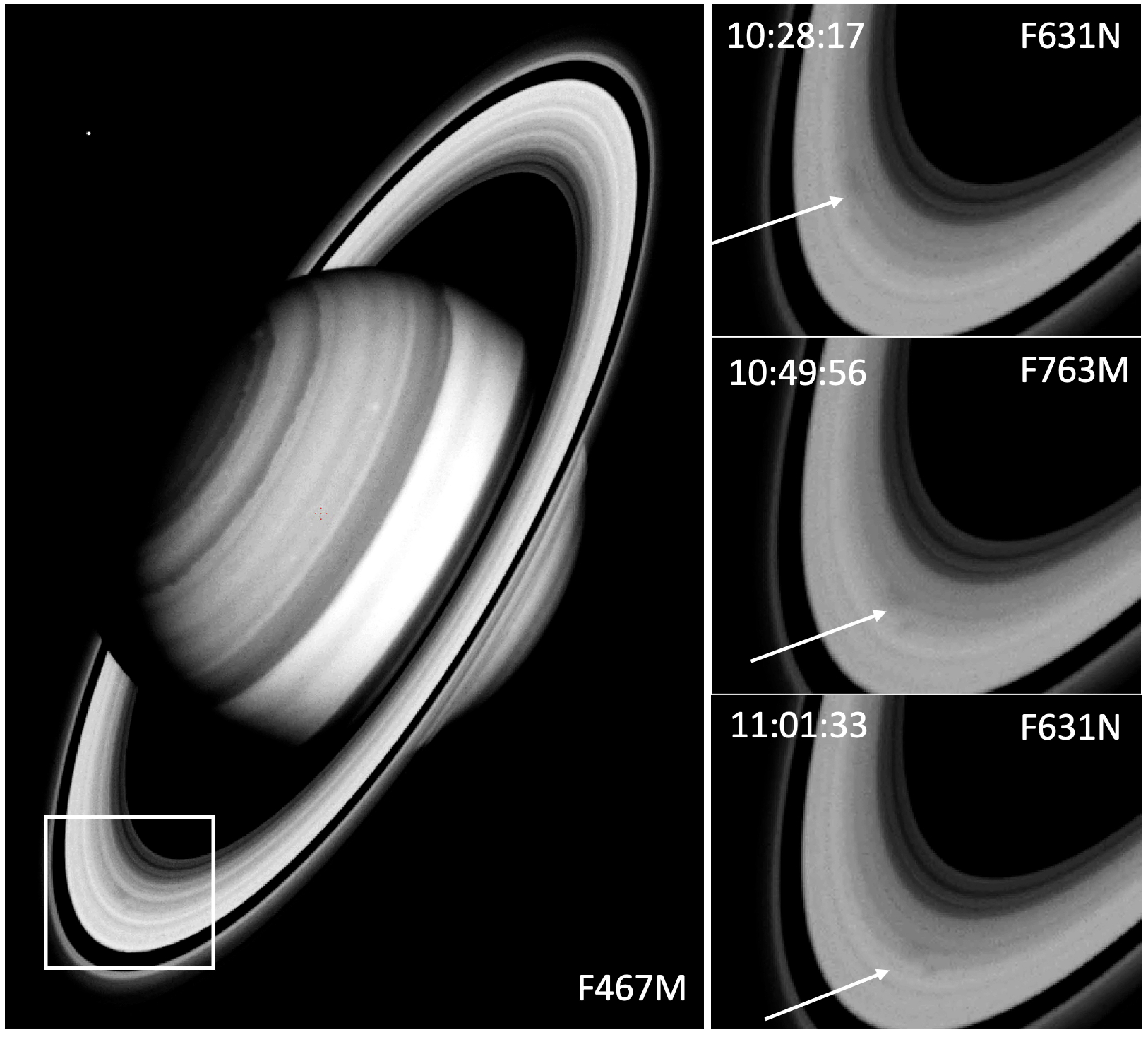
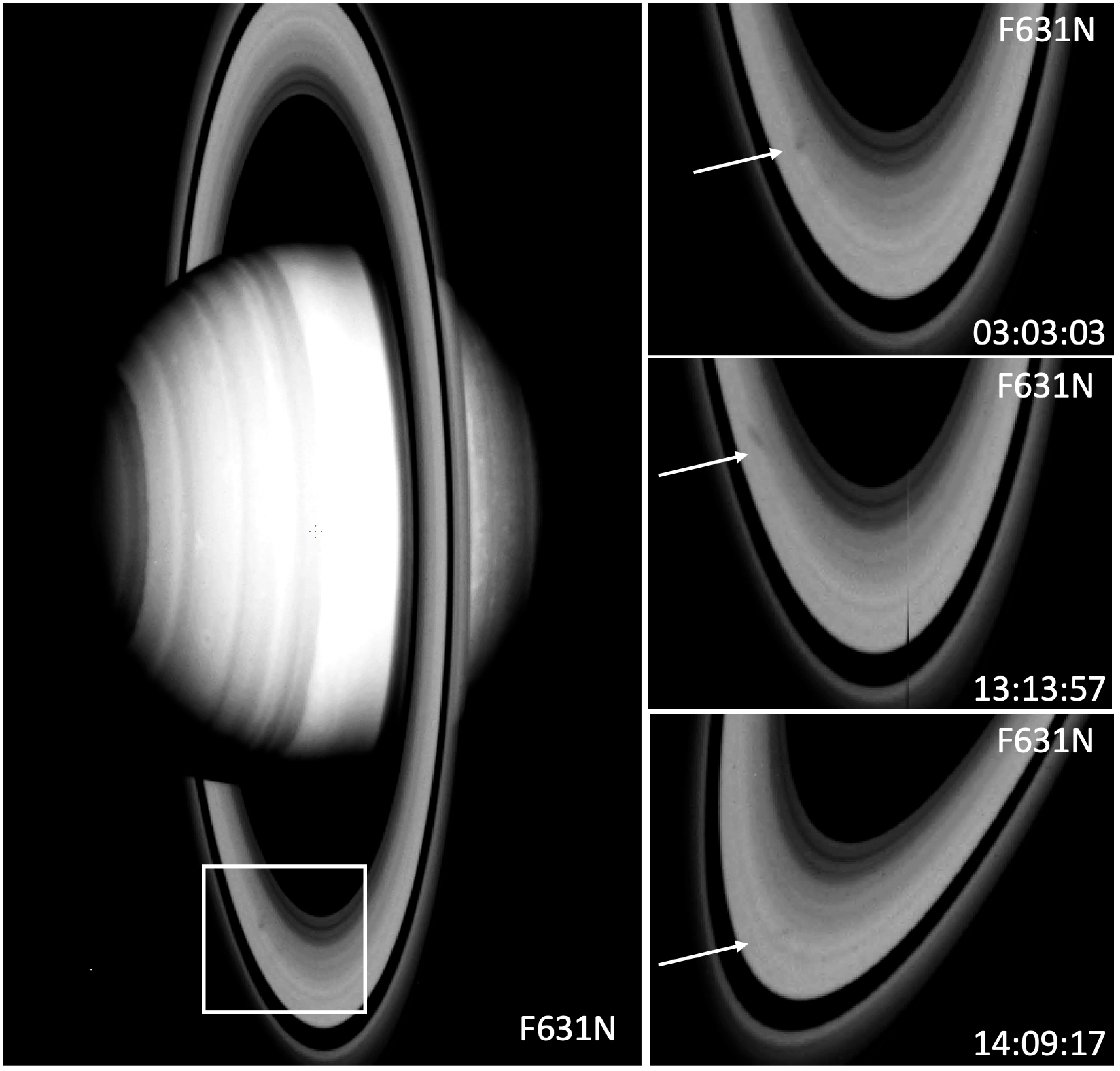

F467M
10:28:17
F631N
10:49:56
F763M
11:01:33
F631N

Figure 2.



F631N
F631N
03:03:03
F631N
13:13:57
F631N
14:09:17

Figure 3.

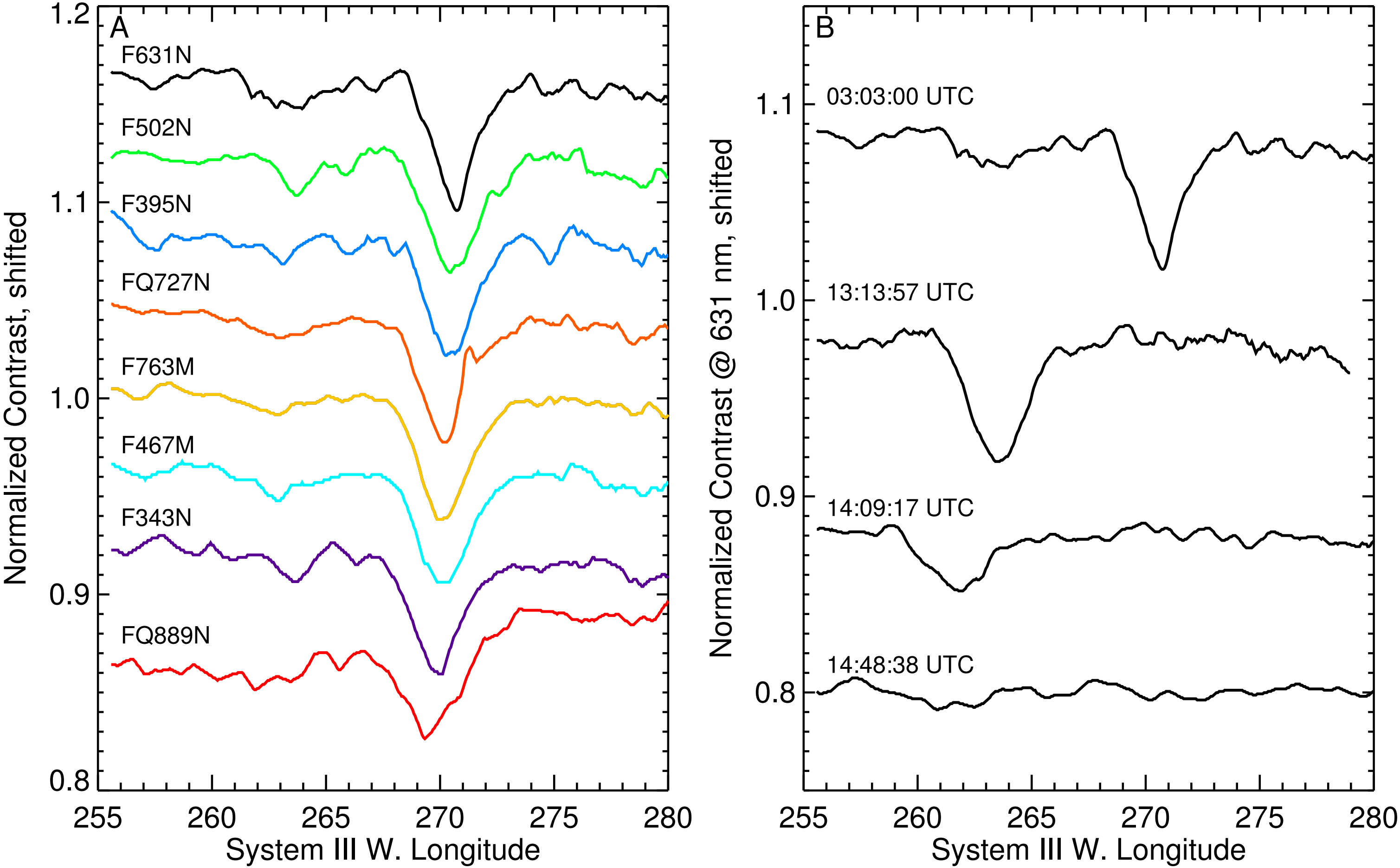
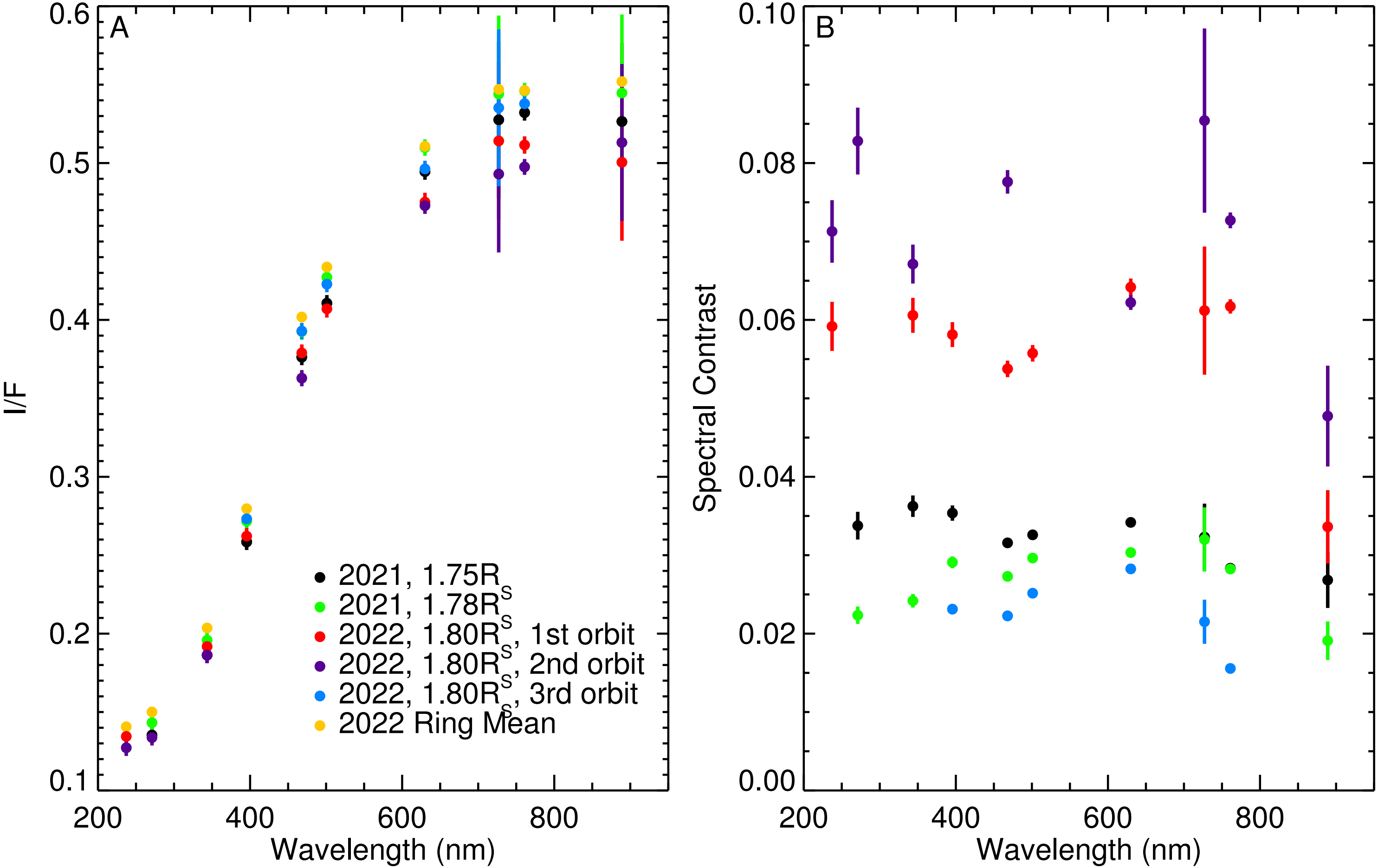

A
B
F631N
F502N
F395N
FQ727N
F763M
F467M
F343N
FQ889N
Normalized Contrast, shifted
1.2
1.1
1.0
0.9
0.8
255
260
265
270
275
280
System III W. Longitude
03:03:00 UTC
13:13:57 UTC
14:09:17 UTC
14:48:38 UTC
Normalized Contrast @ 631 nm, shifted

Figure 4.

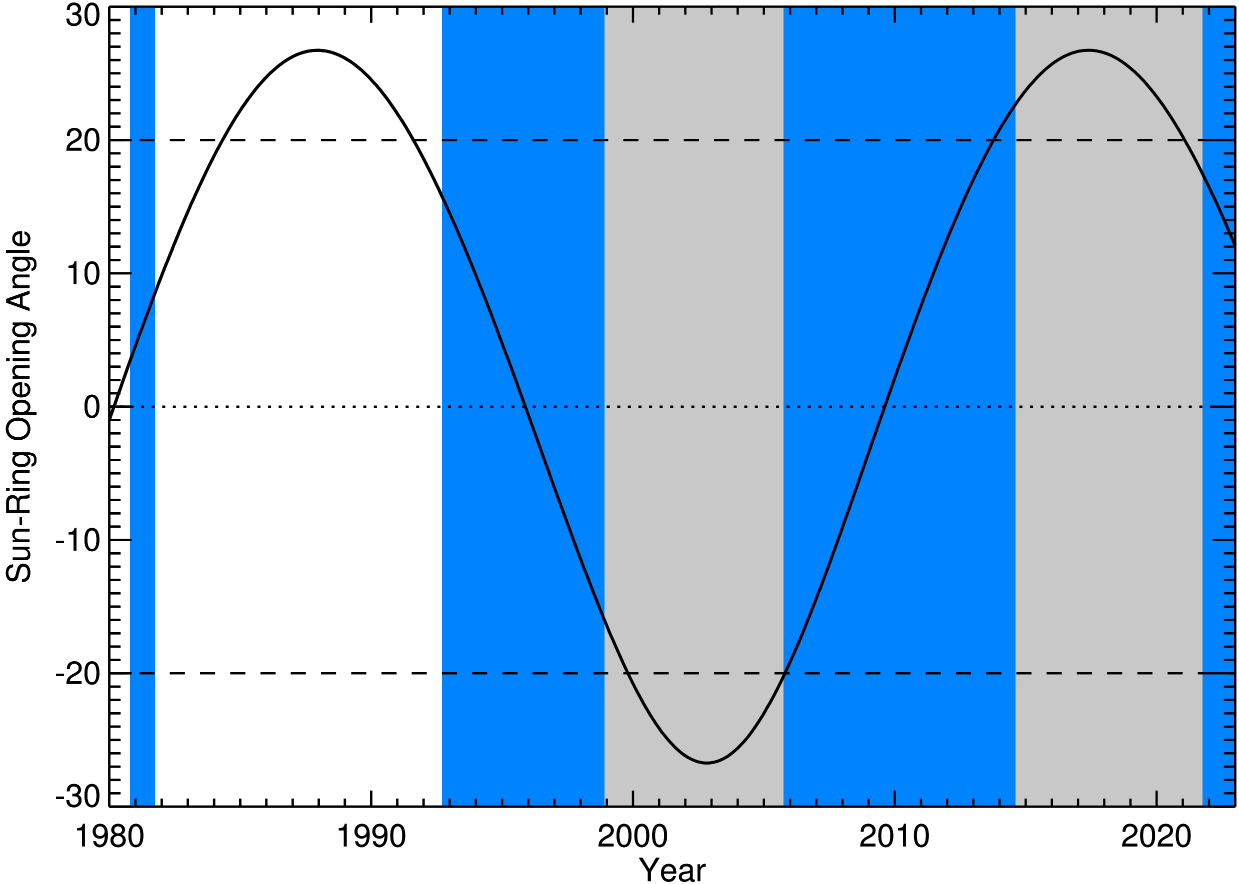


A
B
I/F
Spectral Contrast
Wavelength (nm)
Wavelength (nm)
2021, 1.75R_S
2021, 1.78R_S
2022, 1.80R_S, 1st orbit
2022, 1.80R_S, 2nd orbit
2022, 1.80R_S, 3rd orbit
2022 Ring Mean

Figure 5.


6 FEB 2014
17 JUL 2014

Figure 6.


30
20
10
0
-10
-20
-30
Sun-Ring Opening Angle
1980
1990
2000
2010
2020
Year