Time Domain Coronagraphy: Diagnosing the Stripping of AU Mic's Debris Disk

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ABSTRACT

Boccaletti et al. 2015 discovered substructures moving within the starlight-scattering AU Mic debris disk at super-Keplerian tangential velocities in spatially resolved imagery of the disk. To date, AU Mic possesses the only moving physical features seen in spatially resolved imagery of any debris disk. The surface brightness, number, morphology, and velocities of these moving features constrain their physical location and mass, and thus are critical quantities needed to elucidate the origin of this dynamical phenomenon. We are now following up our epoch 2010/2011 and 2017/2018 HST/STIS visible-light observations of the AU Mic disk (Schneider et al. 2014, Wisniewski et al. 2019; HST/GO programs 12228 and 15219, respectively), in three contiguous HST cycles just commenced by investigating feature temporal evolution with revisits to the system at six epochs over the next three years (initially HST/GO 15907 in cycle 27). With these new long-term observations we aim to determine: (a) What are the surface brightnesses of all features, and how do the surface brightness and morphology of features change over time? (b) What are the detailed vertical motions of the features? (c) Do the amplitudes of the motions depend on stellocentric distance? (d) What are the motions of newly discovered features on the NW-side of the disk? These data will then be used to test hypotheses that suggest such features may be caused by the stellar wind expelling grains originating from a parent body that orbits at 8 ± 2 au (Sezestre et al. 2017) or by interaction between the star's wind and repeated dust avalanche events (Chiang & Fung 2017). *Herein we summarize the program plan for the next three years and report on preliminary observational results from the first epoch of recently obtained GO 15907 observations.*

1 – Planned HST/GO 15907 "Long Term Program" Observations

- HST/STIS (broadband optical) coronagraphy in six observational epochs circa 2019 – 2022.
- Utilizing occulting WedgeA-(0.6 & 1.0) and BAR5 in sequentially alternating epochs.
- Reduction/post-processing plan inclusive of both 3-roll PSF Template Subtracted Coronagraphy (PSFTSC) and coronagraphic 3-Roll Differential Imaging (3RDI), for complementarity and robustness.

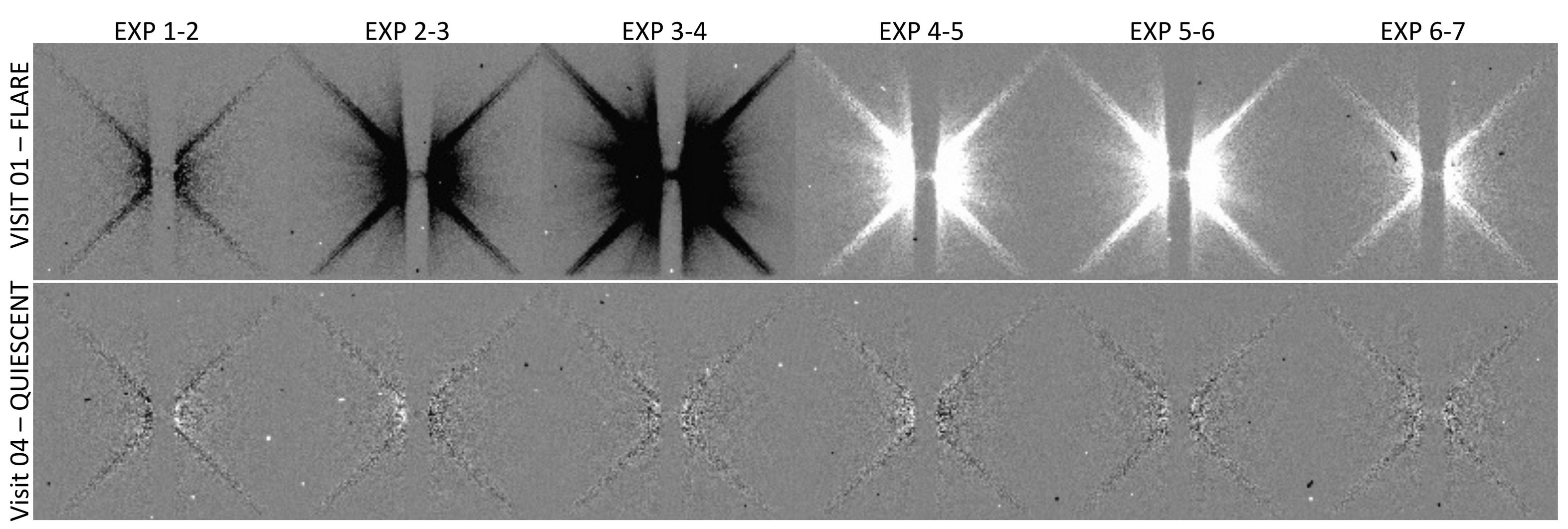
Imaging at each Wedge A epoch (recurring Visits 01 – 04; **1st executed 28 Oct 2019**), for high dynamic range imaging with sensitivity to dust-scattered starlight extending to r ≈ 120 au with:

- 4 sequential single-orbit visits including interleaved color-matched PSF star after AU Mic Visit 02, for A-0.6 & A-1.0 combined 3-roll PSFTSC.
- ±20° AU Mic differential rolls w.r.t. Visit 02 with disk major axis orthogonal to occulting wedge, for [recombined] 3RDI with the edge-on disk fully unobscured @ r ≳ 1.0".
- AU MIC visit exposures: 13 x 46s (68s cadence) with A-0.6, 3 x 531s (560s cadence).
- PSF star (HD 191849) Visit 03 similarly constructed for a single roll angle.

Imaging at each BAR5 epoch (recurring Visits 05 – 07; 1st scheduled ~ 07 Aug 2020), for highest image fidelity at smallest effective inner working angle via roll+dither pixel sub-sampling with:

- 3 sequential single-orbit visits with ±6.5° differential rolls w.r.t Visit 05 with disk major axis orthogonal to the long axis of BAR5.
- 51 x 16.7s (75% full-well at BAR5 edge) exposures segmented with:
- ± ¼ pixel 3-point cross-BAR5 dithers

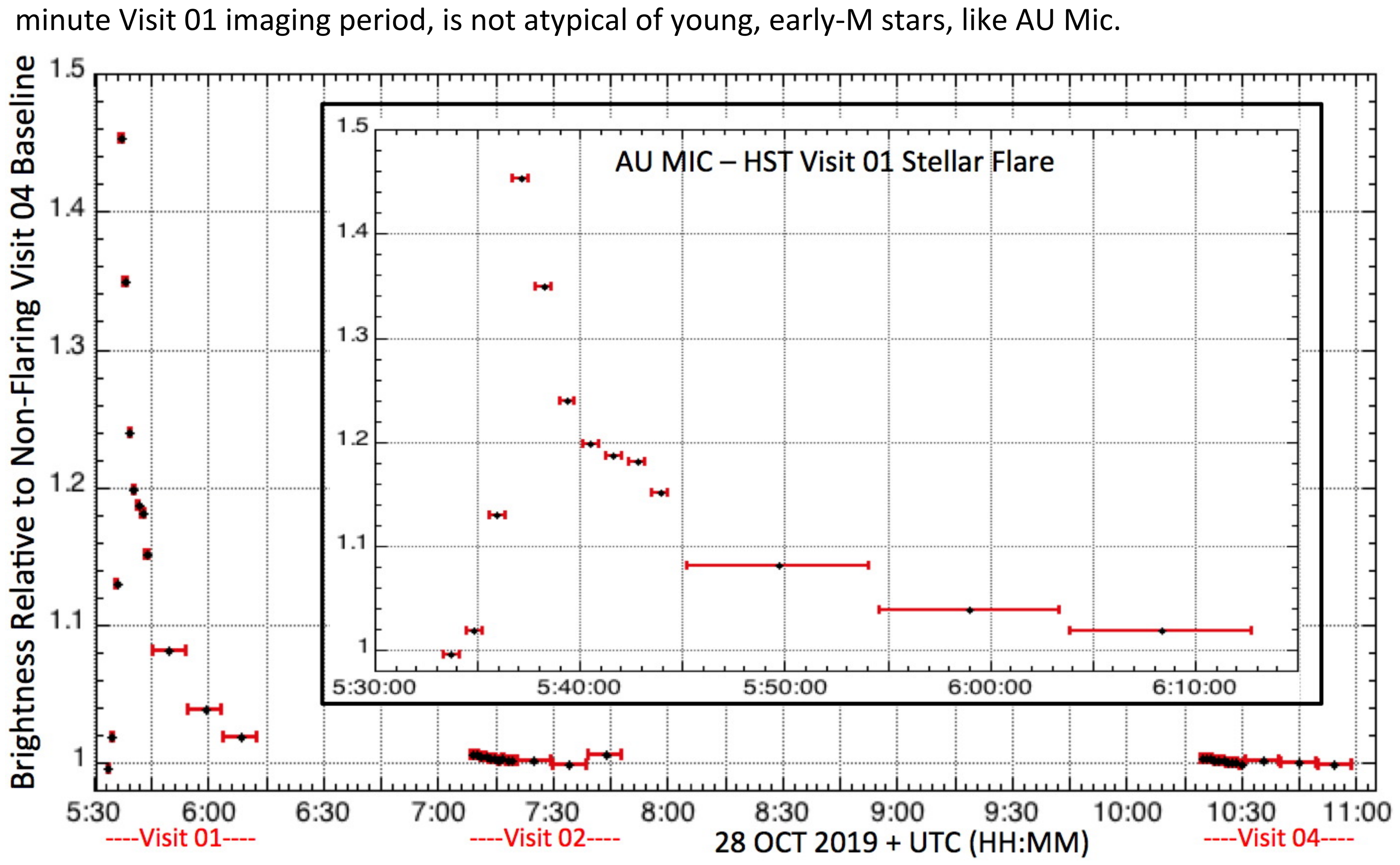
2 – *Digression*: THE 2019 "OCTOBER SURPRISE"– Caught In the Act



Intra-visit sequential first-differenced coronagraphic images are routinely checked to vet for anomalous pointing instabilities or drifts that are nominally null within the level of the photon noise. Such images from AU Mic Visit 01 (top row), with 68 s inter-exposure cadence, clearly betray ***the onset of a stellar flare event*** with sequentially increasing first-differenced over-subtractions through exposure 4 (at the peak of the flare) and then with diminishing under-subtractions during its subsequent decline. By the time of execution of identically-observed Visit 04 (bottom row, 3 hours later), AU Mic had returned to a fully quiescent state.

3 – The HST Visit 01 Stellar Flare Light Curve & Visit 02, 04 Return to Baseline

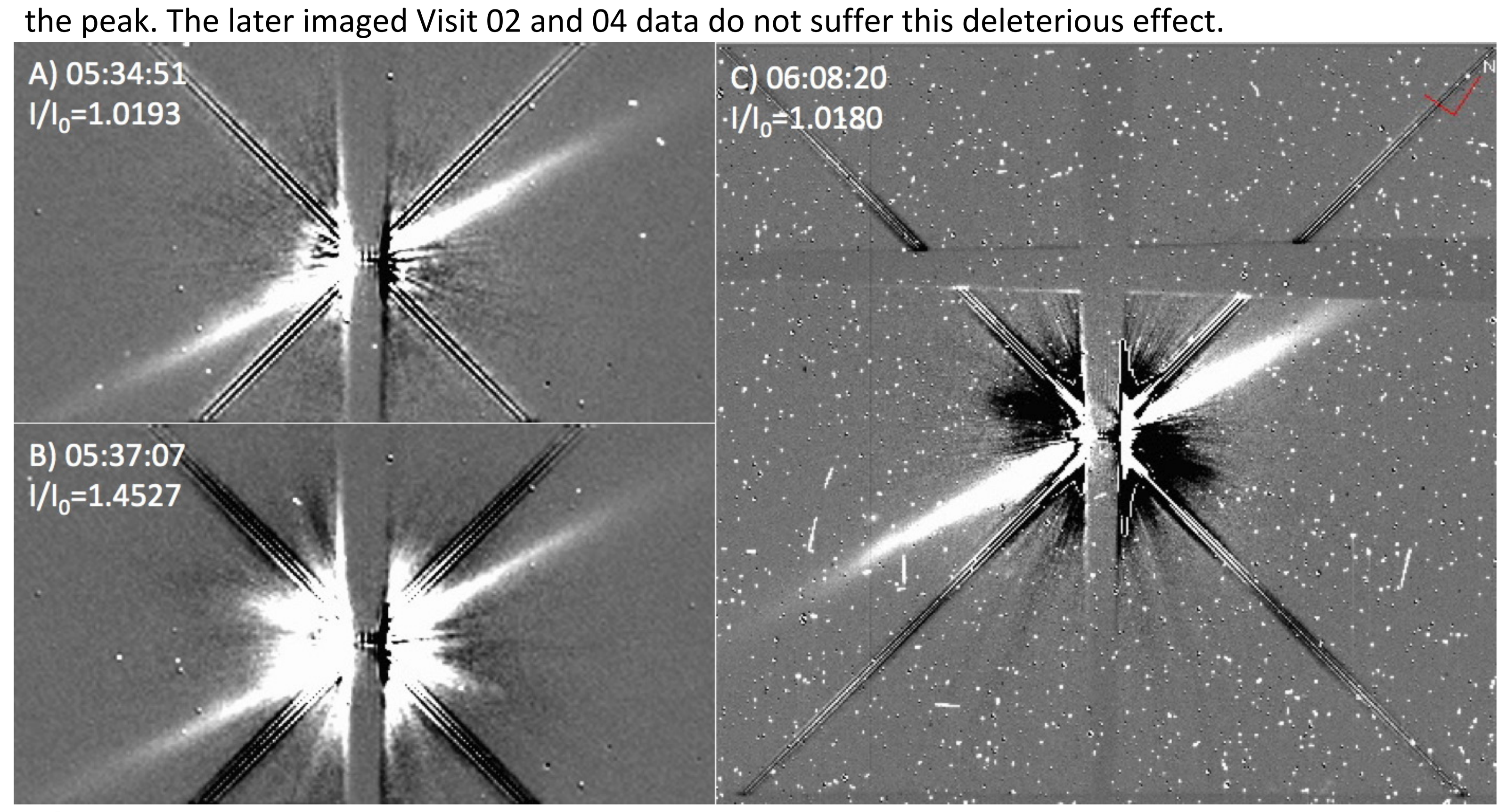
Quasiperiodic stellar flares from AU Mic, a young (24 ± 3 Myr) and chromospherically-active BY Dra type variable M1Ve star, are not unexpected, but the occurrence of one during our coronagraphic observations designed to image its debris disk was purely by happenstance and unpredicted. The 28 Oct 2019 AU Mic stellar flare light curve in the broad STIS 50CCD band (λ_c = 0.575 μm, FWHM = 0.433 μm) is shown below in comparison to its post-flare quiescent state (measured with large aperture photometry enclosing the coronagraphically unsuppressed stellar PSF halo). By pure coincidence, the flare event began immediately after our constant-cadence imaging commenced in Visit 01. The rapid rise-time over 3.4 minutes to a peak intensity +45.3% over its quiescent level (V=8.63), with then a shallow (and perhaps two-component) decay contiguously seen over the remainder of the 39.3 minute Visit 01 imaging period, is not atypical of young, early-M stars, like AU Mic.



Measurement uncertainties are comparable to or smaller than the size of the plot symbols used. Red bars indicate data collection (shutter open) intervals.

4 – Flare-Induced Intra-Visit 01 PSFTSC and RDI Chromatic Residual Evolution

To minimize or mitigate PSF-subtraction residuals of chromatic origin, we planned a robust two-stage approach. First, imposing a PSFTSC constraint on PSF star selection with |Δ[B-V]| and |Δ[V-R]| < +0.04 w.r.t. AU Mic's optical color indices. Second, using 3RDI with AU Mic as its own self-referential stellar PSF at roll angles where the disk is not self-obscured. Both, however, assumed temporal stability in the target/template PSF spectral energy distributions, which is not the case during a flare event, ***rendering PSF-subtracted coronagraphic data from Visit 01 polluted with chromatic residuals unsuitable for high-fidelity disk-image recovery***. Below, by example: (A) near-nominal PSFTSC at the start of the flare event, (B) unsuitable PSFTSC at the peak of the flare and, (C) still so 31 minutes after the peak. The later imaged Visit 02 and 04 data do not suffer this deleterious effect.



→ Thus the Visit 01 data, for high-fidelity disk-image recovery, acquired during the flare event were excluded at this early juncture from subsequent reduction and analysis.

5 – Turning Visit 01 Lemons (Polluting Flare) into Lemonade (Debris Disk Reverberation)?

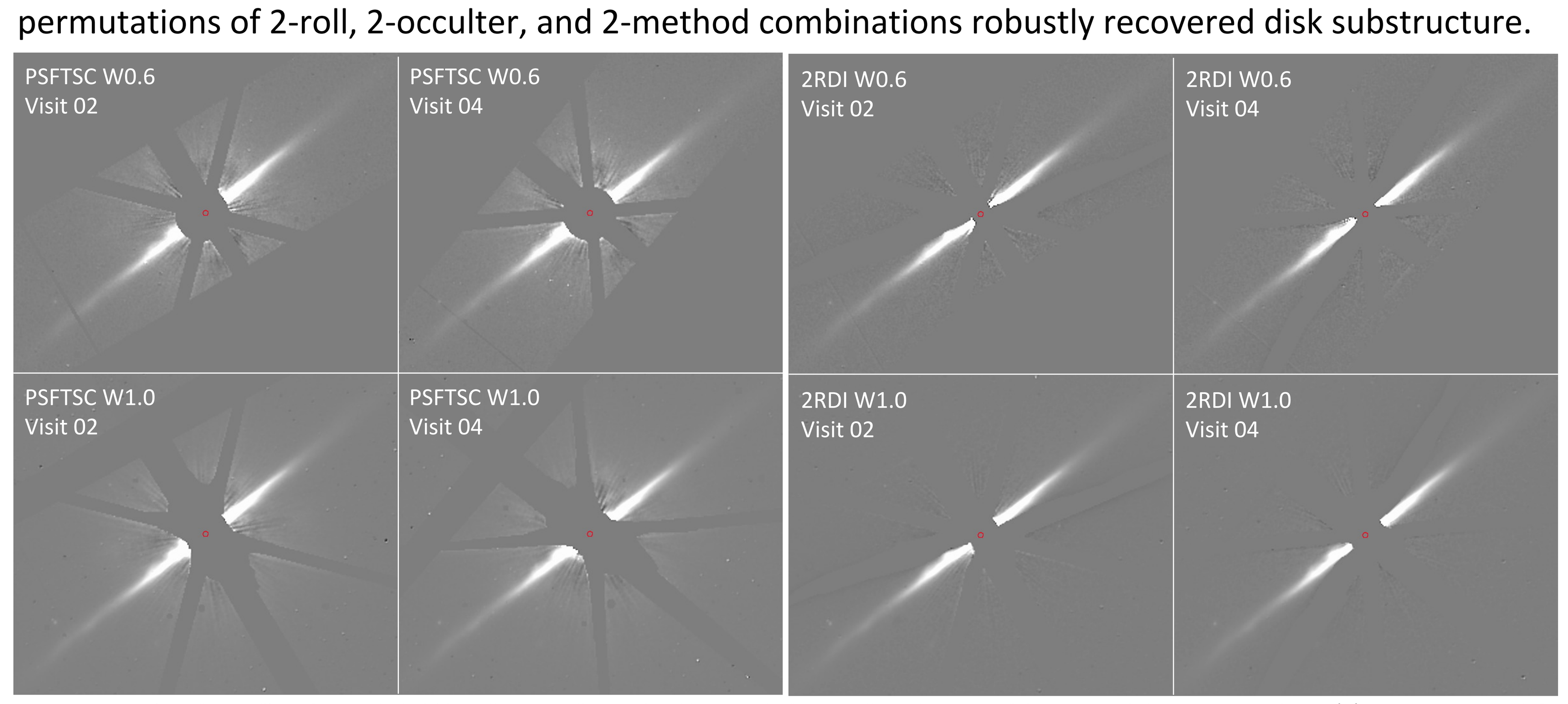
Substructures in our 1st epoch GO 15907 AU Mic disk images are well recovered and resolved at stellocentric distances ≳ 8 AU (≳ 0.8"; see § 8 image panels). In this spatial regime, ***it may be possible to tomographically recover the flare signal propagating outward through the disk***. Individual time-resolved disk images correspond to stellocentric light-travel distances of ~ 11 – 16 au and 34 – 39 au (~ 1.1" – 1.6", and ~ 3.4" – 3.9") in Visits 02 and 04, respectively. These are spatial regimes for which high-fidelity imaging is achieved with multi-image/two-roll combination. "Reverberation mapping" of the flare signal in the disk may help to disambiguate the locations of the moving substructures within the disk which are seen only in edge-on projection. This is (unexpected!) work to be pursued ***– stay tuned!***

6 – Image Validation with 2-Roll Only PSFTSC and RDI

The identification and verification of disk-image substructures of astronomical origin (disambiguated from image artifacts and PSF-subtraction residuals) in PSF-subtracted images usually are enabled by correlation in multi-roll (with #-rolls > 2) observations. To establish the fidelity of independently reduced and post-processed images with only two rolls (due to the loss of suitable data from Visit 01 to the flare event) we intercompare independent results in commonly sampled regions from both occulters used and in Visits 2 and 4 separately reduced (as illustrated in the figure below), before applying 2-roll combination techniques (see § 7 image panels), specifically with:

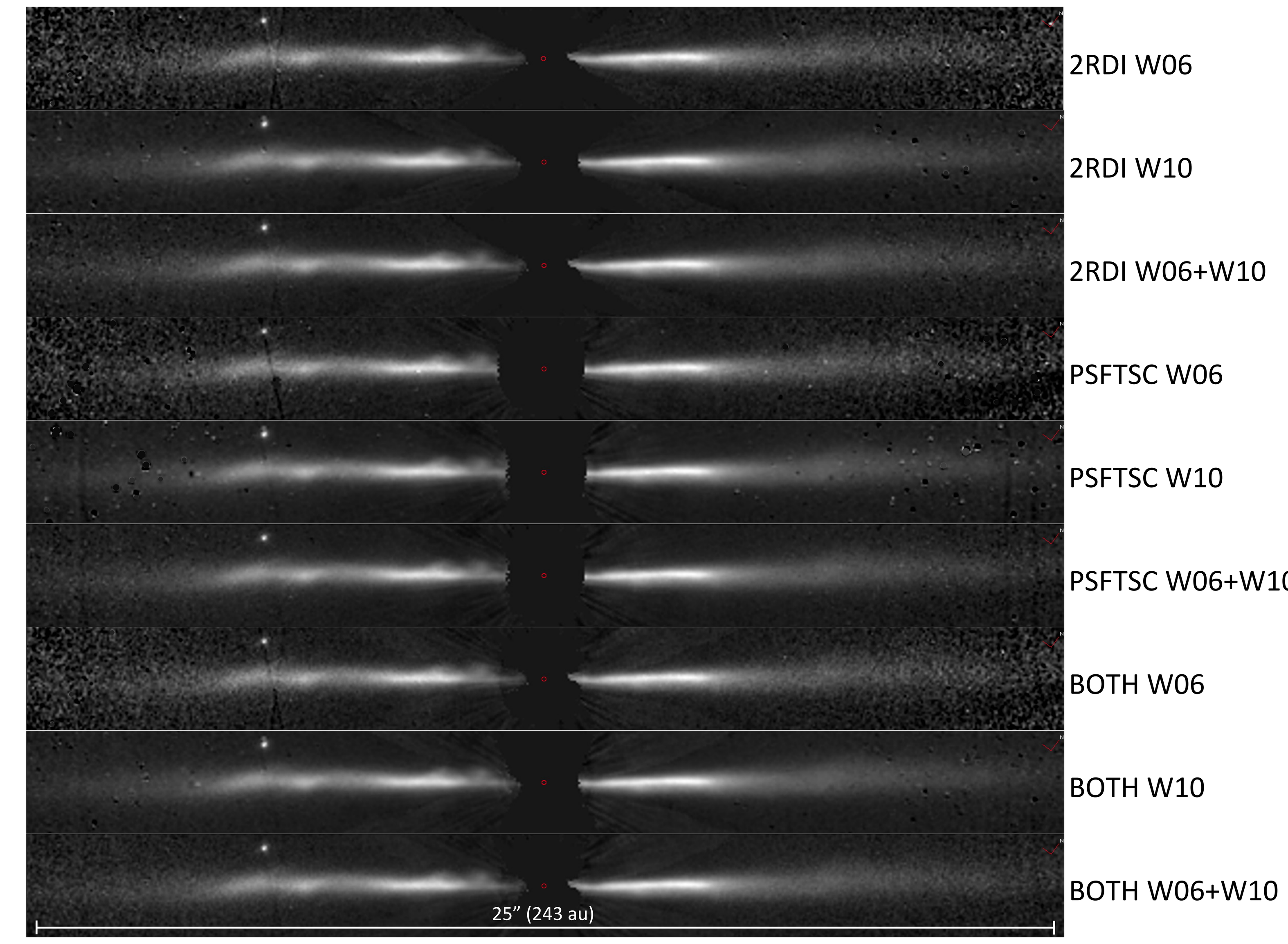
(1) PSFTSC with WedgeA-0.6
(2) PSFTSC with WedgeA-1.0
(3) RDI with WedgeA-0.6
(4) RDI with WedgeA-1.0

Independent "visit level" results, digitally masking artifacts of non-astronomical origin including imprints of occulters, diffraction spikes, residual chromatic artifacts, saturated and bad/anomolous pixels, and (for RDI only) negative disk imprints, are shown below. With such masking, all permutations of 2-roll, 2-occulter, and 2-method combinations robustly recovered disk substructure.



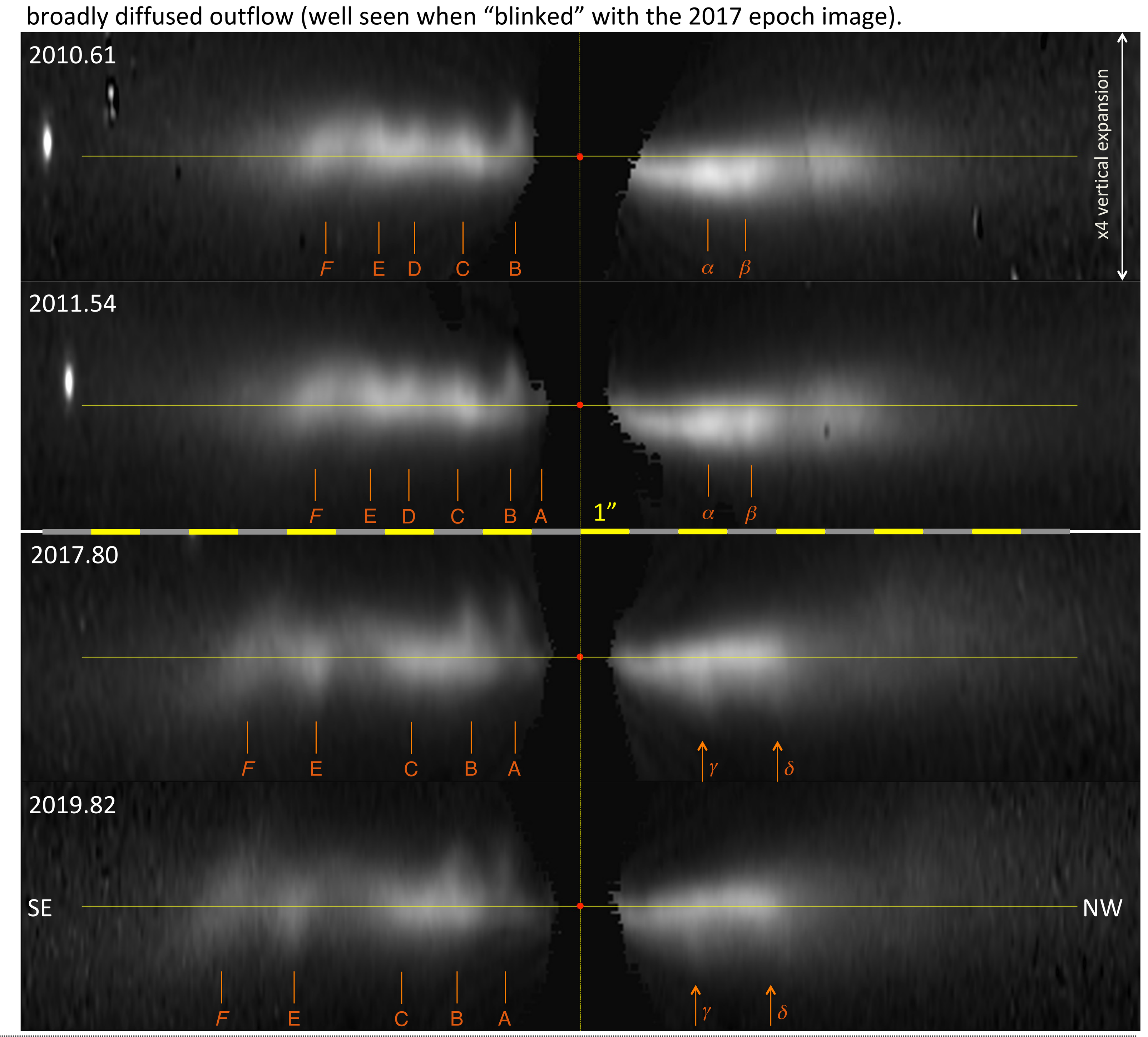
300x250 pixel (15.2"x 12.7") artifact-excluded (digitally masked) "visit-level" images before 2-roll combination of the AU Mic disk. Linear stretch ±2 c/s/pix, north up, east left.

7 – Robustness in 2-Roll Substructure Recovery with Multiple Complementary Observational, Imaging, and Post-Processing Methods



8 – Temporal Evolution of the "Fast Moving" Substructures in the AU Mic Disk

To study the evolving morphology and measure the motions of the AU Mic disk fast-moving features on equal footing over, now, multiple epochs in visible light, we re-processed prior HST GO 12228 and 15219 data in a manner as closely as possible to our recently acquired 2019 epoch data from GO 15907. In the four-panel figure below we present analysis quality images for interpretation that are: (a) scaled stellocentrically in brightness as r^2 to compensate for the radial diminution of illuminating starlight and (b) expanded in vertical spatial scale by a factor of 4 for easy visual recognition and perception of the complex features along and flanking the disk mid-plane. In the 2019 epoch image: (1) Features on the SE side of the disk (labeled A-E from prior identification with SPHERE by Boccaletti et al. 2015), ***continue their apparently radially expansive projected motions, some in excess of Keplerian escape velocity***. (2) Feature D seems to have dissipated or diffused since seen prior with STIS and more recently with SPHERE. (3) Additional features are seen on the NW side of the disk that itself now appears less downwardly "bowed" interior to r ≲ 5" than in the early epoch STIS images. (4) Fainter material in the outer (~ 6" – 10") part of the NW side of the disk seems to be undergoing a broadly diffused outflow (well seen when "blinked" with the 2017 epoch image).



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