



A Python Package for Analyzing Cosmic Rays in HST Calibration Data

Nathan Miles¹, Susana Deustua¹, Gonzalo Tancredi² | 1. Space Telescope Science Institute, Baltimore MD
2. Universidad de la República, Uruguay

Motivation

- **Goal:** Study changes in Earth's external magnetic field at an altitude of ~540 km
- Fluctuations in solar activity throughout the 11-year Solar Cycle drive changes in:
 - the size and shape of Earth's magnetosphere
 - the density of the solar wind throughout the solar system
 - the rate of coronal mass ejections (CMEs)
- 30 years of The Hubble Space Telescope (HST) operation
 - Complete coverage of Solar Cycle 23 and 24
- **How?** Use HST as a particle detector!
 - HST instruments detect cosmic rays (CR)
 - Cosmic rays are affected by the magnetic field
 - Analyze CR rates in HST dark frames over time

Dataset

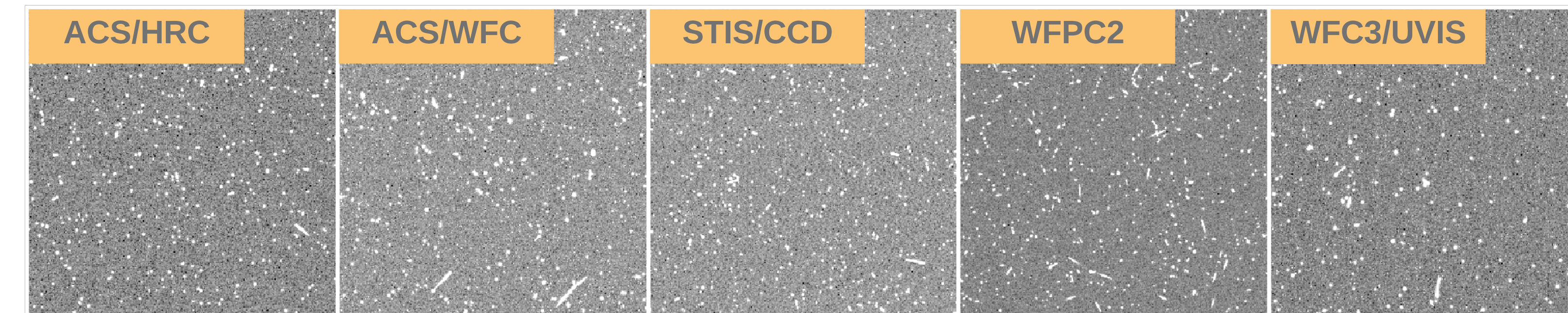


Figure 1: 300x300 pixel cutouts from individual dark frames for each of the 5 CCD imagers analyzed.

- Dark frames are exposures taken with closed shutter to measure the dark current due to thermally generated electrons.
- Every instrument regularly takes darks as part of routine calibration programs
 - Large, uniform dataset over HST's lifetime
 - Sampled at an almost daily cadence!
 - Only external sources are cosmic rays!
- To date we have analyzed CRs from 5 charge-coupled devices (CCDs) between 1994 to the present (Table 1).

Table 1: Dataset and detector properties for the 5 CCD imagers.

Instrument	Images (count)	Data Volume (TB)	Det. Area (cm ²)	Det. Thickness (μm)
ACS/HRC	5,477	0.055	4.624	12.49 - 16.03
ACS/WFC	13,311	2.130	37.748	12.60 - 17.10
STIS/CCD	31,430	0.311	4.624	13.24 - 14.83
WFPC2	13,317	0.131	5.76	~ 10
WFC3/UVIS	12,373	1.980	37.804	13.50 - 18.00
Total	75,908	4.61		

HSTCosmicrays Design

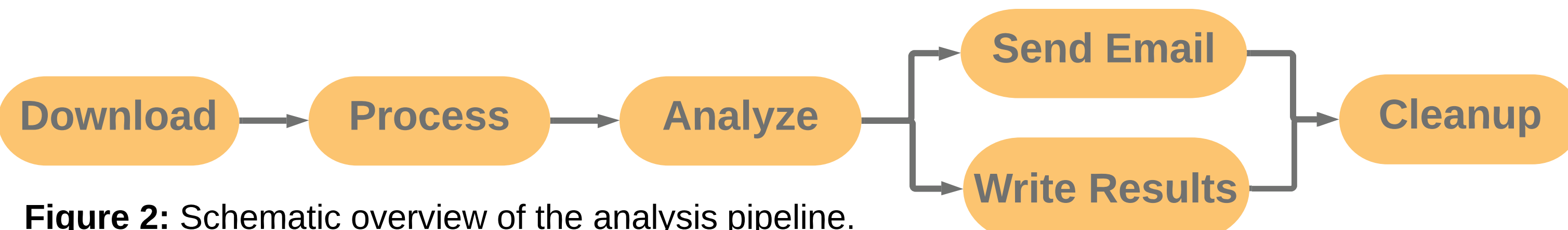


Figure 2: Schematic overview of the analysis pipeline.

- Python 3.5 or higher!
- All instrument characteristics and control structures stored in YAML config file
- Adopted modular approach to improve readability and facilitate debugging
- Lightweight with respect to storage requirements
 - Only analyze darks taken within a one month interval (at most 14 GB)
 - Results stored in HDF5 (177.13 GB)
- Run locally or AWS EC2 using the HST Public Dataset
 - c4.8xlarge (36 cores, 60 GB RAM, 100 GB EBS) processed all ACS/WFC in under 14 hours for ~\$21.00.
 - Download time per month : ~2 minutes AWS vs ~25 minutes locally
- Completely parallelized using dask
- Email notification with summary statistics after analyzing one month interval
- Fully documented with ReadTheDocs

Data Download

- Use `astroquery` to programmatically query and download all darks and their corresponding telemetry files from the Mikulski Archive for Space Telescopes (MAST)


```
>>>from astroquery.mast import Observations
```
- Easily enable cloud functionality when on running on AWS EC2


```
>>>Observations.enable_cloud_dataset()
```
- Download time for one month of darks
 - ~2 minutes AWS vs ~25 minutes locally

Processing and Analyzing

1a) Use active instruments' (ACS, STIS, and WFC3) python packages to access their CR rejection routines which use a noise-based model to identify pixels deviating from their baseline behavior and mark them in the data quality (DQ) array.

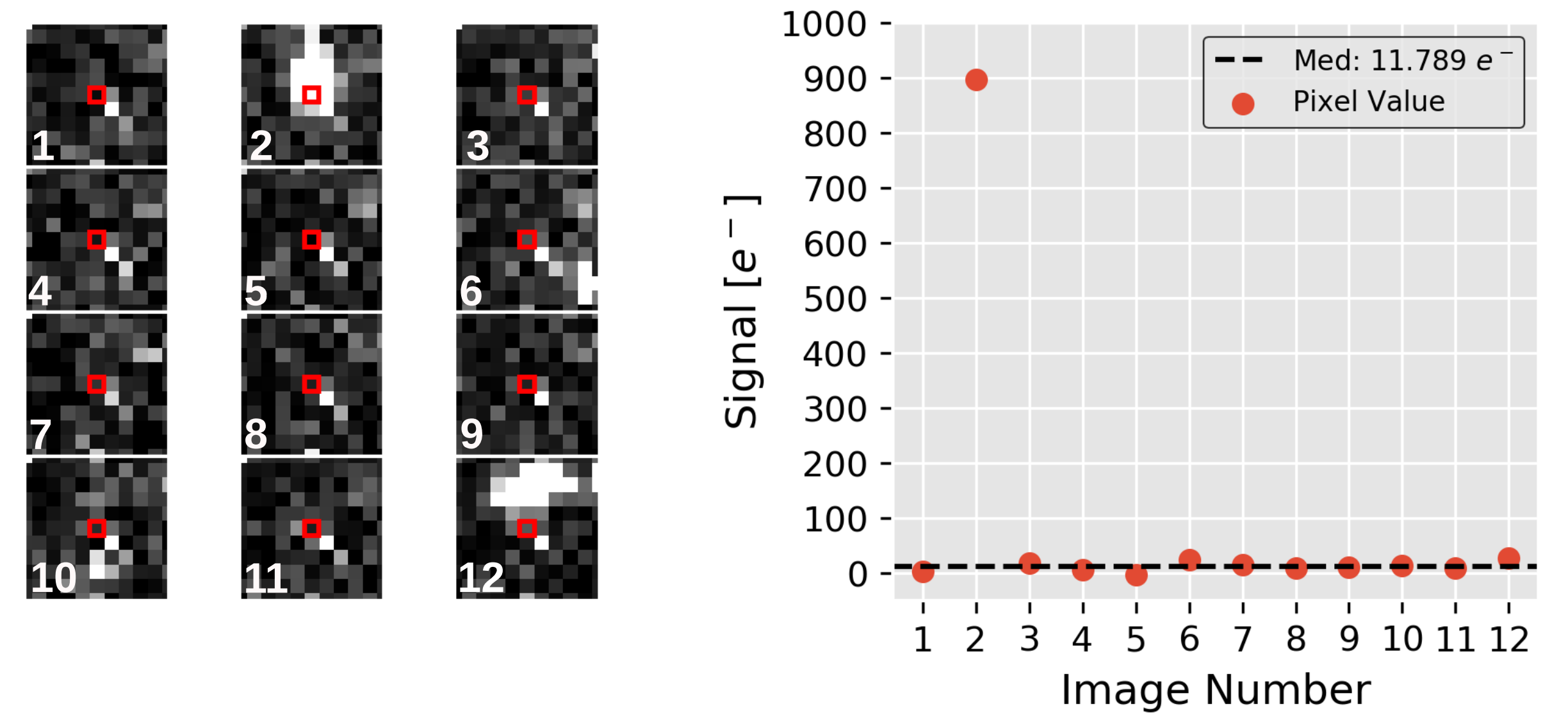


Figure 3: A visual representation of the cosmic ray rejection algorithm. On the left, we show cutouts of the same region from 12 different darks. On the right, we show the value of the pixel marked by the red square in each cutout.

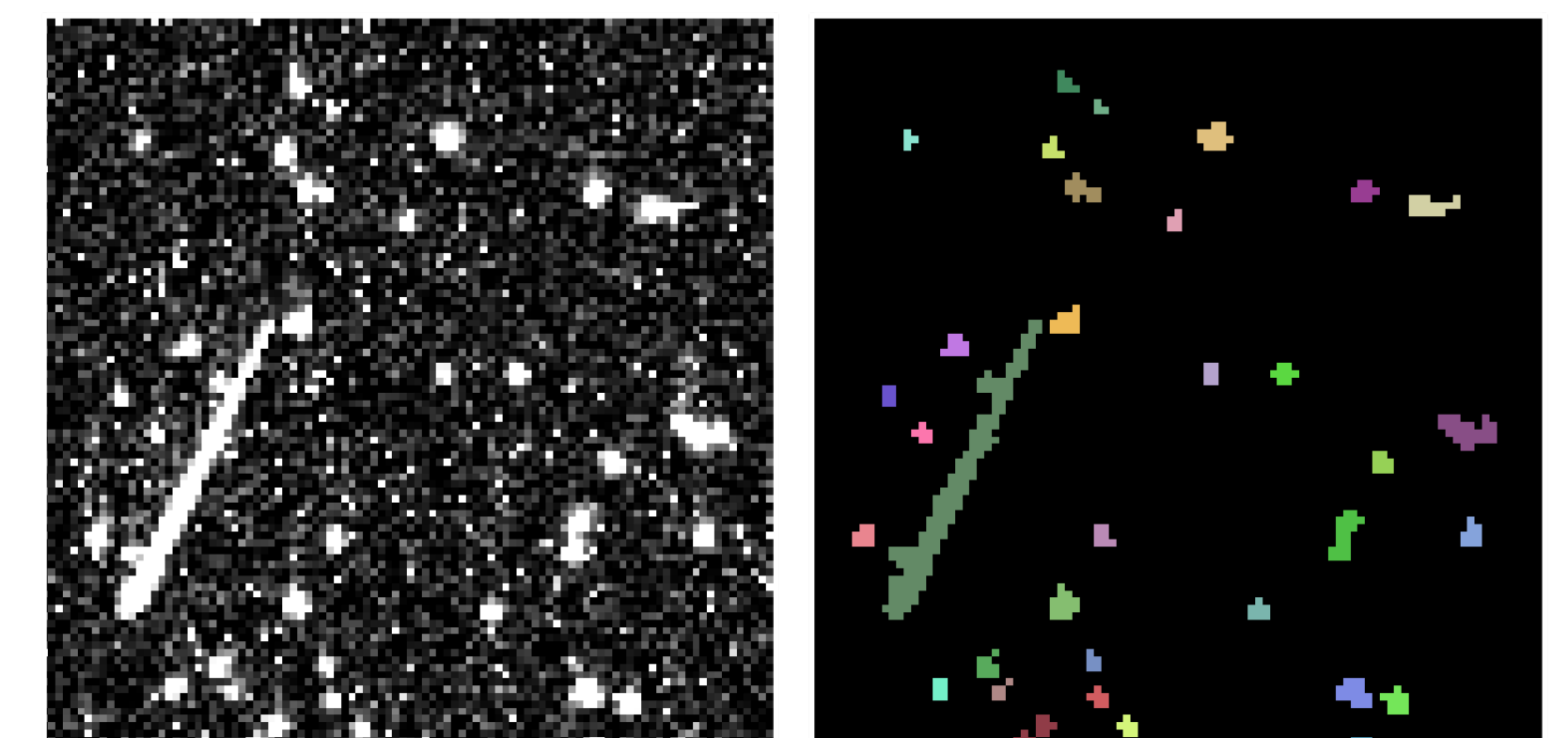
1b) For the legacy instruments (WFPC2), we compute sigma-clipped statistics for the image, then generate a binary image by performing a pixel-wise comparison to the sigma-clipped median:

$$p(x, y) - med > 5\sigma \begin{cases} 1 & \text{if True} \\ 0 & \text{otherwise} \end{cases}$$

2) Create segmentation map of CRs by performing connected-component labeling analysis on the DQ array or binary image.

- Reject objects affecting 2 or fewer pixels (hot pixels).
- Use the segmentation map to extract properties of each cosmic rays

Figure 4: On the left, we show the science extension of an ACS/WFC dark. On the right, we show the corresponding CR segmentation map.



Extracted Image Metadata

- Altitude/Latitude/Longitude
- Observation date
- Start/end of exposure
- Total integration time
- WCS info

Extracted Cosmic Ray Data

- Total energy deposited [e⁻]
- Pixel coordinates of each cosmic ray
- Cosmic ray size and shape in pixels
- Cosmic ray rate [CR/s/cm²]
- Moments of energy distribution

Results

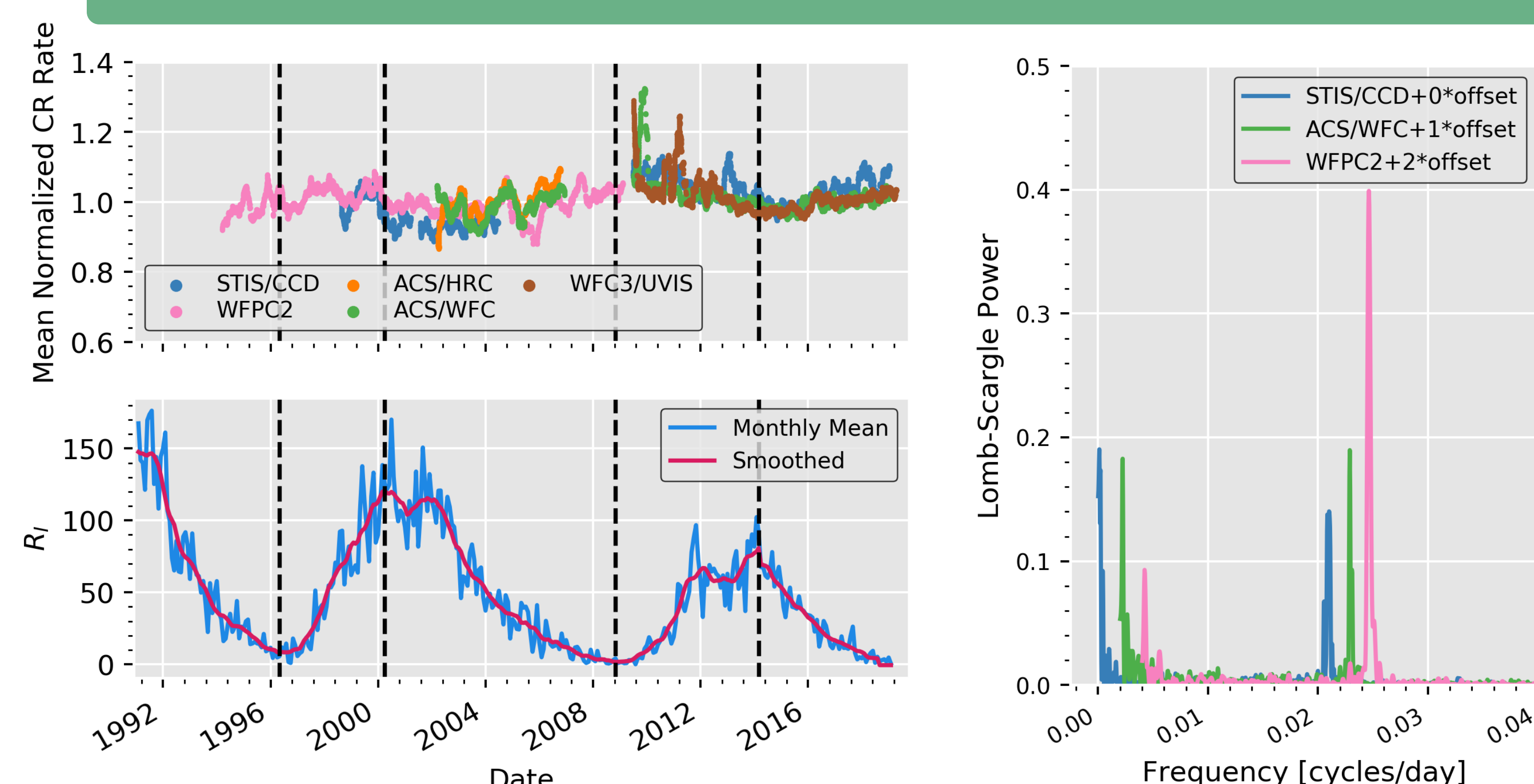
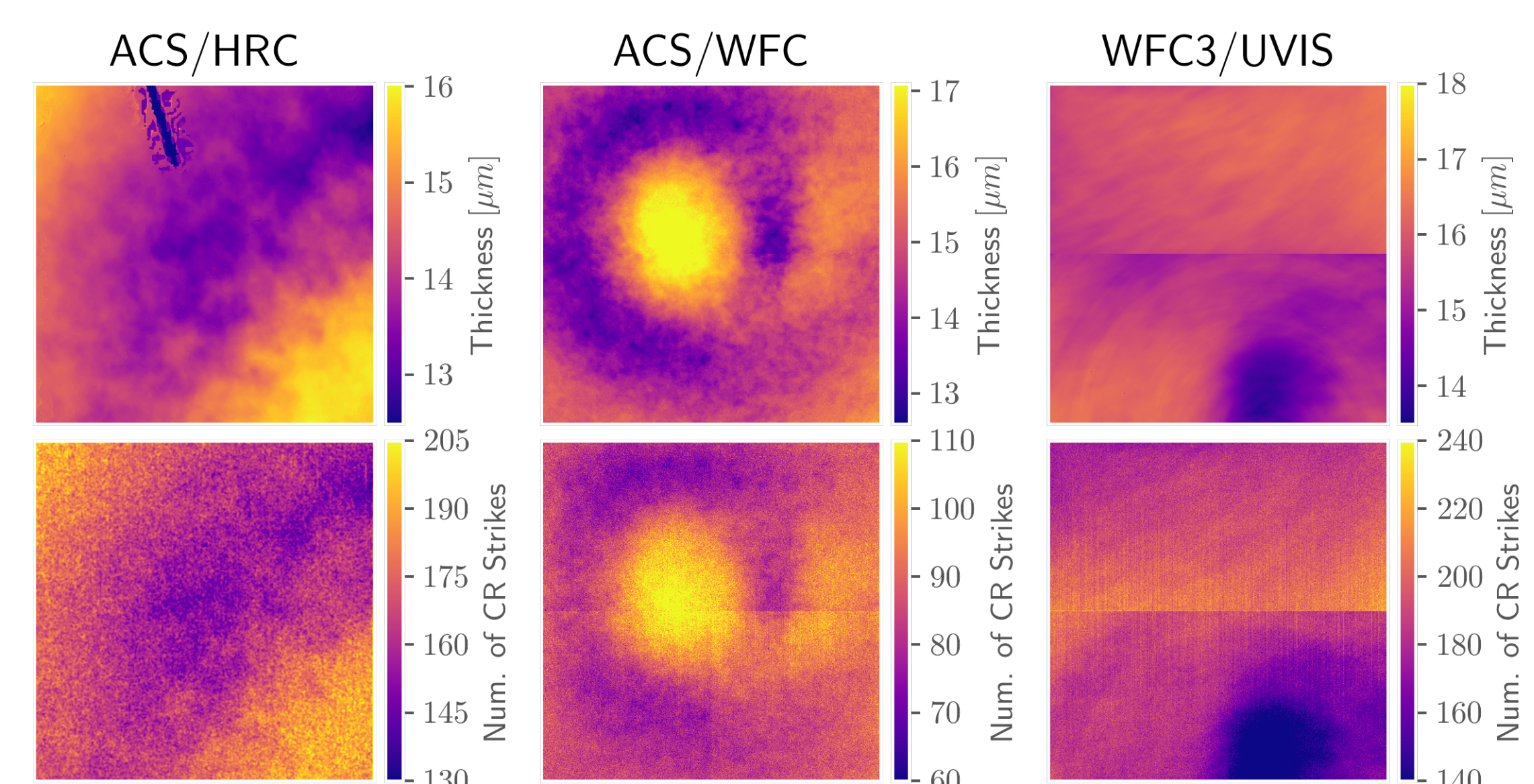


Figure 5: **Upper Left:** Mean normalized cosmic ray rates vs time. **Lower Left:** Solar cycles since 1990. **Right:** Periodogram of CR rate vs time where the peaks have been offset for clarity. The low frequency peaks correspond to 11 year (ACS, WFPC2) or 22 year (STIS) periods, demonstrating the CR modulation by solar activity. The high frequency peaks correspond to 47.5 day; the cause is being investigated.

Figure 6: Comparison of detector thickness maps and cosmic ray incidence heat maps. As expected, the rate of cosmic ray impacts for a given pixel is proportional to its thickness.



References and Acknowledgements