RE-EXAMINING HINODE/XRT'S TE AND EM ANALYSIS : IMPROVED CORRECTIONS OF STRAY LIGHT AND CONTAMINATION ON FILTERS

Aki Takeda (Montana State University, Bozeman MT, USA)

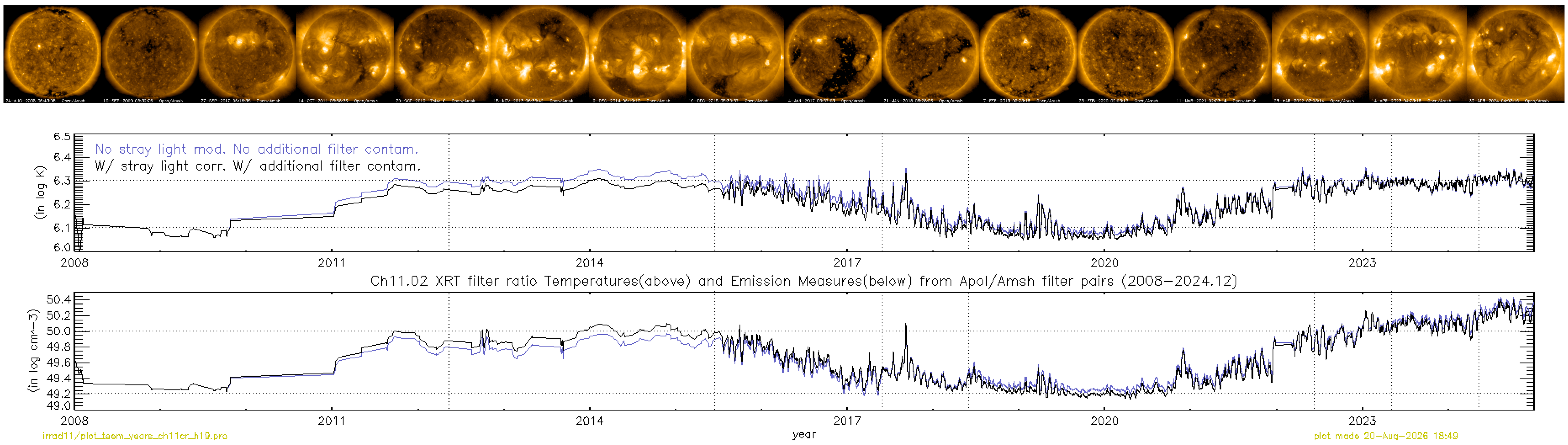

Fig. 1: Top: XRT full-Sun images (with Al-mesh) sampled over a solar cycle. Middle and Bottom plots: XRT full-Sun averated Temperature and Emission Measure obtained with the Al-poly/Al-mesh filter ratio. The Al-poly/Al-mesh filter pairs are sparse before mid-2015, because the synoptic full-Sun observation before then was performed with the Ti-poly filter instead of Al-poly.

Summary

The X-ray telescope onboard the Hinode satellite (Hinode/XRT) is a grazing incidence telescope staying in orbit since September 2006. The XRT equips 9 broad-band X-ray analysis filters, which enable us to perform temperature(Te) and emission measure(EM) analysis through the filter-ratio method assuming the isothermal plasma along the line of sight. The filter-ratio Te and EM calculated from the full-Sun integrated signals are used to synthesize the isothermal coronal spectrum to calculate the energy emitted in a specified wavelength range in the physical unit of W/m^2, i.e., X-ray irradiance. The solar X-ray irradiance obtained for nearly 2 solar activity cycles as well as a series of full-Sun images used to derive it constitute a valuable infrastructure for the the solar research community.

Through nearly 20 years of operation in space, however, XRT instruments have been suffering deterioration, which should be properly corrected for long-term quantitative data products: the visible light contamination from ruptures of pre-filter and the accretive contaminant layers on CCD and X-ray filters have been empirically corrected. Although this way of correction provides reasonable curve of solar irradiance, the determination of contaminant layer thickness was just arbitrary. We recently revised the method to make the correction more accountable: The effect of pre-filter ruptures was reexamined and the contaminant layer thickness on X-ray filters was introduced on the basis of frequency of filter use.

1. Hinode/XRT and the SCIA

- XRT is a grazing incidence telescope on-board the Hinode satellite to form X-ray images in the 6 – 200Å range on a 2048x2048 CCD. The field of view is 2040x2040 arcsec.
- Full-Sun observations by XRT are mainly through the synoptic program that typically runs twice daily, using short/medium/long exposure times, which are later processed into a single composite image to increase the intensity dynamic range. These products are accessible from XRT Synoptic Composite Image Archive (SCIA) located at Montana State University.
http://solar.physics.montana.edu/HINODE/XRT/SCIA

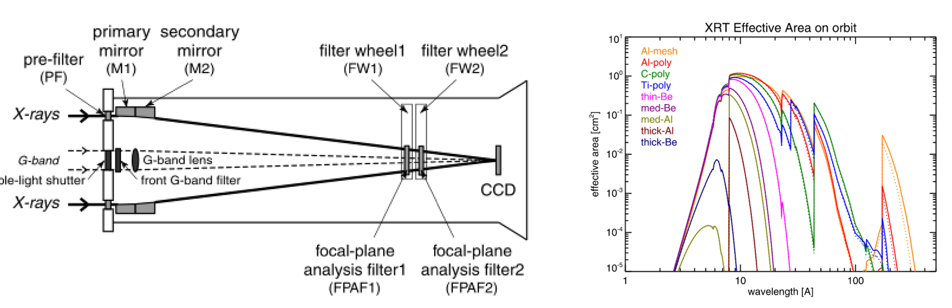

Fig. 2: Hinode/XRT assembly and spectral response of X-ray analysis filters (from Narukage et al., 2011).

2. Derivation of Te and EM

Temperatures(Te) and Emission Measures(EM) of the observed corona are derived using the Filter Ratio Method: The temperature response function of each XRT filters is calculated from XRT's effective area and isothermal coronal spectra. Te of the observed corona is derived from the ratio of the 2 filters, as it is the monotonic function of the temperature. The corresponding EM is calculated as the expected volume of the plasma that explains the observed signals through each XRT filter (details are described in Narukage et al. 2011).

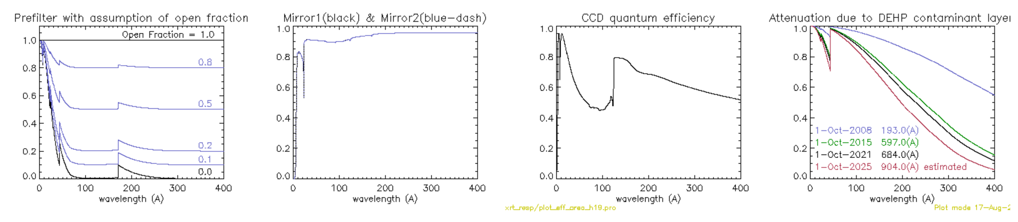

Fig. 3: Common components of XRT effective area functions.

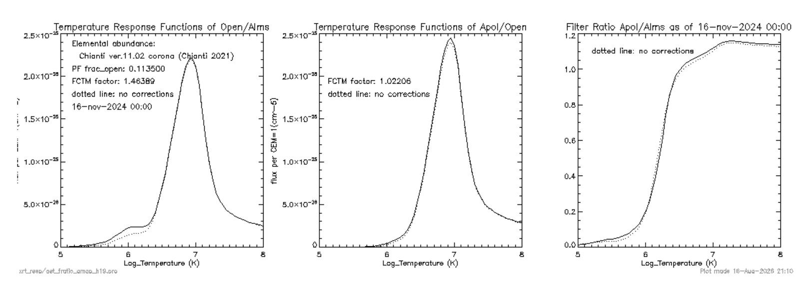

Fig. 4: Example of XRT temperature response of Al-mesh and Al-poly filters and their ratio.

3. New Calibration

3.1 Estimate of CCD contaminant layer thickness

The thickness of contaminant layer on CCD has been measured through the full-Sun G-band intensity which is attenuated by the contaminants. As a general trend, the contaminant layer grows in time and dissipates with the CCD bakeout operations. In Narukage et al (2011), the contaminant layer was assumed to vanish after every CCD bakeout, but later analysis by K. Yoshimura in 2017 suggested that there is a residual layer that gradually grows with time. Since June 2022, the G-band images became unusable for this purpose due to the increased stray light, therefore the contaminant thickness is currently estimated by interpolation.

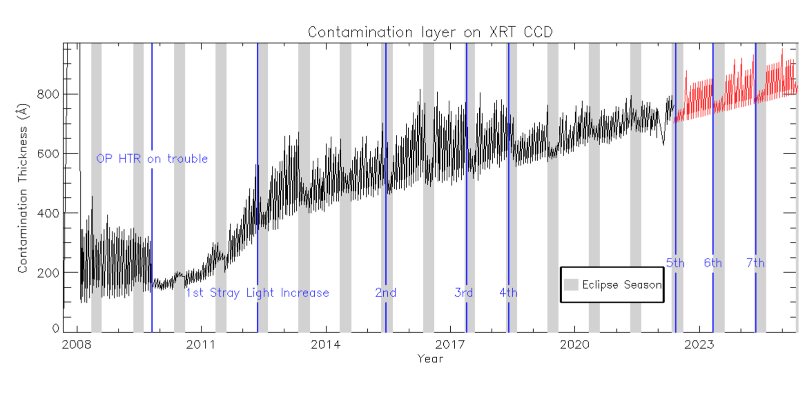

Fig. 5: Long term variation of CCD contamination thickness (by K.Yoshimura). Black line is derived by G-band intensity, while red line is the estimated empirically.

3.2 Correction of visible stray light component

Visible stray light contamination is caused by a crack developed on the XRT's pre-filter (multiple events experienced). The correction takes the following two steps:

1. Subtract visible light component from the X-day images.

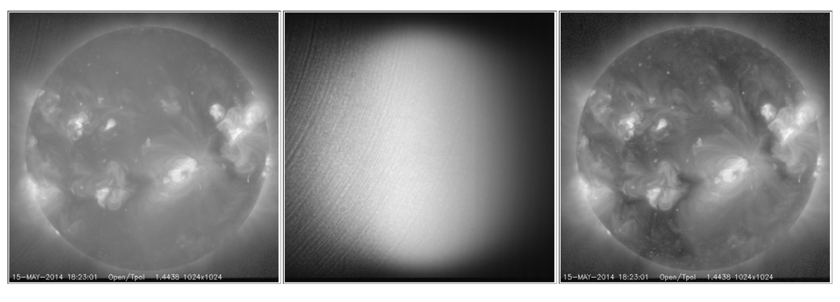

Fig. 6: Example of stray light correction of Ti-poly image. Left: before stray light subtraction. Middle: visible stray light pattern. Right: stray light subtracted image

2. Then modify XRT's effective area function due to the open area of the pre-filter. From the G-band stray light data analysis, we estimated the open area fractions for each event (Table 1), and incorporated them into the effective area functions. These values were recently updated by reconsidering the effective area of the G-band optics (1963.5 to 1256.6 mm^2).

event	date	open fraction (previous values)
1st	9-May-2012	0.1% (0.1%)
2nd	14-Jun-2015	2.3% (3.3%)
3rd	27-May-2017	5.2% (7.5%)
4th	29-May-2018	6.9% (9.9%)
5th	8-Jun-2022	7.6% (10.8%)
6th	5-May-2023	9.3% (13.5%)
7th	11-May-2024	11.4% (16.5%)

Table 1: Estimated open area fraction of XRT pre-filter.

3.3 Reconsidering contamination on X-ray filters

The thickness of contamination layer on the X-ray filters was investigated by Narukage et al (2011) for the initial phase of the mission until 2007. However, additional growth of the contaminant layer is naturally expected after the XRT Operational Heater was permanently turned off in 2010. We determined the amount of additional contaminant so that it provides natural curve of irradiance evolution over a solar cycle:

1. Figure out the total exposure time of each X-ray filters during Hinode's eclipse seasons from 2010 to 2016 when the filter wheel temperature lowers 5 deg.
2. Calculate the contaminant layer growth during the total exposure time using the grow rate derived by Narukage et al.(2011).
3. Add up each year's contaminant layer thickness to obtain the cumulative thickness of the contaminant layer.

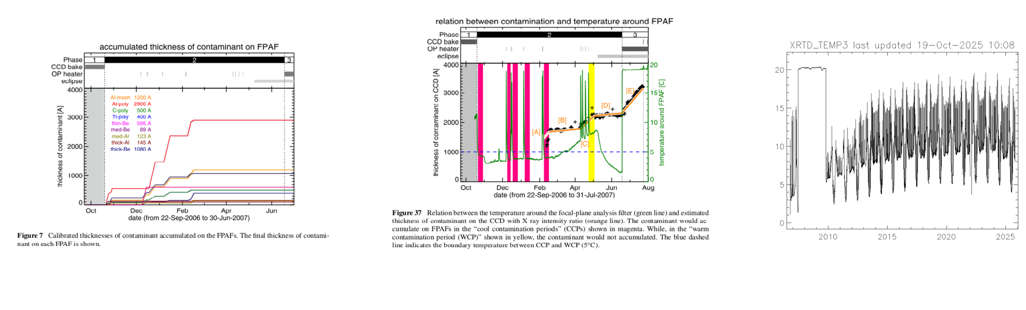

Fig. 7: Left and Middle: Thickness of contaminant layer on X-ray filters and Telescope temperature around the filter wheel both from Narukage et al (2011). Right: Long term temperature plot around the filter wheel.

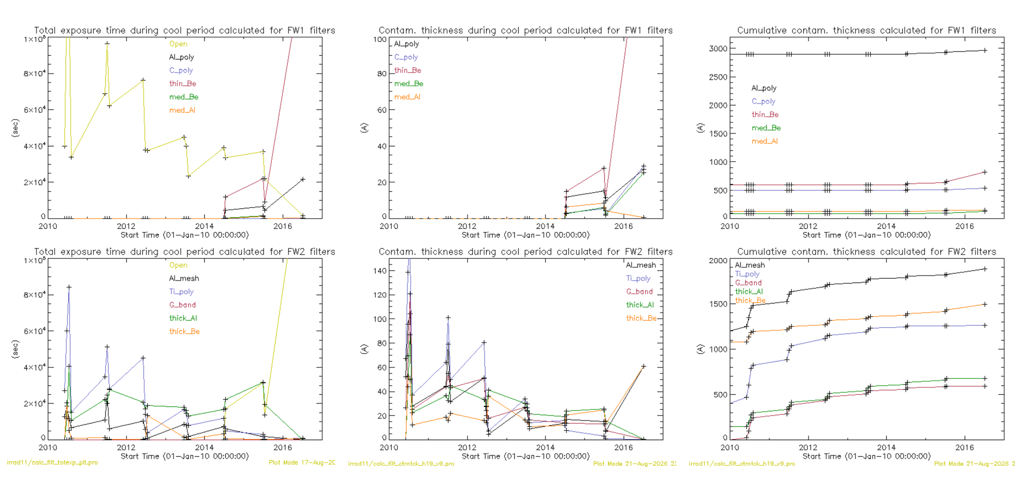

Fig. 8: Left: Total exposure time of each filter during Hinode's eclipse seasons for 2010 - 2016. Middle: Estimated contaminant growth using the rate derived by Narukage et al (2011). Right: Cumulative thickness of the contaminant layer on each filter.

*** Sep-2026 for Hinode-19 science meeting ***