

Scientific Requirements for Thermal Control and Scheduling of the STIS MAMA detectors after SM-3

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ABSTRACT

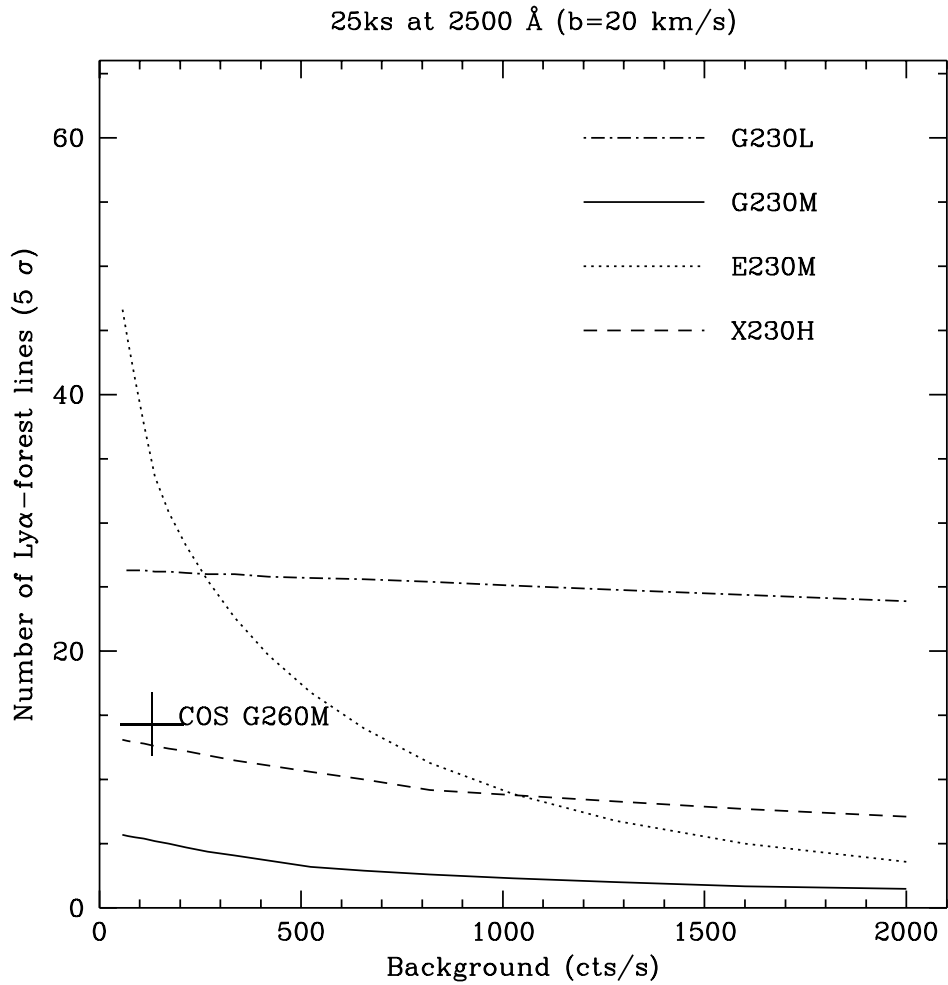
The installation of the Aft Shroud Cooling System (ASCS) on the next HST servicing mission will increase the scientific productivity of STIS by reducing the dark current in the MAMA detectors. The “dark glow” now observed in the FUV-MAMA detector is expected to go away at the $\sim 24^{\circ}\text{C}$ nominal operating temperature after SM3. For the NUV-MAMA, typical dark currents will range from 800 to 1100 cts/s. However, for periods of roughly 10 days at a time, the dark current can be reduced to 200-450 cts/s. This is accomplished by warming the NUV-MAMA to $\sim 38^{\circ}\text{C}$ for about 15 days, then cooling rapidly to as low an operating temperature as possible (20°C is assumed here). This ISR presents an analysis of the NUV-MAMA dark current behavior during the HDF-S campaign, where a similar “cooling campaign” was attempted. It then makes predictions for the NUV-MAMA performance after SM3 and presents recommendations for the number and duration of cooling campaigns. Finally, some preliminary technical requirements for such campaigns are set out.

1. Introduction

The scientific benefit of lowering the dark current in the STIS MAMA detectors is considerable. The ability to maintain a routine dark current of 950 counts/sec over the NUV-MAMA detector (or roughly 1/2 that currently realized), and the ability to achieve a dark current of ~ 300 counts/sec over the detector (or $\sim 1/5$ that currently realized) for periods of ~ 10 days, is one of the anticipated benefits of attaching STIS to the Aft Shroud Cooling System (ASCS) in 1999 (see, Baum et al. memo, March 2, 1998, for more details).

STIS TIR98-06 presented some explicit calculations of the S/N ratio (or alternatively integration time) benefits achieved by operating the STIS NUV-MAMA with lowered dark current for two scientific goals; imaging in the NUV with the purpose of detecting Lyman-break galaxies (also known as “UV-dropouts;” Steidel et al. 1996, AJ, 112, 352; Madau et al., 1996, MNRAS, 283, 1388) and QSO spectroscopy with the purpose of detecting line-of-sight absorption systems for cosmological studies. The observing time benefits of lowered NUV-MAMA dark current are quite substantial for these kinds of sensitive searches. For example, the time it takes to detect 100 Lyman break galaxies at redshifts ~ 1.5 - 2.5 is 275 orbits at the current NUV-MAMA dark rate, and 100 orbits at a dark count rate of 100 counts/sec/detector (both numbers quoted are for low sky conditions). The time it takes to detect 100 intervening Ly α absorption lines in the line of sight to a quasar with $F_{\lambda} = 10^{-15}$ erg cm $^{-2}$ sec $^{-2}$ Å $^{-1}$ at a limiting equivalent width of 0.2 Å is roughly 45 orbits at the current dark rate, ~ 25 orbits at a dark count rate of 500 count/sec/detector and ~ 15 orbits at a dark count rate of 100 counts/sec/detector. Figure 1 shows the expected number of absorption lines detectable in a 25ks observation as a function of dark current for different STIS NUV-MAMA observing modes. Even after the installation of COS, statistical studies requiring a large number of absorption lines in the NUV (redshifts 0.5-1.5) may be more efficiently carried out with STIS.

Figure 1: Number of lines versus dark current



2. MAMA Thermal control with ASCS

For the purposes of this report, the thermal design goals for the ASCS relevant to STIS are taken from “Thermal Peer Review Notes, 15 October, 1998.” As the system design is not yet complete, these numbers must be regarded as preliminary, but nevertheless they are probably not more than a few degrees off what will ultimately be achieved. We envision three thermal modes for STIS:

1. Nominal operations -- CCD at -83°C ; MAMAs at $+24^{\circ}\text{C}$;
2. Warming period -- CCD at -83°C ; MAMAs at $+38^{\circ}\text{C}$; and
3. Cooling campaigns -- CCD at -83°C ; MAMAs at $+20^{\circ}\text{C}$.

The thermal modeling presented in the peer review suggests the campaign mode temperature will be $\sim 20^{\circ}\text{C}$, although $+18^{\circ}\text{C}$ is stated as a design goal. It also indicates that the thermal cycling of STIS around SAAs will be similar to that seen now, with daily fluctuations of 3.5 to 5°C .

These are the numbers we will use for the analysis in this ISR. The ideal is to have the nominal operating temperature be as cool as possible (above the -5°C safety limit), and as stable as possible with both MAMAs on, and to have the cooling campaign temperature be as cool as possible with the FUV-MAMA powered off.

3. FUV-MAMA Dark Current

The FUV-MAMA dark current is on average very low ($\sim 8 \times 10^{-6} \text{cts s}^{-1} \text{pix}^{-1}$), but varies with detector temperature, and can be up to a factor of ten higher in one quadrant of the detector when the detector is warm. The exact physical origin of the excess dark current has not been identified, but it is not window phosphorescence: the high dark currents were seen on the ground, and so is clearly not related to the higher charged-particle background seen on orbit. Studies of the on-orbit behavior indicate that the high dark currents are seen only at high detector temperatures (Landsman, 1998, STIS IDT analysis report 057 “Characteristics of the FUV-MAMA dark rate”). For FUV-MAMA tube temperatures less than 28°C , the dark current is expected to be low and nearly uniform across the detector.

Thus the lower nominal operating temperature of the FUV-MAMA should cure the problem with the dark current, with no special operations or scheduling needed.

4. NUV-MAMA Dark Current

The NUV-MAMA dark current typically varies between 0.001 and $0.0017 \text{cts s}^{-1} \text{pix}^{-1}$, and is strongly dependent on detector temperature.

Physical Understanding

Most of the background in the NUV-MAMA detector comes from phosphorescence in the detector faceplate window. This is a well-known phenomenon, and is due to impurities in the MgF_2 . The STIS detector windows were tested for phosphorescence during the construction of the detectors, but an error in the test led to selection of a window with more impurities than desired.

A theoretical model of the STIS window behavior was presented in a December, 1997 Memorandum “A study of near-UV MAMA dark count rates: Modeling and predictions” by Edward Jenkins of the STIS IDT. The model assumes there is a population of impurity sites each having three energy levels: (1) a ground state, (2) an excited level which can

decay immediately to the ground state by emitting a UV photon, and (3) a metastable level that is at an energy slightly below the one that can emit radiation. The metastable state can be thermally excited to the upper level, and this excitation rate is proportional to $e^{-\Delta E/kT}$, where ΔE is the energy difference between the levels. If we imagine a total number of impurity sites n_{tot} , of which n_e are excited, then the number of emissions per unit time is

$$\frac{dn_e}{dt} = \Gamma n_{\text{tot}} - [\Gamma + p(T)]n_e,$$

where Γ is the excitation rate due to charged-particle impacts for any particular site, and $p(T)$ is the temperature-dependent probability per unit time that the metastable state will undergo a thermal excitation to the higher level and will subsequently emit a photon. A solution to this equation is proposed which gives the number of excited states n_e as a function of the equilibrium value $n_{eq}(T)$ and an initial value n_i :

$$n_e = n_{eq} + (n_i - n_{eq}(T))e^{-\gamma(T)t}$$

The model makes two simplifying assumptions. The first is that Γ is constant over timescales of order the time needed to reach an equilibrium value. The second is that only one set metastable level is important. Given that the model matches the behavior of the MAMA dark current quite well, both assumptions appear to be reasonable.

The dark current in this model is

$$C = p(T)n_e,$$

which, when the temperature is held constant, reaches an equilibrium value

$$C_{eq} = p(T)n_{eq} = n_{\text{tot}}\left(\frac{1}{p(T)} + \frac{1}{\Gamma}\right)^{-1}.$$

The energy difference $\Delta E = 1.095$ eV, was determined from a fit to the dark current vs. temperature during periods of SMOV where the detector was turned on after prolonged periods in the off state. The assumption here is that while the detector was off the number of excited states approached an equilibrium value for the 8.5°C equilibrium temperature.

The Jenkins memo then derives values for the other relevant quantities

$$p(30^\circ\text{C}) = 1.18 \times 10^{-6} \text{ s}^{-1},$$

$$n_{\text{tot}} = 4.18 \times 10^9, \text{ and}$$

$$\Gamma = 2.63 \times 10^{-7} \text{ s}^{-1}.$$

These were derived from the estimates of the equilibrium count rates at 8.5°C and 30°C, and the estimate that the time constant for reaching equilibrium is about 8 days. The estimates were uncertain by at least 20%, and so it makes sense to see how well the model fits more recent data. That will be done in the next section.

As the detector temperature changes, the dark current adjusts over an e-folding timescale γ^{-1} , where $\gamma(T)=\Gamma+p(T)$. The thermal time-constant for detector itself change its temperature is roughly 5 hours. Thus for any given temperature set point the behavior of the NUV-MAMA dark current is a rather complicated function of time and temperature.

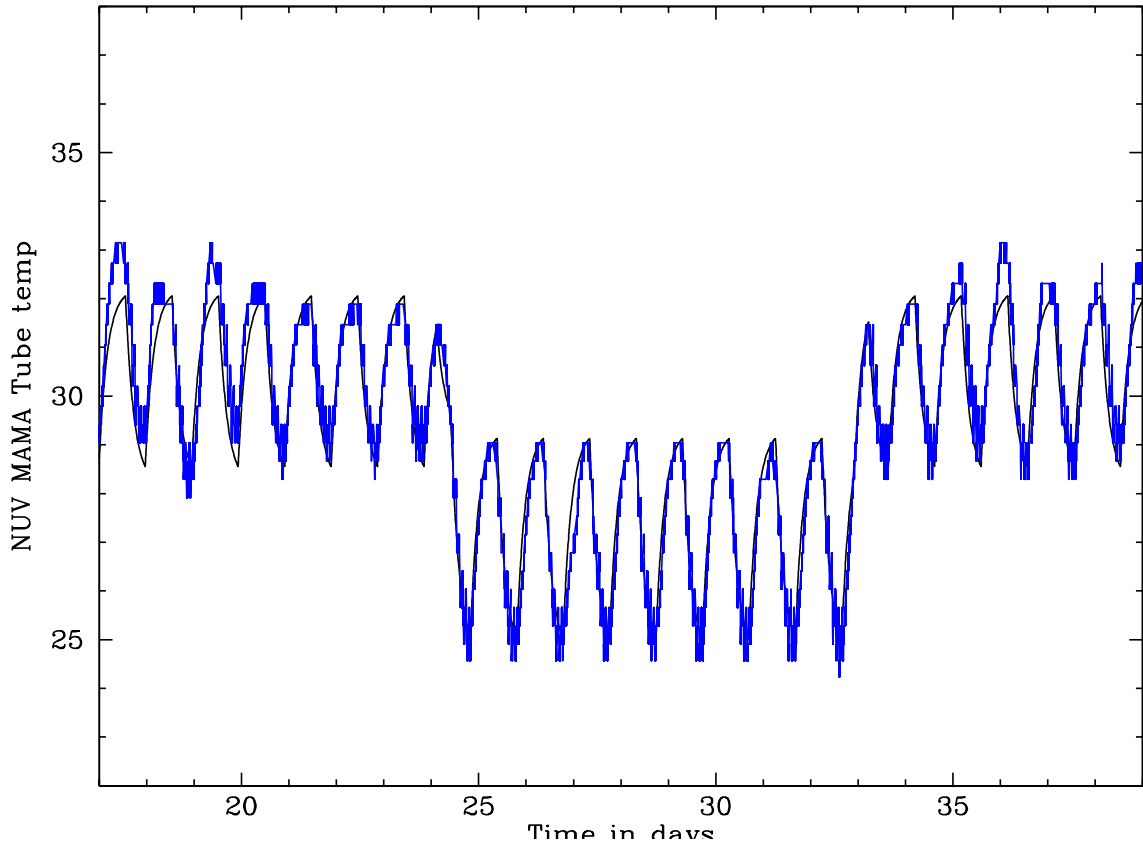
Comparison to HDF-S data

During the HDF-S campaign in October, the temperature of the NUV-MAMA was cooled below nominal by turning off the FUV-MAMA power supply for about 8 days. The comparison of the model predictions to the observed dark rates and temperatures allows us to test and refine some of the parameters in the model.

NUV-MAMA Thermal Response

Figure 2 shows the NUV-MAMA tube temperature during the period surrounding the HDF-S campaign (late September to early October 1998). The roughly sinusoidal variations are due to the daily temperature cycling of the MAMA high-voltage around the SAAs. Superimposed on that is a high-frequency ripple due to temperature fluctuations in the aft shroud as HST moves around in its orbit. The decrease in the average NUV-MAMA tube temperature when the FUV-MAMA was powered off can be seen clearly. The overall behavior can be modeled quite well (smooth curve in Fig. 2) by assuming the thermal time constant for the NUV-MAMA is 4.18 hours (slightly shorter than assumed in the Jenkins memo). Also relevant to the model are the assumed temperatures of the thermal bath surrounding the NUV-MAMA. These have best-fit values of 28.2 and 32.2 °C in the SAA and non-SAA periods, respectively, prior to the cooldown, and values of 24.6 and 29.3 °C, respectively during the period when the FUV-MAMA was off.

Figure 2: NUV-MAMA tube Temperature vs. time during the HDF-S campaign. The jagged curve is the telemetry data. The smooth curve is a model that assumes a thermal time-constant for the NUV-MAMA of 4.18 hours. Time is in days from MJD=51060.



NUV-MAMA Dark current

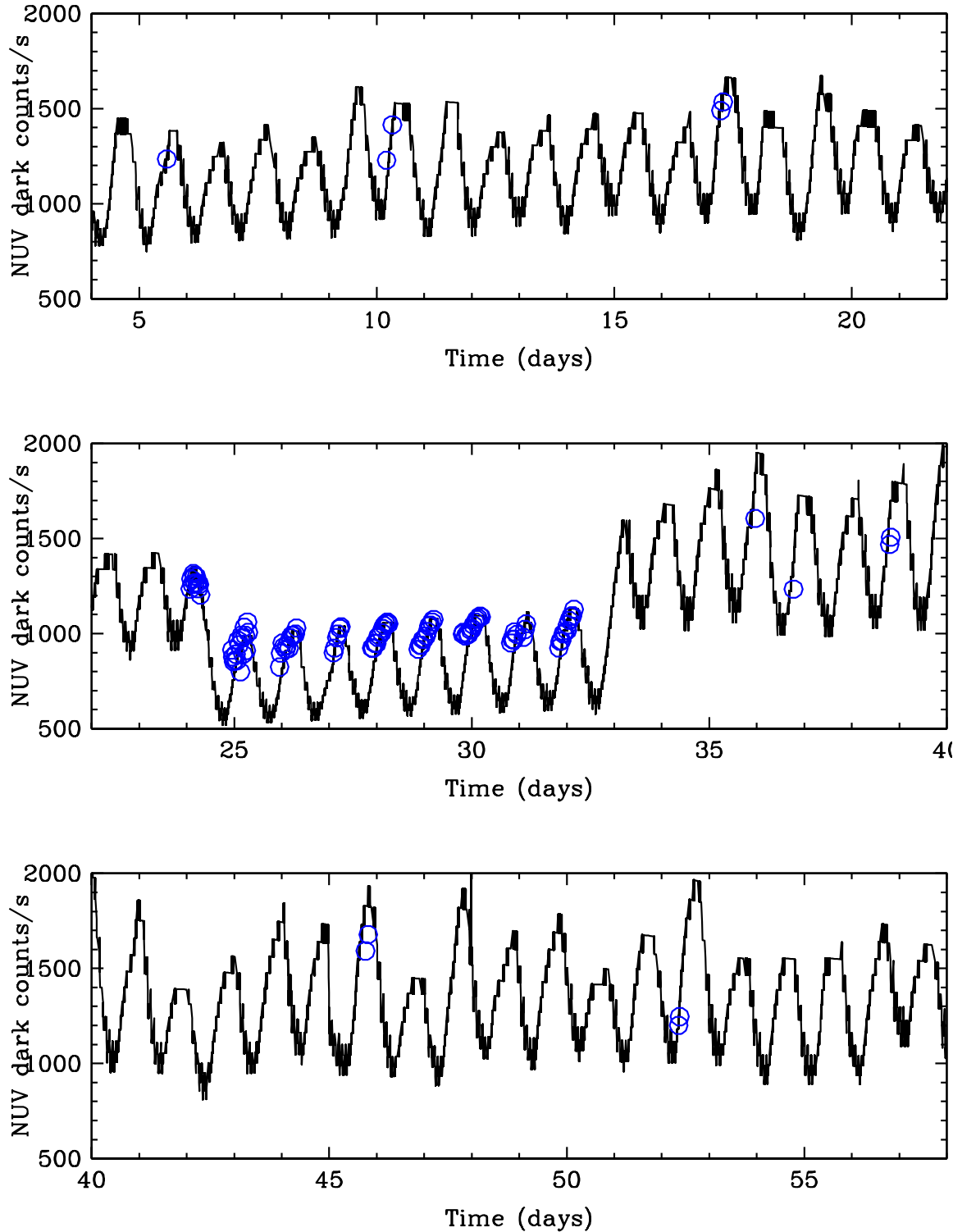
During the HDF-S campaign, the NUV-MAMA dark current was monitored by means of dark frames and was also measured in the science data. The data are shown in Fig. 3, along with the prediction from the model. The model prediction is computed using the actual measured tube temperatures. To achieve a reasonable match to the data, it was necessary to adjust two of the constants in the Jenkins model. The revised values for the total number of impurity sites and the excitation rate are

$$n_{\text{tot}} = 7.0 \times 10^9, \text{ and}$$

$$\Gamma = 2.4 \times 10^{-7} \text{ s}^{-1}.$$

These parameters yield a time-constant $\gamma(30^\circ\text{C}) = 12.8$ days, significantly longer than the original estimate from SMOV data. This time constant is not well constrained, however, and values as long as 20 days also produce a reasonable match to the data.

Figure 3: NUV-MAMA Dark current during September and October, 1998. The data points are measured from dark frames and from source-free regions of HDF-S science frames. The period of low-dark current is the when the FUV-MAMA was turned off during the HDF-S campaign. The curve is the model prediction based on the measured tube temperature. Time is in days from MJD=51060.



5. NUV-MAMA Dark Current History

While not directly relevant to the requirements after SM-3, it seems useful to include here a brief summary of the trend in NUV-MAMA dark current over time. On average two dark frames per week are obtained for each MAMA detector. Figure 4 shows the dark current vs. time since June 1997. The dark current has risen by about 25% over the past 2.5 years. Most of that trend is due to the warming of the detector, which in turn is partly due to a change in the MAMA operating procedures around SAAs in February of 1998 to reduce the overall temperature fluctuations (which raised lifetime concerns for the detector electronics). In February 1998 the size of the SAA contour for cycling the MAMA low-voltage power supplies was reduced. This reduced the temperature fluctuations, but raised the average temperature. Figure 5 shows the trend in the MAMA charge-amplifier temperature vs. time. A simple model for the relation between dark count and temperature (which ignores the detailed time dependence discussed in the previous section) is

$$C = 9.012 \times 10^{20} e^{-12710/T},$$

where T is the charge-amplifier temperature in Kelvin. This model takes out most of the trend with time, as shown in Fig. 6. It is possible that the more precise model of section 4 will account for the remaining trend. Further investigation of the trend is underway using the full thermal history of the detector

Figure 4: (Left) NUV-MAMA Dark current vs. time from June 1997 to December 1998.

Figure 5: (Right) NUV-MAMA Charge Amplifier Temperature vs. time. For both figures, the straight line shows the overall trend, while the jagged line shows the trends before and after February 1998.

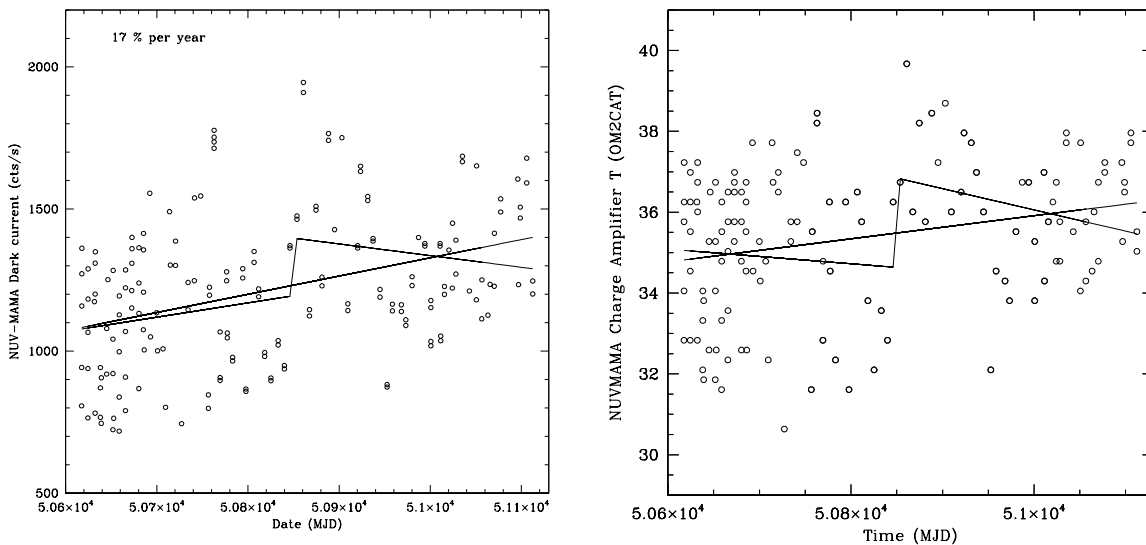
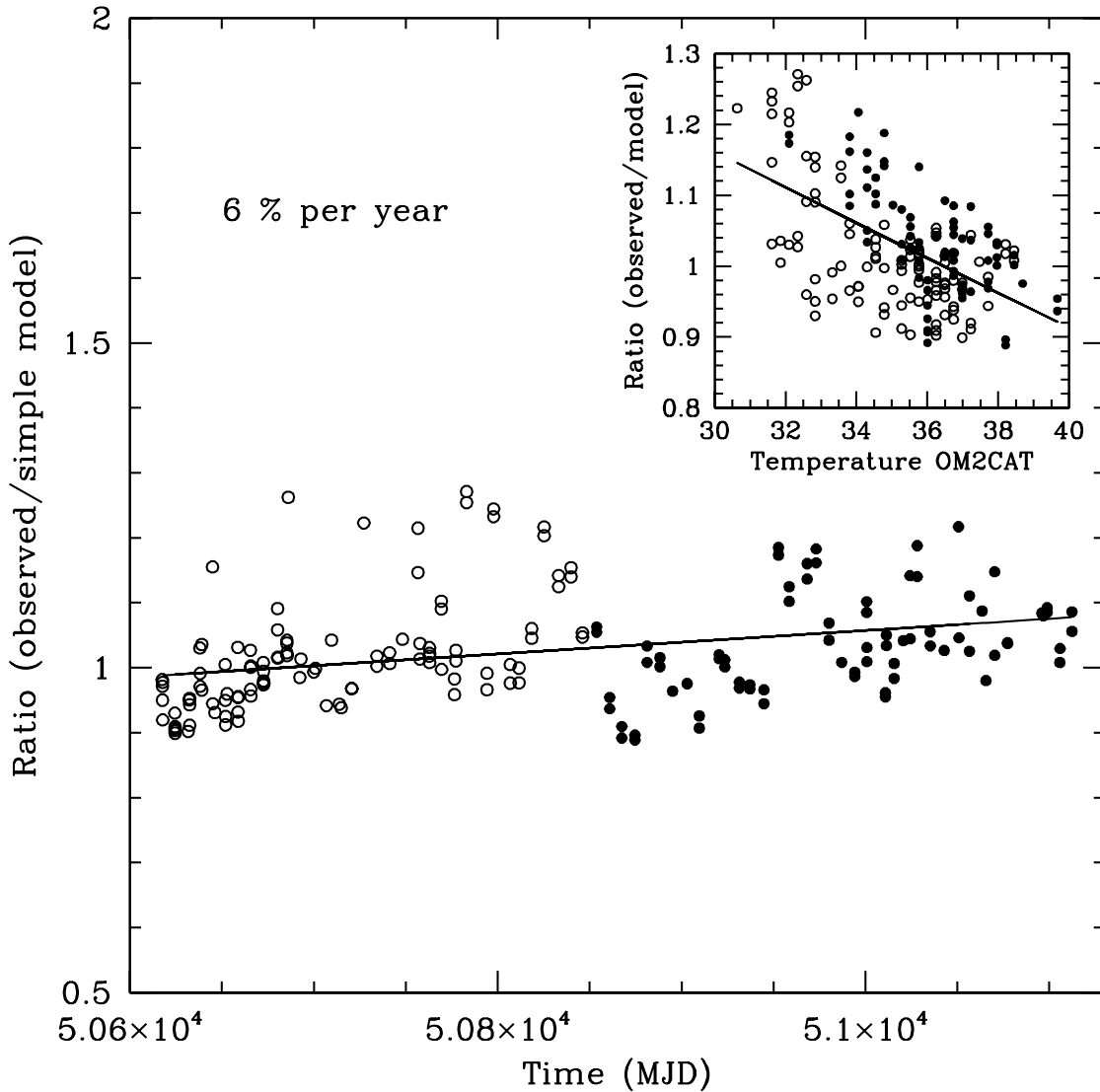


Figure 6: Ratio of NUV-MAMA dark current to simple model, as a function of time. The inset shows the residuals as a function of temperature.



6. Behavior of the NUV-MAMA after SM-3

After the cooling system is attached in SM-3, the nominal operating temperature of the NUV-MAMA is expected to range from 20 to 24 degrees, following the typical cycle of daily fluctuations due to the cycling of the high-voltage around the SAA orbits. With this nominal temperature, typical dark currents will range from about 800 to 1100 cts/s. This is a significant improvement over the 1100-1800 cts/s rates currently measured, but is nevertheless still the limiting factor for many of the likely observations.

Cooling Campaigns

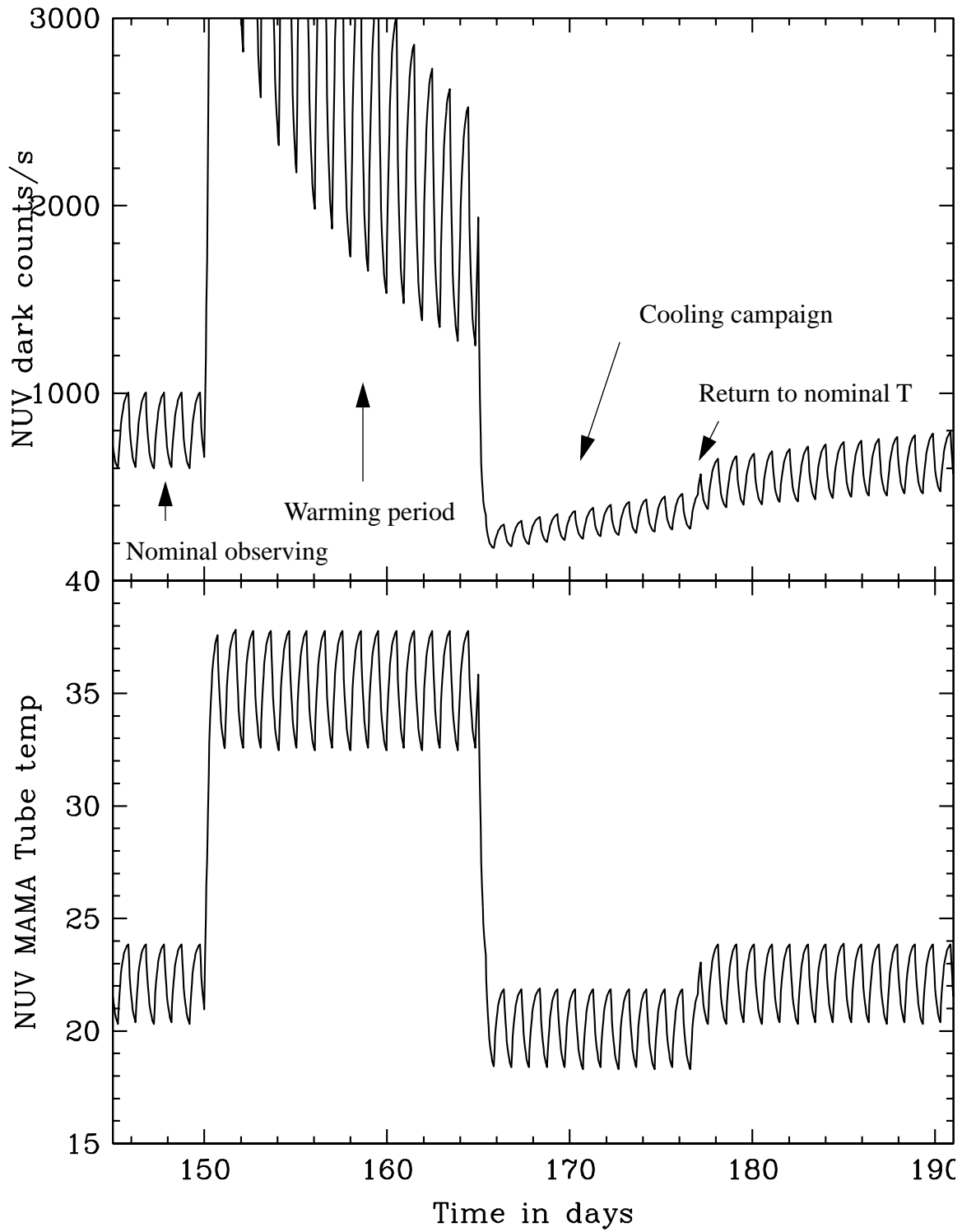
Periods of lower dark current can be achieved by warming the detector for a period longer than the time-constant $\gamma(T)$, then cooling it rapidly to as low a temperature as possible. While the detector is at a high temperature, thermal excitations induce more transitions from the metastable state and deplete the reservoir in the metastable state. If the temperature is subsequently lowered rapidly, the dark current will fall to a low level and gradually rise to the equilibrium value for that temperature.

As mentioned in section 2, we assume that detector temperature during the warming period will be roughly 38°C, and the temperature during the cooling campaign will be roughly 20°C. For the model discussed in section 4, $\gamma(38^\circ\text{C}) = 5.3$ days, and $\gamma(20^\circ\text{C}) = 29$ days. Table 1 shows the values of the dark current as a function of time during a cooling campaign for different lengths of warming period.

Warming period	Dark current, day 1	Dark current, day 7	Dark current, day 11	Dark current, day 15	Dark current, day 30
5 days	380-490	430-560	470-590	480-640	560-730
10 days	280-350	350-450	390-510	420-570	530-670
15 days	230-300	290-400	350-460	390-530	500-660
30 days	190-235	270-360	320-400	360-490	480-640

If dark campaigns are going to be worthwhile, the dark current must be substantially lower than that obtained during normal observations. A 11 day campaign preceded by a 15 day warming period would give a typical dark current a factor of three lower than nominal. Figure 4. shows the temperature and NUV-MAMA dark current for such a campaign. Note that the dark current remains below nominal for several weeks after the end of the cooling campaign, even after the detector is returned to its nominal temperature.

Figure 7: Temperature profile and dark current for a 11-day cooling campaign, preceded by a 15-day warming period.



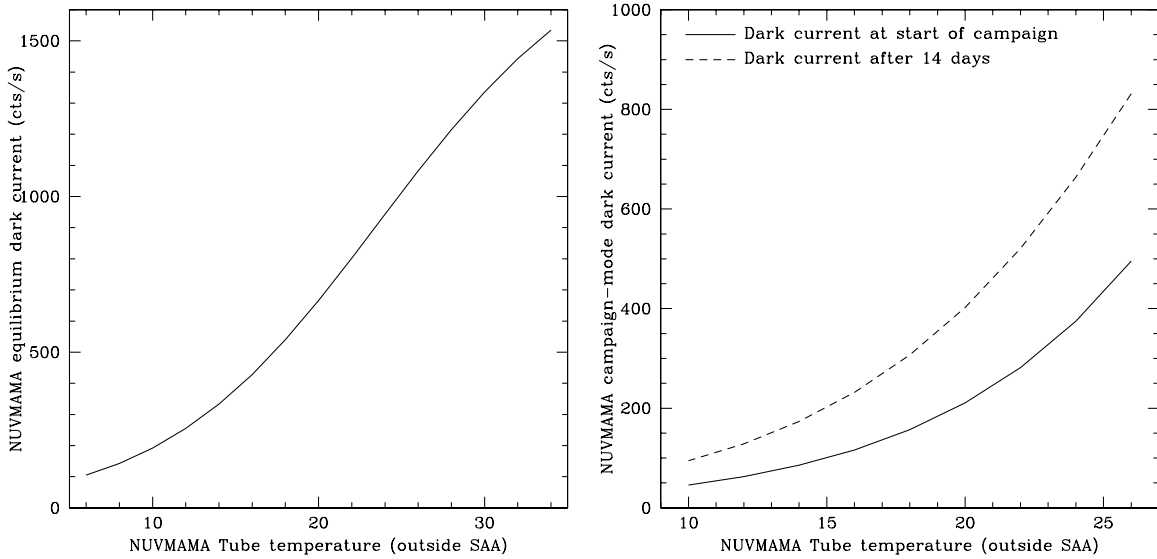
7. The Effect of Cooling System Performance

Since there are tradeoffs still to be made in the design of the cooling system and the design of cooling campaigns, it is important to understand the effect of temperature on the NUV-MAMA dark current. The following points should be noted:

1. From the scientific point of view, it is desirable to run the MAMA detectors as cold as possible, even outside of cooling campaigns. Figure 8 shows the equilibrium dark current as a function of temperature (computed from the model described in section 4). Operating at 20 °C would reduce the mean dark current to 670 cts/s, compared to 950 cts/s expected at 24 °C.
2. The concept of a cooling “campaign” changes slightly if turning off the FUV-MAMA does not result in significant additional cooling for the NUV-MAMA. In that case there is still significant motivation for warming the NUV-MAMA to drive off stored energy, but it may be possible to allow limited amounts of FUV-MAMA observing in the period immediately after cool down. That would simplify scheduling. Our current understanding is that a lower limit of 18 °C for the cooling-campaign temperature is imposed by the survival temperature of STIS, regardless of whether one or two detectors are on.
3. The actual dark current, and the duration of the low dark-current period is strongly dependent on the NUV-MAMA temperature during the campaign. Figure 9 shows the dark current on day 1 and day 14 of a campaign (preceded by a 15 day warming period at 38 °C) as a function of NUV-MAMA temperature during the campaign. Significant gains could come from reducing the campaign temperature, if a way around the survival temperature constraint could be found. For example, if a mean campaign temperature of 15°C could be maintained, the dark current during the campaign could be reduced by more than a factor of two compared to that at 20°C .

Figure 8: NUV-MAMA equilibrium dark current as a function of temperature.

Figure 9: NUV-MAMA campaign-mode dark current as a function of temperature.



8. Rationale for offering NUV-MAMA cooling-campaign observations

To a large extent, the types of observations proposed for HST instruments are dictated by what can be accomplished in a “reasonable” number of orbits, where “reasonable” varies from proposer to proposer but is typically ~ 10 and almost always less than ~ 100 for a single proposal.

For observations that are entirely dark limited, even at the low dark currents, the exposure time to reach a fixed S/N scales linearly with the dark current. Thus a 10 orbit proposal that would achieve $S/N = 10$ at a dark current of 300 cts/s would require 33 orbits at a dark current of 1000 cts/s. For many proposers and TAC members this would be the difference between a viable proposal and one that is simply too expensive. Therefore the major benefit of cooling campaigns is to enable observations that would otherwise be too costly to carry out. Examples include QSO absorption line spectroscopy and NUV imaging of distant galaxies. High-resolution echelle spectroscopy of Galactic sources also often falls into the dark-limited regime.

Expected number of campaigns

It is difficult to anticipate the demand for dark-current limited NUV-MAMA observing in cycle-9. To make a crude estimate, we use cycle-7 as a guide. Cycle-7 proposals were submitted prior to the discovery of the window phosphorescence, and so there was not a great disincentive to propose observations of faint targets. A rough accounting suggests that roughly 150 orbits were being used for dark-current limited observations. The 150

orbits proposed at the nominal cycle-7 handbook value of the dark current (130 cts/s) correspond to roughly 1500 orbits (for the same S/N) at the present value. Cycle-7 observers were not generally given any more time, but most opted to observe at lower S/N or with reduced spectral resolution, rather than give up.

For cycle-9, then, a ballpark estimate is that roughly 150 orbits would be proposed. Two eleven-day cooling campaigns (each preceded by a 15-day warming period) would be sufficient to schedule all of the observations during SAA-free orbits, with a mean dark current ~ 300 cts/s (ranging from 230 to 400 cts/s).

9. Preliminary Technical Requirements

Implementing cooling campaigns would require the following items.

1. Cooling campaigns would need to be described in the call for proposals. It would probably be wise to limit the number of orbits accepted to no more than could be accomplished in 2 campaigns.
2. A new special requirement DARK-CURRENT would need to be introduced for the MAMA detectors. We propose that this have two possible values: LOW, and ALLOW-HIGH. The LOW special requirement would be supported only for the NUV-MAMA and would be a limited resource that observers would need to justify in their phase-1 proposals. The ALLOW-HIGH special requirement would be offered to observers who can tolerate the high dark currents (in either detector) during the warming period. This will increase their scheduling opportunities, and reduce the overall impact of cooling campaigns on HST scheduling.
3. Due to the limited scheduling opportunities, it would probably be best to decide on the dates of the campaigns *prior to the call for proposals*. This would allow proposers to select targets and orient that are compatible with scheduling during those periods. It would also help reduce the overlap with time-dependent observations using other detectors/instruments.
4. Observers would be required to construct their proposals so that they do not require FUV-MAMA observations in the same visits as the NUV-MAMA observations.
5. A ~ 15 day warming period, with the MAMA detector temperatures raised to $\sim 38^\circ\text{C}$ would precede the cooling campaign. Only observations with DARK-CURRENT=ALLOW_HIGH should be scheduled in this period.
6. A ~ 11 day cooling campaign, with the MAMA detectors at $\sim 20^\circ\text{C}$, would follow the warming period. NUV-MAMA observations would be scheduled as densely as possible in the SAA-free orbits. To achieve the cooling-campaign temperature, the FUV-MAMA power supply would be turned off. Therefore observations with the FUV-MAMA cannot be scheduled during the cooling campaign.