AFRL-RV-PS-
TM-2023-0001

AFRL-RV-PS-
TM-2023-0001

AN EARLY PROXY FOR SOLAR FLARE SOFT X-RAY FLUENCE

Stephen M. White

Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

28 October 2022

Interim Report

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

DTIC COPY

NOTICE AND SIGNATURE PAGE

AFRL-RV-PS-TM-2023-0001 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNED//

Dr. Stephen M. White
Program Manager/AFRL/RVB

//SIGNED//

Mark E. Roverse, Chief
AFRL Geospace Technologies Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
28-10-2022

2. REPORT TYPE
Interim Report

3. DATES COVERED *(From - To)*
01 Aug 2022 to 01 Sep 2022

4. TITLE AND SUBTITLE
An Early Proxy for Solar Flare Soft X-ray Fluence

5a. CONTRACT NUMBER
FA9453-19-C-0400

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Stephen M. White

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
EF132583

5f. WORK UNIT NUMBER
V17X

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-PS-TM-2023-0001

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited AFRL-2022-4429 dtd 14 Sep 2022

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The relationship between the soft X-ray fluence of a solar flare and the combination of its rise time and its peak flux is investigated in order to derive a proxy for the fluence that can be estimated at the peak of the flare, i.e., significantly earlier than the "end" of the flare (by convention, the half-power point on the decay). The result will be used in forecasting solar energetic particle events.

15. SUBJECT TERMS
solar flares; solar soft X-ray emission; solar energetic particles

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. Stephen M. White
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code),*
Unclassified	Unclassified	Unclassified	Unlimited	14	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

This page is intentionally left blank.

An Early Proxy for Solar Flare Soft X-ray Fluence

Stephen White (AFRL/RVBXD)

September 8, 2022

Executive Summary The relationship between the soft X-ray fluence of a solar flare and the combination of its rise time and its peak flux is investigated in order to derive a proxy for the fluence that can be estimated at the peak of the flare, i.e., significantly earlier than the "end" of the flare (by convention, the half-power point on the decay). The result will be used in forecasting solar energetic particle events.

Introduction

The soft X-ray fluence of a solar flare is a quantity commonly used in models for the prediction of solar energetic particle events (e.g., Smart & Shea 1989; Balch 1999; Laurenza et al. 2009; Trottet et al. 2015), which seems appropriate since it is one of the simplest readily-available proxies for the total energy in a flare. Soft X-ray flare lists are compiled by NOAA from measurements by the XRS detectors on the GOES series of weather satellites. The fluence is defined to be the integral of the soft X-ray flux (reported in W m^{-2}) over time from the onset of the flare to the half-peak point on the decay of the event. However, for long-duration soft X-ray events, it may be an hour from onset before the half-peak level is reached on the decay, by which time solar energetic protons may have already started arriving. In order to have an early forecast of the likelihood of an SEP event, an earlier estimate of the fluence is desirable. The purpose of this report is to assess the feasibility of using some product of the flare rise time and peak flux to derive an estimate of the fluence at the time of the flare soft X-ray peak. The relationship between these quantities will be investigated, and an expression for generating a fluence estimate at the time of the soft X-ray peak will be derived.

Analysis

We use a list of M- and X-class soft X-ray flares from 1986 to 2021. NOAA has maintained lists of soft X-ray flares and reported peak fluxes and durations from which fluences can be derived. NOAA provides fluences in the daily event files, at least since 1996. However, prior to May 1997 there was no standardized protocol for defining the start and end of the soft X-rays from a flare,[1]

[1] Veronig et al. (2002) reported that the timing prior to 1997 was based on Hα flare observations.

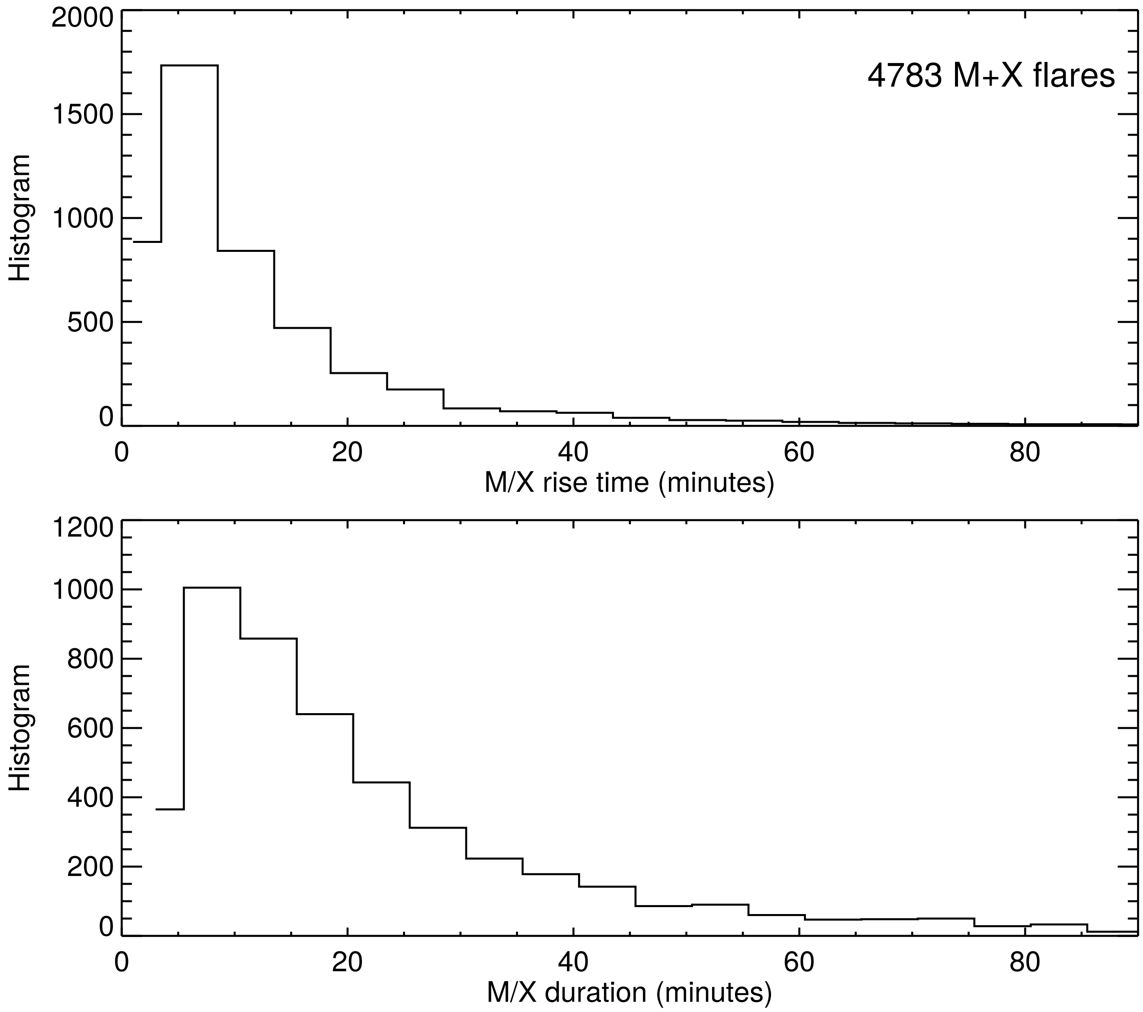

Fig. 1.— Histograms of the flare soft X-ray rise times (upper panel) and total duration (lower panel) for the 4783 M- and X-class flares used in this study.

resulting in a sharp boundary in the reported properties of flares such as rise time and duration (Swalwell et al. 2018). NOAA's protocol for the period after 1997 is that the start time of a GOES SXR flare is the time when four consecutive values in the 1-minute 1-8 Å data meet all three of the following conditions:

1. All four values are above the B1 threshold.
2. All four values are strictly increasing.
3. The last value is greater than 1.4 times the value which occurred 3 min earlier.

The flare end time is defined as the time when the flux declines to one half of the flare peak, where the peak is the flux at maximum minus the flux value at the start of the event. For the M- and

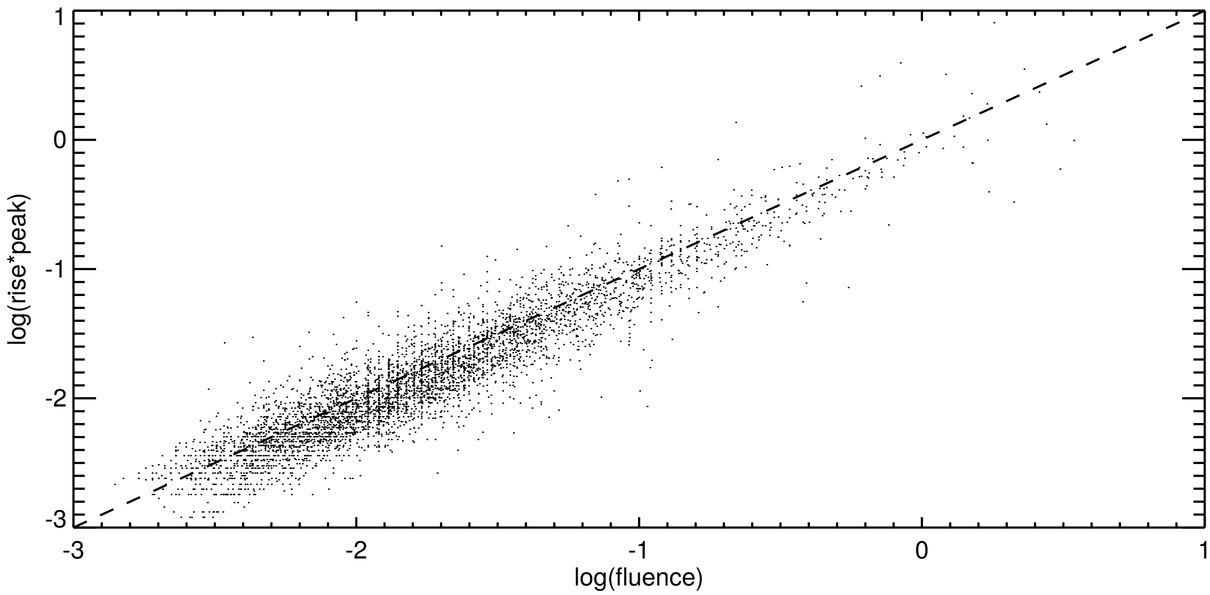

Fig. 2.— A plot of the product of the rise time and the peak flux versus the measured fluence for 4783 M- and X-class flares from 1986 to 2021. For convenience, the $\log_{10}$ of the quantities (both in units of J m^{-2}) is plotted. The dashed line corresponds to equality of the 2 quantities.

X-class flares considered here, the preflare subtraction should have minimal impact on the timing in most cases.

The GOES soft X-ray data from 1986 to 1997 available in FITS files at NASA[2] have been reprocessed (by the author) to match the standard prevailing since 1997 for all M and X flares (Swalwell et al. 2018, carried this out for >M5 flares). The NASA FITS files often have data gaps, so not all flares in the period are included. The resulting list of M- and X-class flares has 4783 entries with fluence measurements. Figure 1 shows histograms of the rise times and durations of the event sample used here. More than half of all M/X flares have rise times of 10 minutes or less and durations of 20 minutes or less. Rise time and duration are correlated: a fit finds that the duration can be represented as $2.24\,t_R^{0.93}$, where t_R is the rise time (both in minutes), with a spread of $\pm$ 22% between the predicted and the actual durations. Thus there is nearly a linear relationship between duration and rise time.

Figure 2 plots (the logarithm of) the product of the flare rise time and the peak flux against (the logarithm of) the measured fluence. This figure demonstrates the strong relationship between the fluence and the product of rise time and peak.

Linear fit. The simplest possible relationship between flare rise, peak and fluence is linear:

[2]https://umbra.nascom.nasa.gov/goes/fits/

$$F = a t_R P_X \tag{1}$$

where F is the fluence (J m^{-2}), t_R is the rise time (seconds), P_X is the flare soft X-ray peak (W m^{-2}) and a is a constant. Fits for a for the full data set, as well as fits for each of the 3 complete solar cycles in the period covered, are shown in Table 1.

In effect, the uneven treatment in the definitions of the rise and end of the flare result in almost half of the fluence of the event occurring during the rise phase. Linear fits using $a = 1.19$ (the median for the whole set of flares) have a spread of $\pm$ 34% about the median of the ratio of predicted fluence to actual fluence.

Product power-law. The next option for a fluence proxy is to allow a power-law dependence in the product of rise time and peak flux:

$$F = a(t_R P_X)^b \tag{2}$$

A fit for this relationship using all 4783 flares gives $a = 0.771 \pm 0.009$ and $b = 0.900 \pm 0.003$, resulting in a uncertainty of $\pm$ 32% in the predicted fluence compared to the actual fluence. Veronig et al. (2002) carried out a similar analysis of a sample of flares from 1997 to 2000, ranging from B- to X-class, and found $b = 0.96$: the inclusion of smaller flares, which dominate M/X flares by number in that sample, may play a role in the difference.

Separate power-laws. Finally, we can separate out the dependence on the rise time and peak flux, requiring 3 parameters:

$$F = a t_R^b P_X^c \tag{3}$$

Again fittting this relationship using all 4783 flares gives $a = 0.635 \pm 0.035$, $b = 0.913 \pm 0.004$, and $c = 0.890 \pm 0.004$. Figure 3 compares the prediction from this expression with the actual fluence, plotting the ratio of the two as a function of time. Note that the power-law exponents

Table 1. Linear relationship between fluence (F) and $t_R * P_X$

	No. of M/X flares	Median a	σ_a
Cycle 22	2407	1.27	0.42
Cycle 23	1576	1.14	0.41
Cycle 24	769	1.06	0.37
All	4783	1.19	0.42

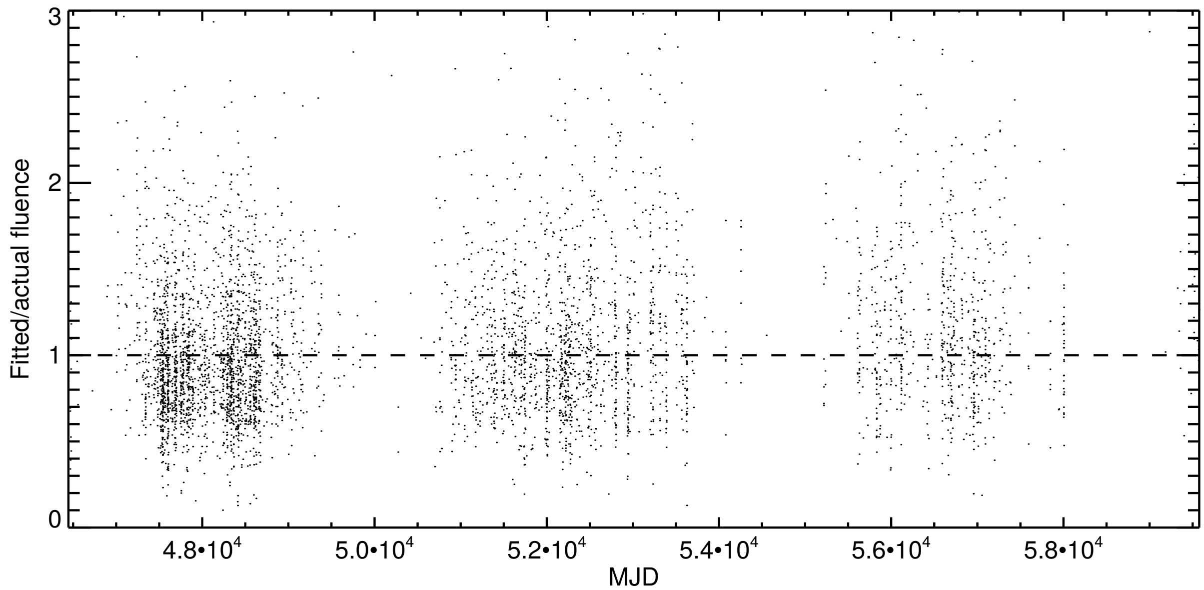

Fig. 3.— A plot of the ratio of the ($\log_{10}$ of the) fluence derived from the power-law fits in rise time and peak flux to the ($\log_{10}$ of the) measured fluence (equation 3) for 4783 M- and X-class flares from 1986 to 2021. The horizontal axis is modified Julian date (MJD), in order to show that the same relationship is essentially valid over multiple solar cycles.

for rise time and peak flux are very similar, and accordingly this fit only marginally improves the uncertainty, which is again around $\pm$ 32% in the predicted fluence compared to the actual fluence.

Summary

The following simple power-law in the flare soft X-ray rise time t_R and peak flux P_X can be used to estimate the NOAA-defined fluence of the event at the time of the soft X-ray peak, to within an uncertainty of about 32%:

$$F = 0.771\,(t_R * P_X)^{0.900} \tag{4}$$

The (simpler) 2-parameter fit is recommended since the 3-parameter fit gives essentially the same results and performance.

References

Balch, C. C. 1999, Radiation Measurements, 30, 231

Laurenza, M., Cliver, E. W., Hewitt, J., Storini, M., Ling, A. G., Balch, C. C., & Kaiser, M. L. 2009, Space Weather, 7, S04008

Smart, D. F. & Shea, M. A. 1989, Advances in Space Research, 9, 281

Swalwell, B., Dalla, S., Kahler, S., White, S. M., Ling, A., Viereck, R., & Veronig, A. 2018, Space Weather, 16, 660

Trottet, G., Samwel, S., Klein, K. L., Dudok de Wit, T., & Miteva, R. 2015, Sol. Phys., 290, 819

Veronig, A., Temmer, M., Hanslmeier, A., Otruba, W., & Messerotti, M. 2002, A&A, 382, 1070

This preprint was prepared with the AAS LATEX macros v5.2.

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVIL Kirtland AFB, NM 87117-5776	1 cy
Official Record Copy AFRL/RVB/Dr. Stephen M. White	1 cy

This page is intentionally left blank.