Instrument Science Report STIS 2017-02

Bright Object Protection Considerations for M Dwarf Flare Events

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December 21, 2017

ABSTRACT

We provide clear and concise guidance for Guest Observers and Contact Scientists to evaluate the health and safety of the instrument while observing M dwarfs, taking into consideration current scientific research about the frequency with which large flare events occur, and a risk tolerance level for causing an inadvertent detector shutdown due to overlight conditions from a large flare during an observation.

Contents

Operated by the Association of Universities for Research in Astronomy, Inc., for the National Aeronautics and Space Administration.

1. Introduction

With photon counting detectors as part of the COS, STIS-MAMA and ACS-SBC instrument suites, there is a long history of observers needing to demonstrate the health and safety of their targets when using instruments on HST subject to overlight conditions. Previous ISRs have addressed this in a general way: Clampin et al. 1995; Clampin & Kinney 1996; Leitherer et al. 1996; Leitherer et al. 1996; Walborn et al. 2006. Language in the Call for Proposals specifically calls this out, as in Section 4.1.3 of the current (Cycle 25) CfP:

> "Proposals to observe variable objects with the COS, STIS/MAMA, or ACS/SBC detectors must pass bright-object checking before they can be scheduled (see Section 5.1 of the Primer). Proposers should assume the maximum flux values for targets unless there are specific reasons for adopting other values (for example, time constrained observations of periodic variables at flux minima). . . . "

This ISR is motivated by two related issues: observers in recent cycles are more interested in obtaining UV spectra of nearby M dwarfs to study exoplanets and the influence of the short wavelength radiation from the host star on close-in exoplanets; and more information is known about how often extremely energetic flare events occur which may cause health and safety issues. For this reason, additional language has been inserted into the CfP regarding M dwarfs:

> "Observers interested in proposing for UV observations of cool stars should keep in mind the possibility that low mass stars may undergo extreme enhancements during stochastically occurring flares. Proposers must demonstrate the health and safety of their targets under these extreme conditions." (Section 4.1.3)

The intent of this ISR is to provide a clear and concise method to ensure the safety of the photon-counting detectors when observing M dwarfs.

2. Estimating the Frequency of Large Flaring Events on M Dwarfs

M dwarfs are subject to irregular and unpredictable flaring outbursts, which may increase the FUV and NUV light by possibly large factors. Recent examples of large flares observed at UV and/or optical wavelengths published in the literature include Robinson et al. (2005), Osten et al. (2010), Kowalski et al. (2010), and Schmidt et al. (2016). These flaring outbursts are thought to be caused by the rearrangement of magnetic fields in the outer stellar atmosphere through magnetic reconnection processes, which results in the liberation of potentially large amounts of energy. While flares occur on almost all stars in the cool half of the HR diagram, historically M dwarfs have exhibited extreme enhancements, as measured by the peak luminosity enhancment. U-band increases in the largest flares can be around 6 magnitudes, but there is evidence for more extreme behavior in the NUV (Robinson et al. 2005) and the V band (Schmidt et al. 2016). See Osten (2016) for a review of stellar flare activity in different wavelength ranges across the electromagnetic spectrum, and on cool stars of a range of ages.

The two most important factors known at this time for determining the flaring rate of an M dwarf are its spectral subtype and magnetic activity level. Three broad bins of spectral subtype are used here: early (M0-2), mid (M3-5), and late (M6-9). While there are several ways to estimate a star's activity level, the most broadly used criterion is based on equivalent width (EW) of the Hα line. The distinction has traditionally been set (e.g. West et al. 2008) at an equivalent width of > 1 Å; i.e., stars with an EW in Hα larger than this are classed as magnetically active, and stars with an EW less than 1 Åin Hα are inactive.

Table 1 lists the flare energies for M dwarfs of differing spectral types and magnetic activity levels, using flare frequency distributions (FFD) compiled using mostly U band measurements. These data are taken from Hilton (2011). The flare frequency distribution is quantified as a power-law occurrence rate (# flares/hr) as a function of the integrated flare energy. We assume conservatively that a flare will have its peak brightness for at most 5 minutes, and use this duration as well as the timescale on which statistically a flare of a given energy will occur, to estimate the probability. That is, the probability is (5/60)$\times\nu$, where ν is the # of flares per hour predicted by the FFD. I determine flare energies for three different values of probability, from 10^{-2} to 10^{-4}. In the Hilton (2011) study, there were only 3 flares observed from inactive mid-M dwarfs, leading to large uncertainties in this calculation. More recent studies of Lurie et al. (2015) have examined FFDs for inactive mid-M dwarfs using Kepler data with a significantly larger number of flares, so we use this compilation instead, after correcting for the difference between the radiated flare energy in the Kepler bandpass and that radiated in the U filter bandpass (Osten & Wolk 2015, $E_U/E_{Kp} = 0.7$).

Table 1.: U band flare energies in erg for M dwarfs of differing spectral type and magnetic activity level estimated to have the listed probability of occurring.

	Spectral Type					
Activity level	M0-2		M3-5		M6-9 [†]	
inactive	$P=10^{-2}$	8×10^{29}	$P=10^{-2}$	8×10^{29}	…	
	$P=10^{-3}$	7×10^{30}	$P=10^{-3}$	7×10^{30}	…	
	$P=10^{-4}$	6×10^{31}	$P=10^{-4}$	6×10^{31}	…	
active	$P=10^{-2}$	2×10^{31}	$P=10^{-2}$	2×10^{31}	$P=10^{-2}$	2×10^{29}
	$P=10^{-3}$	6×10^{31}	$P=10^{-3}$	2×10^{33}	$P=10^{-3}$	5×10^{30}
	$P=10^{-4}$	10^{32}	$P=10^{-4}$	10^{35}	$P=10^{-4}$	10^{32}

[†] Almost all late M dwarfs are considered active; West et al. (2008).

While integrated flare energies are a useful metric for stellar flare studies, a more practical quantity for estimating the impact on detector health and safety is the peak increase in flare magnitude. Table 2 lists a conservative value for the peak increase in the flare in the U band above quiescence, ΔU, corresponding to flares of the integrated flare energies listed in Table 1. This is based on an upper curve to flares with tabulated ΔU increases and integrated U-band flare energies from Hilton (2011). Specifically, the equation used is

$$-\Delta U = 54.5 - 4.66 \log E_U + 0.095 (\log E_U)^2 \ . \tag{1}$$

Table 2.: Maximum U band magnitude increases (ΔU) corresponding to flare energies listed in Table 1.

Activity level	Spectral Type					
	M0-2		M3-5		M6-9 [†]	
inactive	P=10^{-2}	-0.07	P=10^{-2}	-0.07	...	
	P=10^{-3}	-1.1	P=10^{-3}	-1.1	...	
	P=10^{-4}	-2.3	P=10^{-4}	-2.3	...	
active	P=10^{-2}	-1.8	P=10^{-2}	-1.8	P=10^{-2}	...[‡]
	P=10^{-3}	-2.3	P=10^{-3}	-4.6	P=10^{-3}	-1
	P=10^{-4}	-2.8	P=10^{-4}	-8.0	P=10^{-4}	-2.8

[†] Almost all late M dwarfs are considered active; West et al. (2008).

[‡] Δ U for flare energy E_U too small, out of range of validity using data from larger flares.

3. Determining Global and Local Count Rates

Using Table 2 above, a proposer and/or contact scientist should be able to at a first pass, determine the maximum U band flare enhancement expected for a star of a given spectral type and activity level, and feed this into the Exposure Time Calculator (ETC) to determine if there are health and safety issues. The stellar flare spectral energy distributions in the FUV and NUV are comprised of both line and continuum emission. In this section I lay out information about how both types of emissions scale with the flare energy in the U band, in order to determine the global and local count rates.

The dominant continuum emission arises from a hot blackbody with a temperature T_{BB} of ~9000 K (Hawley et al. 2003). The ETC already includes the possibility to model the spectral energy distribution with a blackbody of a specified temperature, normalized to a brightness in various filters. This emission will dominate the NUV bandpass and should be used to assess health and safety for NUV modes. There will also be a tail of continuum emission extending into the FUV bandpasses.

The strongest lines in the NUV are the Mg II h and k lines at 2803.52 and 2796.34 Å, respectively. Their increase during flares is smaller than what is expected from the continuum, and there do not appear to be any established scalings to estimate the amount of increase for a U-band flare of a given strength. In the FUV bandpass strong lines also contribute to the quiescent and flare emission. The three strongest emission lines are Lyα, C IV, and Si IV. The latter two occur as part of doublets. Hawley et al. (2003) shows flux-flux relations during flares between the stronger of the doublet lines of C IV, Si IV, and the U-band continuum flux, and these relations can be used to estimate the amount of flux in these lines to use as input to the ETC, for a flare of a given U band magnitude increase. These are:

$$\begin{aligned} \log f_{\mathrm{C\ IV}} &= 0.32 + 0.92 \log f_{\mathrm{U}} \qquad (2) \\ \log f_{\mathrm{Si\ IV}} &= 2.4 + 1.10 \log f_{\mathrm{U}} \qquad (3) \end{aligned}$$

where $f_{\mathrm{C\ IV}}$ and $f_{\mathrm{Si\ IV}}$ are integrated line fluxes and have units of erg cm^{-2} s^{-1}; f_{U} is a continuum flux and has units of erg cm^{-2} s^{-1} Å^{-1}. These are fluxes at Earth.

Lyα is the strongest emission line in the FUV spectrum, but usually has considerable ISM absorption in it. Nevertheless, there are scaling relations between Lyα surface flux and excess FUV and NUV continuum fluxes (above that expected from photospheric emission) in Shkolnik et al. (2014) which can be used to estimate the fluxes of these lines. The photospheric contribution for M dwarfs is $<$10% of the quiescent flux, and so the flare-only fluxes can be used to estimate the Lyα flux for a large flare. Shkolnik et al. (2014) give equations for the surface flux of Lyα given the FUV and NUV excess flux above photospheric levels:

$$\begin{aligned} \log F_{\mathrm{Ly}\alpha} &= (0.43 \pm 0.07) \log F_{\mathrm{FUV,exc}} + 3.97 \pm 0.36 \qquad (4) \\ \log F_{\mathrm{Ly}\alpha} &= (0.45 \pm 0.07) \log F_{\mathrm{NUV,exc}} + 3.55 \pm 0.41 \ . \qquad (5) \end{aligned}$$

Note that these relations were established only under quiescent conditions and have not been tested empirically with flare data. The GALEX FUV and NUV bandpasses, upon which these relations were established, are 1350-1750 Å and 1750-2750 Å, respectively. Since these equations are based on stellar surface fluxes, stellar radius and distance must be used to convert to fluxes at Earth. The usual formula is $f_\star = f\left(\frac{d}{R_\star}\right)^2$, where $f_\star$ is the stellar surface flux, f is the flux at Earth, d is the distance to the star, and $R_\star$ is the stellar radius. Linsky et al. (2013) computed intrinsic Lyα fluxes for AD Leo, the same M dwarf for which the C IV and Si IV to f_U flaring flux relations above were established, as well as a C IV doublet flux. The integrated line flux of the C IV doublet can be used to estimate the line flux of the stronger line by using the fact that the line ratios are 2:1 when conditions are optically thin. Although there may be small departures from this ratio, it should hold approximately. Then the C IV 1548 Å flux is $2/3$ of the doublet flux, and the ratio of intrinsic Lyα to C IV flux is $\approx$37. This can be used as a floor for the Lyα calculations described below as both emission lines will increase during a flare.

4. Information Needed to Perform BOP Screening on M Dwarfs

The following information is needed to perform BOP screening on M dwarfs:

1. **Quiescent Screening** The target must first clear screening based on its quiescent flux values.
2. **Spectral Type** Targets with uncertain spectral types should use the nearest spectral type which gives the most stringent flare requirements, based on Tables 1 and 2. Stellar objects with spectral types falling just outside of the M spectral sequence M0-M9 should use the nearest tabulated M spectral type; i.e. an L0 dwarf should use the results for an M9 dwarf.
3. **Distance** SIMBAD lists parallaxes to most nearby stars (parallax in mas), from which distance in pc can be determined as 1/parallax, with parallax in arcsec.
4. **Quiescent U Band Magnitude** If SIMBAD does not list the quiescent Johnson U filter magnitude for the star, it can be estimated from the Table 3 from Pecault & Mamajek (2013). Late M spectral types should use colors appropriate for the closet spectral type for which such tabulation is available.
5. **Hα equivalent width** The equivalent width of the Hα spectral line is used to assess magnetic activity level. EW(Hα)$>$1 indicates a magnetically active star. Possibly useful references of Hα magnetic activity in nearby M dwarfs include Reid et al. (1995), Hawley et al. (1996), Gizis et al. (2002), Lépine et al. (2013), or more recently, Newton et al. (2016). In Newton et al. (2016) the activity flag label in Table 1 has been erroneously inverted. The activity flag should read: 0=inactive, 1=active. Note that for late M spectral types (M7-M9), essentially all stars are magnetically active. In the absence of Hα equivalent width information, the more restrictive assumption (i.e. a magnetically active star) should be made.
6. **Stellar Radius** Stellar radius is needed to compute surface flux. Table 4 tabulates stellar radius versus spectral type and effective temperature from Reid & Hawley, corrected as noted by Kaltenegger & Traub (2009). The stellar radius is expected to vary with stellar age and may additionally vary with metallicity and activity level, so these should be used as approximate numbers.

Table 3.: Tabulation of colors for M Dwarfs

Spectral Type	Effective Temperature[1]	B-V[1]	U-B[1]
M0	3850	1.431	1.190
M1	3700	1.480	1.171
M1.5	3650	1.486	1.170
M2	3550	1.500	1.170
M2.5	3500	1.522	1.175
M3	3400	1.544	1.181
M4	3200	1.661	1.222
M4.5	3100	1.72	1.23
M5	3050	1.874	1.24
M5.5	3000	1.91	1.3
M6	2800	2.00	1.3
M7	2650	2.06	…
M7.5	2600	2.17	…
M8	2500	2.20	…
M9	2450	…	…

[1] Taken from Pecault & Mamajek (2013)

Table 4.: Approximate stellar radii for M dwarf spectral types

Spectral Type	Effective Temperature[1] K	Stellar Radius[1] $R_\odot$
M0	3800	0.62
M1	3600	0.49
M2	3400	0.44
M3	3250	0.39
M4	3100	0.26
M5	2800	0.20
M6	2600	0.15
M7	2500	0.12
M8	2400	0.11
M9	2300	0.08

[1] From Reid & Hawley (2005), as corrected by Kaltenegger & Traub (2009)

5. Steps in BOP Screening

The following steps should be used to assess health and safety of UV observations of M dwarfs for COS and STIS:

1. Use spectral type and magnetic activity level to determine which part of Table 2 is applicable. If an object is on the cusp of one of these categories (e.g. a late K dwarf or early L dwarf), use the appropriate spectral type bin. If the uncertainty in the spectral type of the object places it across one of the spectral type boundaries above, use the more restrictive bin. If the magnetic activity level as judged by Hα is unknown, assume the star is magnetically active.

2. Find the ΔU magnitude of the brightest flare that would occur with a probability of 10^{-4}, compute $U_{\rm flare}$=U$_{\rm quiescent}$+ΔU.

3. Determine global and local count rates for a flare of this magnitude using ETC calculations for the NUV, if applicable. Use a blackbody with T=9000K, normalized to the appropriate U band magnitude for peak flare brightness.

4. Determine global and local count rates for a flare of this magnitude using ETC calculations for the FUV, if applicable.

   - Determine continuum level using a blackbody with T=9000K, normalized to the appropriate U band magnitude for peak flare brightness.
   - Estimate C IV and Si IV line fluxes. First, convert peak flare brightness $U_{\rm flare}$ to flux density f_U at Earth. As a reminder, the magnitude zeropoint for the Johnson U filter is $zpt = -20.94$, so the conversion from U band magnitude to flux density follows from the magnitude equation as

     $$\log f_U = -0.4 * (U_{\rm flare} - zpt) \quad . \tag{6}$$

     Compute integrated line fluxes scaled from peak U band flux f_U using equations 2 and 3. Use a line FWHM of 0.2 Å as input to ETC; line centers are listed in Table 5.
   - Add Lyα flux to ETC calculation. The calculation in the previous step returns f_U, which combined with the blackbody temperature, stellar distance and radius, constrains the flare area X$_{\rm fl}$:

     $$f_U = X_{\rm fl} \left(\frac{R_\star}{d}\right)^2 \pi B_\lambda(9000K) + \left(\frac{R_\star}{d}\right)^2 \pi B_\lambda(T_{\rm eff}) \tag{7}$$

     where $B_\lambda(9000K)$ is the Planck function evaluated at the flare temperature of 9000 K, and $T_{\rm eff}$ is the effective temperature of the star in quiescence. The wavelength at which the Planck function is evaluated should be the effective wavelength for the U band filter, 3650 Å. The second half of the

Table 5.: Wavelengths of Strongest FUV Emission lines

Ion	Wavelength (Å)
H I Lyα	1215.7
C IV	1548.2
Si IV	1393.8

equation comes from the fact that f_U includes the contribution of the quiescent flux. The stellar surface flux $F_{FUV,exc}$ or $F_{NUV,exc}$ in excess above the photospheric flux (where the flare emission is assumed to dominate above any quiescent levels) can then by determined from

$$F_\lambda = X_{\text{fl}} \pi B_\lambda(9000K) \tag{8}$$

where λ is the FUV wavelength range (1350-1750 Å) or the NUV wavelength range (1750-2750 Å) appropriate to the two equations in Shkolnik et ak. (2014). Application of either equation 4 or 5 will yield an estimate of F$_{Ly\alpha}$, which is a surface flux. The Lyman α flux at Earth is then determined through f$_{Ly\alpha}$ $= F_{Ly\alpha} R_\star^2 / d^2$. Use a line FWHM of 0.5 Å for Lyα and line center 1215.7 Å. Compare this flux to that estimated from a ratio of Lyα/C IV in quiescence of $\approx$37, as described above. If the Lyα flux from equations 4 or 5 is lower, then use the higher estimated flux.

6. Comparison With Screening Limits

It has always been the case that proposers need to prove the safety of their observations. The HST Mission Office has decided on a probability threshold of 10^{-4} as an appropriate risk level for shutting down the detector when it comes to bright object protection for flares from M dwarfs. This acknowledges that the frequency of extreme flaring events, which can range up to $\Delta NUV = -7.5$ (Robinson et al. 2005) or even $\Delta V = -11$ (Schmidt et al. 2016), can occur rarely in some types of M dwarfs, and does not result in automatic preclusion of observing M dwarfs in the ultraviolet with HST. This level is set for the target, not based on the duration of the exposures, although that would be a more realistic assessment of the probability of overlight conditions resulting from such an event. Table 6 lists the count rate limits for the photon-counting detectors on STIS at which detector shutdown occurs. These are the flight software limits. Local rate checks are performed at the beginning of an exposure, while global count rate checks occur throughout the exposure. Nevertheless, both quantities are important to estimate as they represent different types of detector exposure and potential damage. Calculations of peak flare brightness must not exceed these limits in order for the target to be cleared.

Table 6.: Count rate limits for detectors at which detector shutdown occurs

Detector	Channel	Mode	FSW global limit (cts s^{-1})	FSW local limit[†] (cts s^{-1} $pixel^{-1}$)
STIS/MAMA	FUV&NUV	1st-order spectroscopy	120,000	136[‡]
STIS/MAMA	FUV&NUV	All other modes	770,000	136[‡]

[†] Local rate check is only done at the beginning of an exposure.

[‡] Local limit is mode and source dependent. Adopted value is lowest reported in Clampin 1996.

If the results of the above ETC calculations return count rates under an extreme event with a 10^{-4} probability of occurring which would result in detector shutdown, then the target is considered unsafe and cannot be observed.

7. Targets Which Fail the BOP Screening

Possible mitigation steps depend partly on the nature of the failure. If a target fails on the acquisition (which would be the situation for COS observations, as STIS uses a CCD for target acquisition), then observers can explore alternate acquisition scenarios,

1. use of the COS Bright Object Aperture (BOA),
2. use of a dispersed light target acquisition through the Primary Science Aperture (PSA),
3. use of an offset pointing image acquisition with the PSA, provided there are reasonably bright stars sufficiently close to allow this (which themselves are safe to observe).

If the target fails on the science exposures with COS, observers have three options:

1. switching off the detector segment on COS which causes the potential overlight condition (as long as the remaining detector segment passes local and global rate checks and can accomplish the stated science goals),
2. switching to a target which passes the above screening with the same COS configuration,
3. or exploring the use of suitable configurations with STIS which may be safe.

If the target fails on the science exposures with STIS, switching to a configuration which provides higher spectral resolution and hence lower throughput may be suitable; the alternate option is to explore different targets.

References

Clampin, M. STIS ISR 96-31
Clampin, M. et al. STIS ISR 95-01
Clampin, M., and Kinney, M. STIS ISR 96-021
Gizis, J. et al. 2002 AJ 123, 3356
Gomez de Castro, A. I. 2002 MNRAS 332, 409
Gudennavar, S. B. 2012 ApJS 199, 8
Hawley, S. L., & Pettersen 1991 ApJ 378, 725
Hawley, S. L. et al. 1996 AJ 112, 2799
Hawley, S. L. et al. 2003 ApJ 597, 535
Hilton, E. 2011 PhD dissertation, U. Washington
Kaltenegger, L, & Traub, W. 2009 ApJ 698, 519
Kowalski, A. et al. 2010 ApJ 714, L98
Leitherer, C. et al. STIS ISR 96-024
Leithere, C. et al. STIS ISR 96-028
Lépine, S. et al. 2013 AJ 145, 102
Linsky, J. L. et al. 2013 ApJ 766, 69
Lurie, J. C. et al. 2015 ApJ 800, 95
Newton, E. et al. 2016 ApJ, in press (https://arxiv.org/abs/1611.03509)
Osten, R. A. et al. 2010 ApJ 721, 785
Osten, R. A. & Wolk, S. J. 2015 ApJ 809, 79
Osten, R. A. 2016, chapter "Stellar Explosive Events Throughout the Age of the Solar System", chapter in Heliophysics: Active Stars, their Astrospheres, and Impacts on Planetary Environments, eds. C. J. Schrijver, F. Bagenal, and J. J. Sojka, Cambridge University Press
Pecault, M. J., & Mamajek, E. E. 2013 ApJS 208, 9
Reid, I. N. et al. 1995 AJ 110, 1838
Reid, I. N. & Hawley, S. L. 2005 New Light on Dark Stars Book
Robinson, R. D. et al. 2005 ApJ 633, 447
Schmidt, S. J. et al. 2016 ApJ 828, L22
Shkolnik, E et al. 2014 ApJ 796, L20
Walborn, N. et al. ACS SIR 2006-05
West, A. A. et al. 2008 AJ 135, 785

Acknowledgements

RAO would like to thank discussions with the COS and STIS team after the release of the memo on which this ISR is based, which clarified several items. Special thanks go to Andrew Fox, John Debes, and Gisella De Rosa. RAO would also like to thank Adam Kowalski of U. of Colorado for reading and providing insights on flare studies.

Appendix

After publication of this ISR, the HST Mission Office (HSTMO) received several comments from the community responding to the COS and STIS ISR revising the Bright Object Protection Policy for M dwarf flare stars. The policy sets up a formalism with a well-measured activity indicator, and uses that to predict the probability of a flare of a particular strength at any future time. The methodology presented in the ISR provides a consistent treatment of rare but extreme events on M dwarfs. If users have additional information specific to the target in question these can be used to supplement the procedure and demonstrate safety. We stress again the need for communication between the PI and her/his Contact Scientist to resolve any issues. It is the PI's responsibility to demonstrate the health and safety of observations using scientifically motivated arguments. If in the end a target cannot be demonstrated to be safe it cannot be observed.

In this appendix we discuss some additional pieces of information that may be used to help in demonstrating safety.

1. **Assumption of negligible Lyman Alpha absorption** Since many targets are nearby, negligible ISM absorption is assumed by default in lieu of information on the target. The amount of absorption can vary dramatically due to line of sight effects (passing through different local interstellar clouds) and object distance. This is not included in ETC calculations. For many nearby stars, estimates can be made using a model of local interstellar clouds or constraints from other wavelengths or targets in close proximity to the line of sight. A survey of line-of-sight absorption towards nearby stars from Gudennavar et al. (2012) reveals a floor of 6×10^{16} cm^{-2} in ISM hydrogen column density; stars within about 30 pc can have a spread of a factor of 100 above this value. Using this value of N(H) reduces the Lyman alpha peak count rate by 70%, and potentially more for larger column densities. If proposers have additional information on the amount of ISM absorption and its estimated impact on peak Lyman alpha emission during the flare estimation, they can and should communicate that to contact scientists and demonstrate whether it alleviates the health and safety concerns.

2. **Use of single line width for flare and non-flare emission lines** The line widths specified for use as input to the ETC in the ISR are 0.5 Å for Lyman alpha and 0.2 Å for C IV and Si IV. These are based on quiescent line widths. There have been very few flare studies that quantify the effect of changing line widths during flares, and none (after a literature review) that indicate how line widths during flares might change with flare size. One of the few studies appears to be that of Gomez de Castro (2002), who reported on UV observations of flares with HST/GHRS from the young rapidly rotating star AB Dor. Flaring line widths with FWHM of 80 km/s were most commonly found in this study (implying 0.3-0.4 Å line width), with one event containing 300 km/s line widths in the profile of C IV (implying 1.2-1.5 Å line widths). These may be more representative of line widths during flaring events, and observers could argue that these are more appropriate for the

extreme flares being considered.

3. **Spectral type bins** The Hilton analysis used six bins of spectral type and activity: early, mid and late M dwarfs, and active/inactive. Some of these bins are more populated than others with stars and flares. In the inactive mid-M dwarfs, the Hilton analysis had only three flares in this bin; those results were supplemented with a Kepler flare frequency distribution from Lurie et al. (2015). Likewise, the active early type bin only has one star (with 3 flares). With the wealth of data coming out of Kepler and K2, it may be possible to supplement the original analysis in the ISR with flare frequency distributions refined to match better the target's parameters.

We also respond to some other comments that arose:

1. **Target sample is biased towards highly active stars** Most targeted flare studies admittedly concentrated on observations of known highly active stars, which have a high flare rate; this is related to the well-known rotation-activity-age correlations for stars. The Hilton study alleviates this by sampling a spread in spectral type and activity level (as measured by Hα equivalent width). There are possible biases due to binarity; other samples, such as those of solar neighborhood single stars, will be biased to be older on average. The dependence of flare rate on stellar parameters is almost certainly more nuanced than this, and future work will hopefully elucidate some of these topics. Improved information on the flare rate for a particular target can always be used to demonstrate safety.

2. **Past observations demonstrate safety** For nonvariable objects, past UV observations can usually be shown to demonstrate detector health and safety. The concern for M dwarfs is the amplitude of a rarely occurring event. The typically short duration of such previous observations means that these prior observations cannot demonstrate safety as the length of time or number of samples is not long enough to encompass one of these stochastically occurring events. Even with prior UV observations with GALEX or HST, visits spanned a few minutes to a maximum of about 30 minutes in duration. The survey nature did not lead to the buildup of long accumulated on source exposure time. Because the peak in the spectral energy distribution for M dwarf flares occurs in the UV-blue optical, longer time span observations at significantly longer wavelengths, like the near IR, miss flare enhancements and are not appropriate for determining flare rate.

3. **Comments on methodology** The use of U band flare statistics was carefully chosen in order to bridge the two requirements of the new policy: an ability to estimate the frequency of occurrence of events, and an ability to estimate the likely increases of line and continuum flux in the UV by scaling with the size of the event. U band flare statistics have the widest coverage observationally, providing a long time baseline over which to gather statistics of flare frequency occurrence

and its dependence on flare size. This has been the standard filter used for flare patrol observations. The flare emissions in the U filter bandpass are dominated by a continuum formed by a hot blackbody, which at a temperature of 10^4K extends into the NUV and FUV bandpasses; this enables better connection with the line and continuum emission in the NUV and FUV. The continuum process is the same, and multi-wavelength flare studies enable scaling between U band flare fluxes and line emission. In order to connect the radiated energies in the U band to the U band peak fluxes, we did employ an upper bound to the ΔU vs. $E_{\rm flare}$ curve from the data in Hilton (2011). This is conservative but encompasses a range of possibilities.