Microflare Heating of a Solar Active Region Observed with \textit{NuSTAR}, \textit{Hinode/XRT}, and \textit{SDO/AIA}

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Abstract

\textit{NuSTAR} is a highly sensitive focusing hard X-ray (HXR) telescope and has observed several small microflares in its initial solar pointings. In this paper, we present the first joint observation of a microflare with \textit{NuSTAR} and \textit{Hinode/XRT} on 2015 April 29 at \textit{~}11:29 UT. This microflare shows the heating of material to several million Kelvin, observed in soft X-rays with \textit{Hinode/XRT}, and was faintly visible in the extreme ultraviolet with \textit{SDO/AIA}. For three of the four \textit{NuSTAR} observations of this region (pre-flare, decay, and post-flare phases), the spectrum is well fitted by a single thermal model of 3.2–3.5 MK, but the spectrum during the impulsive phase shows additional emission up to 10 MK, emission equivalent to the A0.1 \textit{GOES} class. We recover the differential emission measure (DEM) using \textit{SDO/AIA}, \textit{Hinode/XRT}, and \textit{NuSTAR}, giving unprecedented coverage in temperature. We find that the pre-flare DEM peaks at \textit{~}3 MK and falls off sharply by 5 MK; but during the microflare’s impulsive phase, the emission above 3 MK is brighter and extends to 10 MK, giving a heating rate of about \textit{2.5} \textit{\times} 10^{25} \textit{erg s}^{-1}. As the \textit{NuSTAR} spectrum is purely thermal, we determined upper limits on the possible non-thermal bremsstrahlung emission. We find that for the accelerated electrons to be the source of heating, a power-law spectrum of $\delta \geq 7$ with a low-energy cutoff $E_{\text{c}} \leq 7$ keV is required. In summary, this first \textit{NuSTAR} microflare strongly resembles much more powerful flares.

Key words: Sun: activity – Sun: corona – Sun: X-rays, gamma rays

1. Introduction

Solar flares are rapid releases of energy in the corona and are typically characterized by impulsive emission in Hard X-rays (HXRs) followed by brightening in Soft X-rays (SXR) and Extreme Ultraviolet (EUV) indicating that electrons have been accelerated as well as material heated.

Flares are observed to occur over many orders of magnitude, from large X-Class \textit{GOES} (Geostationary Operational Environmental Satellite) flares down to A-class microflares. Observations from \textit{RHESSI} (Reuven Ramaty High Energy Solar Spectroscopic Imager; Lin et al. 2002) have shown that microflares occur exclusively in active regions (ARs), like larger flares, as well as heating material $>10$ MK and accelerating electrons to $>10$ keV (Christe et al. 2008; Hannah et al. 2008, 2011). Although energetically these events are about six orders of magnitude smaller than large flares, it shows that the same physical processes are at work to impulsively release energy. There should be smaller events beyond \textit{RHESSI}’s sensitivity but so far there have either only been limited SXR observations from \textit{SphinX} (Gburak et al. 2011) or indirect evidence of non-thermal emission from \textit{IRIS} observations (e.g., Testa et al. 2014). There are also energetically smaller events observed in thermal EUV/SXR emission that occur outside ARs (Krucker et al. 1997; Aschwanden et al. 2000; Parnell & Jupp 2000).

Smaller flares occur considerably more often than large flares with their frequency distribution behaving as a negative power law (e.g., Hannah et al. 2011). It is not clear how small flare-like events can be, with Parker (1988) suggesting that small-scale reconnection events (“nanoflares”) are on the order of $\sim 10^{24}$ erg. However, at this scale, flares are likely too small to be individually observed, and only the properties of the unresolved ensemble could be determined (Glencross 1975). Nor is it clear whether the flare frequency distribution is steep enough (requiring $\alpha > 2$, Hudson 1991) so that there are enough small events to keep the solar atmosphere consistently heated. It is therefore crucial to probe how small flares can be while still remaining distinct, and how their properties relate to flares and microflares.

With the launch of the \textit{Nuclear Spectroscopic Telescope ARray} (\textit{NuSTAR}; Harrison et al. 2013), HXR (2.5–78 keV) observations of faint, previously undetectable solar sources can be obtained. In comparison to \textit{RHESSI}, \textit{NuSTAR} has over a $10 \times$ larger effective area and a much smaller background counting rate. However, \textit{NuSTAR} was designed for astrophysical observations and is therefore not optimized for observations of the Sun. This leads to various technical challenges (see Grefenstette et al. 2016), but \textit{NuSTAR} is nevertheless a unique instrument for solar observations and has pointed at the Sun several times. \textit{NuSTAR} has observed several faint sources from quiescent ARs (Hannah et al. 2016) and emission from an occulted flare, in the EUV late phase (Kuhar et al. 2017). \textit{NuSTAR} has also observed several small microflares during its solar observations, one showing the time evolution and spectral emission (Glesener et al. 2017).
In this paper, we present NuSTAR imaging spectroscopy of the first microflare jointly observed with Hinode/XRT (Golub et al. 2007; Kosugi et al. 2007) and SDO/AIA (Pesnell et al. 2012; Lemen et al. 2012). This microflare occurred on 2015 April 29 within AR 12333, and showed distinctive loop heating visible with NuSTAR, Hinode/XRT, and the hottest EUV channels of SDO/AIA up to 10 MK. We present an overview of the SDO/AIA and Hinode/XRT observations in Section 2, followed by NuSTAR data analysis in Section 3. In Section 4, we concentrate on the impulsive phase of the microflare and perform differential emission measure (DEM) analysis. Finally, in Section 5, we look at the microflare energetics in terms of thermal and non-thermal emission.

2. SDO/AIA and Hinode/XRT Event Overview

The microflare from AR 12333 occurred during a time when there were two brighter ARs on the disk, as can be seen in Figure 1. Both of these ARs, on either limb, were producing microflares that dominate the overall GOES 1–8 Å SXR light curve (Figure 1, right panels). GOES is spatially integrated, but the contributions from each region can be determined by using the hotter Fe XVIII component of the SDO/AIA 94 Å images. The Fe XVIII line contribution to the SDO/AIA 94 Å channel peaks at log T = 6.85 K (∼7 MK) and can be recovered using a combination of the SDO/AIA channels (Reale et al. 2011; Testa & Reale 2012; Warren et al. 2012; Del Zanna 2013). Here we use the approach of Del Zanna (2013),

\[ F(\text{Fe XVIII}) \approx \frac{F(94 \, \text{Å})}{100} - \frac{F(211 \, \text{Å})}{200} - \frac{F(171 \, \text{Å})}{450}, \]

where \( F(\text{Fe XVIII}) \) is the Fe XVIII flux [DN s⁻¹ px⁻¹] and \( F(94 \, \text{Å}), F(171 \, \text{Å}), \) and \( F(211 \, \text{Å}) \) are the equivalent fluxes in the SDO/AIA 94, 171, and 211 Å channels.

Hinode/XRT observed AR 12333 in a high-cadence mode (∼2–3 minutes), cycling through five different filter channels centered on this region. Full-disk synoptic images were obtained before and after this observation mode (Figure 1). Figure 2 shows the main loops of the region rapidly brightening, indicating that energy is being released to heat these loops. This is apparent in the SXR channels from Hinode/XRT and SDO/AIA 94 Å Fe XVIII, but not in the cooler EUV channels from SDO/AIA, so we conclude that the heating is mostly above 3 MK. For the 95° × 45° loop region shown in Figure 2, we produce the time profile of the microflares in each of these SXR and EUV channels, shown in Figure 3. These light curves have been obtained after processing via the instrument preparation routines, de-rotation of the solar disk (to ∼11:29 UT), and manual alignment of Hinode/XRT Be-Thin to the 1" downsampling SDO/AIA 94 Å Fe XVIII data. Here we again see that the microflare activity is only occurring in the channels sensitive to the hottest material, i.e., the SXR ones from Hinode/XRT and SDO/AIA 94 Å Fe XVIII. This activity is in the form of three distinct peaks, with the first, and largest, impulsively starting at ∼11:29 UT. This is clear in the SXR (with the exception of the low signal-to-noise Hinode/XRT Be-Thick channel) and SDO/AIA 94 Å Fe XVIII light curves, all showing similar time profiles.

3. NuSTAR Data Analysis

NuSTAR is an imaging spectrometer with high sensitivity to X-rays over 2.5–78 keV (Harrison et al. 2013). NuSTAR consists of two identical telescopes, each with the same 12′ × 12′ field of view (Madsen et al. 2015) and is composed of Wolter-I type optics that directly focus X-rays onto the focal-plane modules (FPMA and FPMB) 10 m behind. These focal-plane modules each contain CdZnTe detectors with 64 × 64 pixels providing the time, energy, and location of the incoming X-rays. The readout time per event is 2.5 ms, and NuSTAR accepts a maximum throughput of 400 counts s⁻¹ for each focal-plane module. This makes NuSTAR highly capable of observing weak thermal or non-thermal X-ray sources from the Sun (Grefenstette et al. 2016). However, as it is optimized for astrophysics targets, solar pointings have limitations. In particular, the low detector readout and large effective area produce high detector deadtime even for modest levels of solar activity, restricting the spectral dynamic range, and only detecting X-rays at the lowest energies (Grefenstette et al. 2016; Hannah et al. 2016). NuSTAR solar observations are therefore from times of weak solar activity, ideally when the GOES 1–8 Å flux is below B-level. An overview of the initial
NuSTAR solar pointings, which began in late 2014, and details of these restrictions are available in Grefenstette et al. (2016). An up-to-date quicklook summary is also available online.

The observations reported here are based around the fourth NuSTAR solar pointing, consisting of two orbits of observations covering 2015 April 29 10:50 to 11:50 and 12:27 to 13:27 (Grefenstette et al. 2016). NuSTAR completed a full-disk mosaic observation in each orbit consisting of 17 different pointings: the field of view requires 16 different pointings to cover the whole Sun, with some overlaps between each mosaic tile, followed by an additional disk-center pointing (see Figure 4 Grefenstette et al. 2016). This resulted in NuSTAR observing AR 12333 four times, each lasting for a few minutes. These times are shown in Figure 3. These data were processed using NuSTAR Data Analysis software v1.6.0 and NuSTAR CALDB 20160502\(^8\), which produces an event list for each pointing. We use only single-pixel (“Grade 0”) events (Grefenstette et al. 2016) to minimize the effects of pile-up. Figure 4 shows the resulting NuSTAR 2.5–4.5 keV image for each of the four pointings, and these images are a combination of both FPMA and FPMB with \(\sim 7''\) Gaussian smoothing as the pixel size is less than the full width at half maximum (FWHM) of the optics.

Two of these pointings, the first and last, caught the whole AR, but the other two only caught the lower part as they were observed at the edge of the detector; however, this is the location of the heated loops during the microflares in Figure 2. During some of the observations there was a change in the combination of Camera Head Units (CHUs)—star trackers used to provide pointing information. In those such instances, we used the time range that gave the longest continuous CHU combination instead of the whole duration. Each required a different shift to match the SDO/AIA 94 Å Fe XVIII map at that time, and all were within the expected 1’ offset (Grefenstette et al. 2016). The alignment was straightforward for the NuSTAR maps which caught the whole region but was trickier for those with a partial observation. In those cases (the second and third pointings), emission from another region (slightly to the southwest of AR 12333) were used for the alignment. The resulting overlaps of the aligned Hinode/XRT and NuSTAR images with SDO/AIA 94 Å Fe XVIII are shown in Figure 5. The NuSTAR maps in Figure 4 reveal a similar pattern to the

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\(^8\) http://ianan.github.io/nuish_all/

\(^9\) https://heasarc.gsfc.nasa.gov/docs/NuSTAR/analysis/
heating seen in EUV and SXR with SDO/AIA and Hinode/XRT: emission from the whole region before the microflare, with loops in the bottom right brightening as material is heated during the microflare, before fading as the material cools.

3.1. NuSTAR Spectral Fitting

For each of the NuSTAR pointings, we chose a region at the same location, and of the same area, as those used in the SDO/AIA and Hinode/XRT analysis to produce spectra of the microflare heating. These are circular as the NuSTAR software can only calculate the response files for such regions, but do cover the flaring loop region (rectangular box, Figure 2), and are shown in Figure 4. The spectra and NuSTAR response files were obtained using NuSTAR Data Analysis software v1.6.0. These were then fitted using the XSPEC (Arnaud 1996) software\(^\text{10}\), which simultaneously fits the spectra from each telescope module (FPMA and FPMB) instead of just adding the data sets. We also use XSPEC as it allows us to find the best-fit solution using Cash statistics (Cash 1979), which helps with the non-Gaussian uncertainties we have for the few counts at higher temperatures.

We fitted the spectra with a single thermal model, using the APEC model with solar coronal abundances (Feldman et al. 1992), and the fit results are shown in Figure 6. For the first and fourth NuSTAR pointings, before and after the microflares, the spectra are well fitted by this single thermal model showing similar temperatures and emission measures (3.3 MK and \(6.3 \times 10^{46} \text{ cm}^{-3}\), then 3.2 MK and \(7.0 \times 10^{46} \text{ cm}^{-3}\). Above 5 keV, there are very few counts, and this is due to a combination of the low livetime of the observations (164 and 152 s dwell time with about 2% livetime fraction resulting in effective exposures of around 3.5 s) and the high likelihood that the emission from this region peaked at this temperature before falling off very sharply at higher temperatures. These temperatures are similar to the quiescent ARs previously studied by NuSTAR (Hannah et al. 2016), although those regions were brighter and more numerous in the field of view, resulting in an order-of-magnitude worse livetime. The low livetime has the effect of limiting the spectral dynamic range, putting most of the detected counts at the lower energy range and no background or source counts at higher energies (Grefenstette et al. 2016; Hannah et al. 2016).

The two NuSTAR spectra from during the microflare, the second (impulsive phase) and third (decay phase, weaker peak), both show counts above 5 keV and produce higher temperature fits (5.1 MK and 3.5 MK). This is expected as there should be heating during the microflare, but neither fit matches the observed spectrum well, particularly during the impulsive phase. This shows that there is additional hot material during these times that a single-component thermal model cannot accurately characterize. For the spectrum during the impulsive phase, the second NuSTAR pointing, we tried adding additional thermal components to the fit, as shown in Figure 7. We started by adding in a second thermal component fixed with the parameters from the pre-microflare spectrum, found from the first NuSTAR pointing (left spectrum in Figure 6), to represent the background emission. We did this as NuSTAR’s pointing changed during these two times (changing the part of the detector observing the region, and hence the instrumental response) so we could not simply subtract the data from this pre-flare background time. The other thermal model component was allowed to vary and produced a slightly better fit to the higher energies and a higher temperature (5.6 MK). However, this model still misses counts at higher energies.

So, we tried another fit where the two thermal models were both allowed to vary and this is shown in the right panel of Figure 7. Here, there is a substantially better fit to the data over the whole energy range, fitting a model of 4.1 MK and 10.0 MK. The hotter model does seem to match the bump in emission between 6 and 7 keV, which at these temperatures would be due to line emission from the Fe K-shell transition (Phillips 2004). Although this model better matches the data, it produces substantial uncertainties, particularly in the emission measure. This is because it is fitting the few counts at higher energies which have a poor signal-to-noise ratio. It should be noted that for the thermal model, the temperature and emission measure are correlated and so the upper uncertainty on the

\(^{10}\) https://heasarc.gsfc.nasa.gov/xanadu/xspec/
temperature relates to the lower uncertainty on the emission measure, and vice versa. Therefore, this uncertainty range covers a narrow diagonal region of parameter space, which we include later in Figure 11. These fits do however seem to indicate that emission from material up to 10 MK is present in this microflare and that the NuSTAR spectrum in this case is observing purely thermal emission. A non-thermal component could still be present, but the likely weak emission, combined with NuSTAR’s low livetime (limiting the spectral dynamic range), leaves this component hidden. Upper limits to this possible non-thermal emission are calculated in Section 5.2.

From these spectral fits, we estimated the GOES 1–8 Å flux\(^{11}\) to be $5.3 \times 10^{-9}$ W m\(^{-2}\) for the impulsive phase and $4.0 \times 10^{-9}$ W m\(^{-2}\) for the pre-flare time. This means that the background-subtracted GOES class for the impulsive phase is

\(^{11}\text{https://hesperia.gsfc.nasa.gov/ssw/gen/idl/synoptic/goes/goes_flux49.pro}\)
equivalent to \(\sim A0.1\) and would be slightly larger during the subsequent peak emission time.

4. Multi-thermal Microflare Emission

The NuSTAR spectrum during the impulsive phase of the microflare clearly shows that there is a range of heated material, so to get a comprehensive view of this multi-thermal emission, we recovered the DEM by combining the observations from NuSTAR, Hinode/XRT, and SDO/AIA. This is the first time these instruments have been used together to obtain a DEM.

4.1. Comparison of NuSTAR, Hinode/XRT, and SDO/AIA

To check the compatibility of the NuSTAR, Hinode/XRT, and SDO/AIA observations, we compared the observed fluxes from Hinode/XRT and SDO/AIA to synthetic fluxes obtained from the NuSTAR thermal fits. For the NuSTAR two-thermal fit (Figure 7, right panel), we multiplied the emission measures by the SDO/AIA and Hinode/XRT temperature response functions at the corresponding temperatures and then added the two fluxes together to get a value for each filter channel.

The Hinode/XRT temperature response functions were created using xrt_flux.pro with a CHIANTI 7.1.3 (Dere et al. 1997; Landi et al. 2013) spectrum (xrt_flux713.pro) with coronal abundances (Feldman et al. 1992) and the latest filter calibrations that account for the time-dependent contamination layer present on the CCD (Narukage et al. 2014). The SDO/AIA temperature response functions are version 6 (v6; using CHIANTI 7.1.3) and obtained using aia_get_response.pro with the “chiantifix,” “eve_norm,” and “timedepend_date” flags. The comparison of the observed and synthetic fluxes is shown in Figure 8.

We found that the SDO/AIA 94 Å Fe XVIII synthetic flux is near the observed value, as expected; however, there is a consistent discrepancy for Hinode/XRT. The observed fluxes should match the synthetic fluxes from the NuSTAR spectral fits as they are sensitive to the same temperature range. Other authors have found similar discrepancies (Testa et al. 2011; Cheung et al. 2015; Schmelz et al. 2015), and there is the suggestion that the Hinode/XRT temperature response functions are too small by a factor of 2–3 (see Schmelz et al. 2015). We have therefore multiplied the Hinode/XRT temperature response functions by a factor of two (Figure 8, top right) and find a closer match to the synthetic values derived from the NuSTAR spectral fits. The main effect of these larger temperature response functions is that it requires there to be weaker emission at higher temperatures to obtain the same Hinode/XRT flux.

4.2. Differential Emission Measure

Recovering the line-of-sight DEM, \(\xi(T_j)\), involves solving the ill-posed inverse problem, 

\[ g_i = K_{ij} \xi(T_j) \]

where \(g_i\) is the observable and \(K_{ij}\) is the temperature response function for the \(i\)th filter channel and the \(j\)th temperature bin. Numerous algorithms have been developed for the DEM reconstruction, and we use two methods to recover the DEM: Regularized Inversion\(^{13}\) (RI; Hannah & Kontar 2012) and the xrt_dem_iterative2.pro method\(^{14}\) (XIT; Golub et al. 2004; Weber et al. 2004).

The regularized inversion (RI) approach recovers the DEM by limiting the amplification of uncertainties using linear constraints. Uncertainties on the DEM are also found on both the DEM and temperature resolution (horizontal uncertainties);
see Hannah & Kontar (2012). XIT is a forward-fitting iterative least-squares approach, using a spline model. Uncertainties in the final DEM are calculated with Monte Carlo (MC) iterations with input data perturbed by an amount randomly drawn from a Gaussian distribution with the standard deviation equal to the uncertainty in the observation. The resulting spread of these MC iterations indicates the goodness of fit.

For the DEM analysis, we calculated the uncertainties on the Hinode/XRT and SDO/AIA data. The non-statistical photometric uncertainties for Hinode/XRT were calculated from xrt_prep.pro (Kobelski et al. 2014), and photon statistics were calculated from xrt_cvfact.pro15 (Narukage et al. 2011, 2014). The uncertainties on the SDO/AIA data were computed with aia_bp_estimate_error.pro (Boerner et al. 2012), and an additional 5% systematic uncertainty was added in quadrature to both the Hinode/XRT and SDO/AIA data to account for uncertainties in the temperature response functions. The Hinode/XRT and SDO/AIA data and uncertainties have been interpolated to a common time step and averaged over the NuSTAR observational duration. The uncertainty for the NuSTAR values in specific energy bands was determined as a combination of the photon shot noise and a systematic factor (of 5%) to account for the cross-calibration between NuSTAR’s two telescope modules (FPMA and FPMB). The NuSTAR temperature response functions for each energy range and telescope module (shown in Figure 8) were calculated using the instrumental response matrix for the regions shown in Figure 4.

The resulting DEMs obtained for the impulsive phase are shown in Figure 9 (left) with the quality of the recovered DEM solution shown as residuals between the input and recovered fluxes (right). XIT is used with the addition of 300 MC iterations where outlier XIT MC solutions have been omitted. We have used all available filters with the exception of Hinode/XRT Be-Thick due to large uncertainties that are the result of a lack of counts (Figure 3) and SDO/AIA 335 Å due to the observed long-term drop in sensitivity (see Figure 1 in Boerner et al. 2014). The standard Hinode/XRT responses (Figure 9, top) lead to disagreement between the two methods for DEM recovery, notably at the peak and at higher temperatures ($\chi^2_{\text{HIT}} = 2.77$, $\chi^2_{\text{RI}} = 1.01$). Using the Hinode/XRT responses multiplied by a factor of two results in the methods having much better

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15 Updated from CHIANTI 6.0.1 to CHIANTI 7.1.3 as part of this work.
agreement ($\chi^2_{\text{XIT}} = 1.02$, $\chi^2_{\text{RI}} = 1.00$), and the DEM solutions result in smaller residuals, specifically in the Hinode/XRT filters. These final DEMs (Figure 9, bottom) show a peak at $\sim 3$ MK and little material above 10 MK.

To understand how much of this material has been heated out of the background during the microflare, we performed DEM analysis for the pre-flare NuSTAR time ($\sim 11:10$ UT). There is no Hinode/XRT data for this time so we determined the DEM using NuSTAR and SDO/AIA data. The DEMs for the pre-flare observations are shown in Figure 10. These DEMs for each method peak at a similar temperature ($\sim 3$ MK) and fall off very sharply to $\sim 5$ MK. During the microflare, there is a clear addition of material up to 10 MK (Figure 10, bottom).

We also represent the DEMs as the emission measure distributions (EMDs; $\xi(T)\,dT$), which allows us to compare the DEM results to the NuSTAR spectral fits, shown in Figure 11. Here we have also overplotted the EM loci curves, $\text{EM}_i = g_i/K_i$, which are the upper limits of the emission based on an isothermal model, with the true solution lying below all of the EM loci curves. The NuSTAR thermal model fits are the isothermal (in the pre-flare phase) or two-thermal (impulsive phase) fits to the multi-thermal plasma distribution, and so represent an approximation of the temperature distribution and emission measure. These models produce the expected higher emission measure values compared to the EMD and are consistent with the EM loci curves.

5. Microflare Energetics

5.1. Thermal Energy

For an isothermal plasma at a temperature $T$ and emission measure EM, the thermal energy is calculated as

$$U_T = 3k_B T \sqrt{\text{EM}/V} \ [\text{erg}],$$

where $k_B$ is the Boltzmann constant, $f$ the filling factor, and $V$ the plasma volume (e.g., Hannah et al. 2008). Using the two-thermal fit (Figure 7, right), we calculated the thermal energy during the impulsive phase, finding $U_T = 0.9 \times 10^{28}$ erg ($t_f = 116$ s). Here, the equivalent loop volume, $V_L = fV$, was calculated as a volume of a cylinder enclosing only the flaring loop with length $L \sim 50''$ and diameter $d \sim 6''$. This thermal energy includes both the microflare and background emission. We found the pre-flare energy (using fit parameters;
Figure 6, left) as $U_{T_0} = 0.9 \times 10^{28}$ erg (and $t_0 = 164$ s). The resulting heating power during the microflare from the thermal fits to the NuSTAR spectra is then $P_{T_0} = U_{T_0}/t_0 - U_{T_0}/t_0 = 2.5 \times 10^{25}$ erg s$^{-1}$.

The thermal energy can also be estimated for a multi-thermal plasma using

$$U_T = \frac{3k_B V_E^{1/2}}{\sqrt{\int T_{\xi_0}(T) dT}} \int T_{\xi_0}(T) dT \quad \text{[erg]}$$

(3)

as described in Inglis & Christe (2014), with the filling factor, $f = 1$, and $T_{\xi_0}(T) = n^2 dV/dT$ in units of cm$^{-3}$ K$^{-1}$. For the RI and XIT DEM solutions, we find values of $U_{T_0} = 1.1 \times 10^{28}$ erg and $U_{T_{XIT}} = 1.2 \times 10^{28}$ erg during the impulsive phase of the microflare. For the pre-flare thermal energies, we find $U_{T_0} = 1.2 \times 10^{28}$ erg, and $U_{T_{XIT}} = 1.2 \times 10^{28}$ erg, and this then gives values of the heating power during the impulsive phase of the microflare as $P_{T_0} = 2.3 \times 10^{25}$ erg s$^{-1}$ and $P_{T_{XIT}} = 3.0 \times 10^{25}$ erg s$^{-1}$. All of these approaches give a similar value for the heating, about $2.5 \times 10^{25}$ erg s$^{-1}$, over the microflare’s impulsive period, and a summary of these values with uncertainties are given in Table 1. It should be noted that these values are lower limits as the estimates ignore losses during heating.

From the analysis of 25,705 RHESSI events (Table 1 in Hannah et al. 2008), microflare thermal energies were found to range from $U_T = 10^{26-30}$ erg (5%–95% range; from a 16 s observation). This is equivalent to $P_T = 6.3 \times 10^{24-28}$ erg s$^{-1}$, and therefore the thermal power from our NuSTAR microflare is in the lower range of RHESSI observations. This is as expected as NuSTAR should be able to observe well beyond RHESSI’s sensitivity limit to small microflares.

5.2. NuSTAR Non-thermal Limits

As the NuSTAR spectrum in Figure 7 is well fitted by a purely thermal model, we can therefore find the upper limits of the possible non-thermal emission. This approach allows us to determine whether the accelerated electrons could power the observed heating in this microflare. We used the thick-target model of a power-law electron distribution above a low-energy cutoff $E_c$ [keV] given by

$$F(E > E_c) \propto E^{-\delta},$$

(4)
where $\delta$ is the power-law index, and the power in this non-thermal distribution is given by

$$P_N(>E_c) = 1.6 \times 10^{-9} \frac{\delta - 1}{\delta - 2} N_N E_c \text{ [erg s$^{-1}$]},$$

(5)

where $N_N$ is the non-thermal electron flux [electrons s$^{-1}$].

We determined the upper limits on $N_N$ and $P_N$ for a set of $\delta$ ($\delta = 5, 7, 9$) and $E_c$ consistent with a null detection in the NuSTAR spectrum. We performed this by iteratively reducing the model electron flux $N_N$ until there were fewer than four counts $>7$ keV, consistent with a null detection to $2\sigma$ (Gehrels 1986). We also ensured that the number of counts $\leq 7$ keV are within the counting statistics of the observed counts. For each iteration, we generated the X-ray spectrum for the two-component fitted thermal model (Figure 7, right) and added to this the non-thermal X-ray spectrum for our chosen $\delta$, $E_c$, and $N_N$, calculated using f_thick2.pro$^{16}$ (see Holman et al. 2011). This was then folded through the NuSTAR response to generate a synthetic spectrum (as discussed in Hannah et al. 2016). The upper limits are shown in Figure 12 along with the three estimates of the thermal power for the background-subtracted flare, $P_{N}$ (“NuSTAR Fit,” black), $P_{flu}$ (pink), and $P_{rady}$ (blue). For a flatter spectrum of $\delta = 5$, barely any of the upper limits are consistent with the required heating power. With a steeper spectrum, $\delta \geq 7$, a cutoff of $E_c \lesssim 7$ keV is consistent with the heating requirement. These steep spectra indicate that the bulk of the non-thermal emission would need to be at energies close to the low-energy cutoff to be consistent with the observed NuSTAR spectrum. If we instead consider some of the counts in the 6–7 keV range to be non-thermal (e.g., the excess above the thermal model in the left panel in Figure 7), then we would obtain a higher non-thermal power, about a factor of 0.5 larger. However, this would only substantially affect the steep non-thermal spectra ($\delta \geq 7$) as flatter models would be inconsistent with the data below 7 keV.

We can again compare the microflare studied here to the non-thermal energetics derived from RHESSI microflare statistics. Hannah et al. (2008) report non-thermal parameters of $\delta = 4–10$ and $E_c = 9–16$ keV, and non-thermal power ranges from $P_N(\geq E_c) = 10^{25–28}$ erg s$^{-1}$. The largest upper limits that NuSTAR produces for this microflare are again at the edge of RHESSI’s sensitivity. In a previous study of nanoflare heating, Testa et al. (2014) investigated the evolution of chromospheric and transition region plasma from IRIS observations using RADYN nanoflare simulations. This is one of the few non-thermal nanoflare studies, and they reported that heating occurred on timescales of $\lesssim 30$ s, characterized by a total energy $\lesssim 10^{25}$ erg and $E_c \sim 10$ keV. The simulated electron beam parameters in this IRIS event are consistent with the NuSTAR-derived parameters, but in a range insufficient to power the heating in our microflare.

### Table 1

Summary of Thermal Energies of AR 12333

| Method | $U_{th}^{a}$ $[\times 10^{-28}$ erg] | $U_{th}^{b}$ $[\times 10^{-28}$ erg] | $P_{N}^{f}$ $[\times 10^{-7}$ erg s$^{-1}$] |
|-------|----------------------------------|----------------------------------|----------------------------------|
| NuSTAR fit | 0.9$^{+0.1}_{-0.1}$ | 0.9$^{+0.5}_{-0.1}$ | 2.5$^{+0.4}_{-1.6}$ |
| RI     | 1.2$^{+0.1}_{-0.1}$ | 1.1$^{+0.1}_{-0.1}$ | 2.3$^{+0.9}_{-1.0}$ |
| XIT    | 1.2$^{+0.1}_{-0.1}$ | 1.2$^{+0.1}_{-0.1}$ | 3.0$^{+0.5}_{-0.5}$ |

Notes. The uncertainties on the energies and power derived from the NuSTAR fit are $2.7\sigma$ (90% confidence), and those from RI/XIT are $1\sigma$.

$^{a}$ 164 s observation.

$^{b}$ 116 s observation.

$^{16}$ https://hesperia.gsfc.nasa.gov/ssw/packages/xray/idl/f_thick2.pro

### 6. Discussion and Conclusions

In this paper, we have presented the first joint observations of a microflaring AR with NuSTAR, Hinode/XRT, and SDO/AIA. During the impulsive start, the NuSTAR spectrum shows emission up to 10 MK, indicating that even in this $\sim$A0.1 microflare, substantial heating can occur. This high-temperature emission is confirmed when we recover DEMs using the NuSTAR, Hinode/ XRT, and SDO/AIA data. These instruments crucially overlap in temperature sensitivity, with NuSTAR able to constrain and
characterize the high-temperature emission, which is often difficult for other instruments to do alone.

In this event, we find that the Hinode/XRT temperature response functions are a factor of two too small, suggesting that it would normally overestimate the contribution from high-temperature plasma in this microflare.

Overall, we find the instantaneous thermal energy during the microflare to be \( \sim 10^{28} \text{erg} \); once the pre-flare has been subtracted this equates to a heating rate of \( \sim 2.5 \times 10^{25} \text{erg s}^{-1} \) during the impulsive phase of this microflare. This is comparable to some of the smallest events observed with RHESSI, although RHESSI did not see this microflare as its indirect imaging was dominated by the brighter ARs elsewhere on the disk.

Although no non-thermal emission was detected, we can place upper limits on the possible non-thermal component. We find that we would need a steep (\( \delta \geq 7 \)) power law down to at least 7 keV to be able to power the heating in this microflare. This is still consistent with this small microflare being physically similar to large microflares and flares, but this would only be confirmed if NuSTAR detected non-thermal emission. To achieve this, future NuSTAR observations need to be made with a higher effective exposure time. For impulsive flares, this cannot be achieved with longer duration observations, only with higher livetimes. Observing the Sun when there are weaker or fewer ARs on the disk would easily achieve this livetime increase, conditions that have occurred since this observation and will continue through solar minimum.

These observations would greatly benefit from new, more sensitive, solar X-ray telescopes such as the FOXSI (Krucker et al. 2014) and MaGIXS (Kobayashi et al. 2011) sounding rockets, as well as the MinXSS CubeSats (Mason et al. 2016). New data combined with NuSTAR observations during quieter periods of solar activity should provide detection of the high-temperature and possible non-thermal emission in even smaller microflares, which should, in turn, provide a robust measure of their contribution to heating coronal loops in ARs.

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Facilities: NuSTAR, Hinode (XRT), SDO (AIA), GOES.

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