

Nonthermal Hard X-ray Emission and Iron $K\alpha$ Emission from a Superflare on II Pegasi

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ABSTRACT

We report on an X-ray flare detected on the active binary system II Pegasi with the Swift telescope. The event triggered the Burst Alert Telescope in the hard X-ray band on December 16, 2005 at 11:21:52 UT with a 10–200 keV luminosity of 2.2×10^{32} erg s⁻¹ — a superflare, by comparison with energies of typical stellar flares on active binary systems. The trigger spectrum indicates a hot thermal plasma with $T \sim 180 \times 10^6$ K. X-ray spectral analysis from 0.8–200 keV with the X-Ray Telescope and BAT in the next two orbits reveals evidence for a thermal component ($T > 80 \times 10^6$ K) and Fe K 6.4 keV emission. A tail of emission out to 200 keV can be fit with either an extremely high temperature thermal plasma ($T \sim 3 \times 10^8$ K) or power-law emission. Based on analogies with solar flares, we attribute the excess continuum emission to nonthermal thick-target bremsstrahlung emission from a population of accelerated electrons. We estimate the radiated energy from 0.01–200 keV to be $\sim 6 \times 10^{36}$ erg, the total radiated energy over all wavelengths $\sim 10^{38}$ erg, the energy in nonthermal electrons

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above 20 keV $\sim 3 \times 10^{40}$ erg, and conducted energy $< 5 \times 10^{43}$ erg. The nonthermal interpretation gives a reasonable value for the total energy in electrons > 20 keV when compared to the upper and lower bounds on the thermal energy content of the flare. This marks the first occasion in which evidence exists for nonthermal hard X-ray emission from a stellar flare. We investigate the emission mechanism responsible for producing the 6.4 keV feature, and find that collisional ionization from nonthermal electrons appears to be more plausible than the photoionization mechanism usually invoked on the Sun and pre-main sequence stars.

Subject headings: stars: activity — stars: coronae — stars: flare — stars: late-type — stars: flare — stars: individual (II Peg) — X-rays: stars

1. Introduction

The general model for solar (and stellar) flares involves a release of free energy via magnetic reconnection, which accelerates particles and causes subsequent plasma motions and heating (Dennis & Schwartz 1989). Particle acceleration during solar flares can be diagnosed directly through nonthermal hard X-ray bremsstrahlung emission and radio gyrosynchrotron emission. Until now, evidence for particle acceleration during stellar flares has been either indirect (through proxies such as optical and UV flare emissions; Hawley et al. 1995, 2003) or achieved through the detection of nonthermal radio flare emissions (Klein & Chiuderi-Drago 1987), under the assumption that the observed radiation is gyrosynchrotron emission from accelerated particles. The interpretation of radio observations, while useful for constraining the characteristic magnetic field in the source, is complicated by optical depth effects and spatial inhomogeneities in the emitting source, which are usually not uniquely determined. Previous detections of hard X-ray emission from stellar flares could not demonstrate unequivocally the presence of nonthermal emission; instead, a superhot thermal component could equally well explain the observed 10–50 keV emission (Favata & Schmitt 1999; Pallavicini 2001; Franciosini et al. 2001) without the need for any additional power-law components. The detection and characterization of nonthermal hard X-ray emission during stellar flares would be important, as it would allow a direct investigation of the energy spectrum of accelerated electrons, and a comparison of the total thermal/nonthermal energy budget. Prospects for detecting such emissions have normally been taken to be remote, as during solar flares the nonthermal hard X-ray emission (20 keV– 1 MeV) is $> 10^{-5}$ times less intense than soft X-ray (1–10 keV) emission (see, e.g., the composite solar flare spectrum in Fig. 94 of Aschwanden 2002); this is a consequence of collisional energy losses exceeding bremsstrahlung losses by a factor of 10^5 . This necessitates large flare sizes for hard X-ray detections, which

are intrinsically rare, which coupled with a dearth of pointed observations exacerbates the situation.

Iron K fluorescence emission has been seen during solar flares (Parmar et al. 1984; Zarro et al. 1992) and also seen in impulsive flares from some pre-main sequence stars (Tsujiimoto et al. 2005). The origin on the Sun is attributed to photoexcitation of K shell electrons in photospheric iron by X-ray bremsstrahlung radiation. The emission mechanism for pre-main sequence stars is the same as for the Sun, but the fluorescence is presumed to arise instead from X-ray irradiation of an accretion disk rather than the stellar photosphere. There have not been any previous reports of iron $K\alpha$ fluorescent emission from non-accreting stellar flare sources. Such an identification would provide another link between solar flare physics and the physics of flares on other stars.

II Peg (HD 224085) is a well-known active binary system which displays evidence for starspots covering a large fraction ($>40\%$; Marino et al. 1999) of the primary’s photosphere, and has signatures associated with vigorous magnetic activity across the entire electromagnetic spectrum. At a distance of 42 pc (Perryman et al. 1997), this single-lined spectroscopic binary is composed of a $0.8 M_{\odot}$ K2IV primary tidally locked in a 6.7 day orbit with a $\sim 0.4 M_{\odot}$ secondary (Berdyugina et al. 1998). Space velocities indicate that this binary is a member of the old disk stellar population (Eggen 1978). Both photospheric and coronal metal abundances have been determined, leading to an apparent depletion of coronal iron by about a factor of 4 relative to the photospheric value (Huenemoerder et al. 2001, and references therein)¹. Based on the stellar parameters for II Peg in Berdyugina et al. (1998) and using the bolometric corrections in Flower (1996), we estimate the bolometric luminosity, the power emitted by the two stars over all wavelengths, to be $L_{\text{bol}} \approx 5.5 \times 10^{33} \text{ erg s}^{-1}$.

II Peg was first detected as a flaring X-ray source by the *Ariel-V* Sky Survey Instrument (1.5-20 keV) in the mid-1970s (Schwartz et al. 1981) which detected 2 flares with peak fluxes of 1.1×10^{-9} and $1.5 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 2-10 keV band, equivalent to peak X-ray luminosities of 1.6×10^{32} and $2.8 \times 10^{32} \text{ erg s}^{-1}$. Since then, moderate and large flares from II Peg have been detected by many subsequent X-ray and EUV observatories, including *Ginga* (Doyle et al. 1991), *EXOSAT* (Tagliaferri et al. 1991), *EUVE* (Patterer et al. 1993; Osten & Brown 1999), *ASCA* (Mewe et al. 1997), *BeppoSAX* (Covino et al. 2000), and *Chandra* (Huenemoerder et al. 2001).

In this paper, we report on a large flare observed on II Peg by the detectors on the

¹This is in contrast with the solar corona, where the coronal iron abundance appears to be *enhanced* by a factor of ~ 4 over the solar photospheric abundance (Feldman & Laming 2000). For more discussion on stellar coronal abundances, see Güdel (2004).

Swift Gamma-Ray Burst Mission (Gehrels et al. 2004). Following the discussion in Schaefer et al. (2000) and the characteristics of the flare (radiated energy, luminosity) we term this event a “superflare”. The event triggered Swift’s Burst Alert Telescope (BAT) in the hard X-ray band on December 16, 2005 at 11:21:52 UT², and its characteristics in the soft and hard X-ray bands were determined for the extent of time for which hard X-ray emission was detected, ≈ 7000 s. The UV/Optical Telescope did turn on during the trigger, but the images were saturated due to II Peg’s brightness ($V \approx 7.4$), and the data were of little use. In this paper we concentrate on analysis of the X-ray Telescope (XRT) and BAT spectra.

2. Data Reduction

2.1. BAT Data Reduction

BAT is a coded-mask instrument with a very large (~ 1.2 sr) field of view. The construction and operation of the instrument is discussed in Barthelmy et al. (2005). An overview may be found at: http://swift.gsfc.nasa.gov/docs/swift/about_swift/bat_desc.html. All Swift data are made public as soon as possible, and the raw BAT data are available by navigating from the above site.

The BAT data used in this analysis are “survey” data, intended for the BAT all-sky hard X-ray survey. It consists of accumulated counts, in time bins from 60 to 300 seconds, for each of the 32k CZT detector elements, in 80 energy bins nominally from 10 to 194 keV plus high and low integral energy bins. The survey data are supplemented during an interval around the BAT trigger time, including during the Swift slew maneuver, by “event” data, which contain higher resolution time and energy data on each photon count in the detector array.

We used BAT pipeline software within FTOOLS³ version 6.0.3 to correct the energy from the efficient but slightly non-linear energy assignment made on board. For the spectral data reported here, we used *batbinevt* to produce mask-weighted spectra in several broad time intervals. For the light curve data we created sky images in two broad energy bins for each time interval using *batbinevt* and *batfftimage*, and found the flux at the source position using *batcelldetect*, after removing a fit to the diffuse background and the contribution of

²<http://gcn.gsfc.nasa.gov/gcn/gcn3/4357.gcn3>

³The FTOOLS software package provides mission-specific data analysis procedures; a full description of the procedures mentioned here can be found at <http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/>; the names of individual procedures referred to in this and the following section are italicized.

bright sources in the field of view.

As seen in Figure 1, the spectral data are reported in 3 intervals relative to the BAT trigger time of 11:21:52 UT: “Trigger”, T-760 to T+126 sec; “Orbit 1”, T+126 to T+1661 sec; and “Orbit 2”, T+4810 to T+7451 sec. There was no significant flux in the BAT energy range during Orbit 3. To increase the signal-to-noise ratio at energies above 38 keV, the BAT spectra were grouped by 3 bins.

2.2. XRT Data Reduction

For a technical description of XRT and its operations, we refer the reader to Burrows et al. (2005). XRT started observing at 11:24:16 UT, that is, 144 s after the BAT trigger. XRT observed IIPeg in three different snapshots in three following orbits. The first snapshot (“Orbit 1”) lasted 1518 s. The second snapshot (“Orbit 2”) started at 12:43:28 and lasted 2545 s. The last snapshot (“Orbit 3”) began at 14:24:16 UT and lasted 535 s. To produce the cleaned and calibrated event files, the data were reduced by means of the *xrtpipeline* task and calibration files of the CALDB 20051221 release⁴. Since the source count rate was over 60 counts per second during the entire observation all data were collected in windowed timing (WT) mode. In order to extract the spectrum and light curve, events were selected with grade 0–2⁵ from a 20 pixel (47”) box corresponding to 80% of the encircled energy fraction (EEF) at 1.5 keV. We restricted our analysis to the energy band 0.8-10 keV, ignoring lower energy channels. In fact, the effective area calibration files (ancillary response functions, or ARFs) included in the CALDB 20051221 release were still preliminary and present systematics in the energy range 0.2-0.8 keV, which are noticeable in this high intensity event. Background extraction regions were chosen to be the same shape as the source extraction region, at approximately 50 pixels from the center of the source. The mean count rate in the source region in the three orbits was 161, 118, and 79 counts per second respectively, whereas the background count rate never exceeded 0.5 counts per second. In order to study the spectral variations of the Fe K line (see below), we split the first orbit in three segments (144–650, 650–1156, 1156–1662 s from the trigger), and the second in two (4902–6174, 6174–7447 s from the trigger). The light curve was produced using the standard task *lcurve* and with a temporal bin of 30 sec. The spectra were grouped with the task *grppha* in order to have

⁴A description and history of calibration files for Swift can be found at <http://swift.gsfc.nasa.gov/docs/heasarc/caldb/swift/>

⁵See discussion in §2.3 of http://swift.gsfc.nasa.gov/docs/swift/analysis/xrt.swguide_v1.2.pdf for classification of events and grades.

20 counts as a minimum for each energy bin. The ancillary response function was produced by means of the *xrtmkarf* taking into account the point-spread function correction (Moretti et al. 2005).

3. Spectral Analysis

Figure 1 shows the 0.8–10 keV XRT light curve and BAT light curves in two energy bands. It is evident that the harder X-ray energies have progressively earlier peaks: at 0.8–10 keV, the light curve peaks ~ 1480 s following the BAT trigger, while, for the 14–40 keV band, the peak is ~ 840 s post trigger, and for the 40–100 keV band, the maximum count rate occurs only ~ 480 s after the trigger. This points to the hardest X-ray photons having a more impulsive behavior than the soft X-ray photons. To examine the origin and evolution of these hard X-rays, we examined spectra corresponding to four different time intervals: the trigger spectrum and data collected in spacecraft orbits 1, 2 and 3. Spectral fitting was performed using XSPEC (v12.0)⁶. To describe the line and continuum emission from a thermal, diffuse, collisionally ionized plasma, we used a customized version of the APEC model (Smith et al. 2001)⁷ which has continuum emission calculated out to photon energies of 100 keV. Spectral fitting proceeds via a forward method, computing model spectra with varying input parameters, convolving these with the instrument resolution and sensitivity and comparing them with observed spectra until suitable statistical convergence is achieved. We allow elemental metal abundances to vary in fitting each XRT spectrum, but because of the low spectral resolution in the soft X-ray region, the abundances are scaled to a common multiple A of the solar abundance (e.g. for a best-fit scaled abundance $A = 0.5$, the Fe/H is $2 \times \text{Fe}/\text{H}_{\text{solar}}$, and the Mg/H is also $2 \times \text{Mg}/\text{H}_{\text{solar}}$). We use the solar photospheric composition of Grevesse & Sauval (1998) in our spectral fitting; all fitted abundances quoted in this paper are with respect to these values. In particular, the Fe/H ratio in Grevesse & Sauval (1998) is 3.16×10^{-5} .

There are deviations of the model from the data at low energies; the most prominent of these is a feature near 1.09 keV which appears in all XRT spectra. The residual near 1.09 keV looks very similar, both in amplitude and shape, to those of the Crab spectrum used to calibrate the XRT. This feature is most likely an instrumental effect similar to other features observed in the (excluded) energy range below 0.8 keV. There are other large residuals around

⁶XSPEC, an X-ray spectral fitting package, is part of the Xanadu software package, which is released packaged with the FTOOLS described previously and found at the same website.

⁷For more information see <http://xc.harvard.edu/atomdb/>

1 keV; these may indicate that, instead of the Ne abundance scaling with the Fe abundance (in which case, the Ne/Fe abundance ratio would be one with respect to the solar ratio, which is 3.8), the Ne/Fe abundance ratio is greater than this value. Alternatively, it could also indicate the presence of a lower temperature component, which we could not constrain, as its major contributor is at energies ≤ 1 keV.

We have also included photoelectric absorption in the spectral fit, with the column density N_H as a free parameter. The best-fit values do not show significant variation, but are systematically higher than previously determined interstellar column densities towards II Peg ($\sim 5 \times 10^{18}$ cm $^{-2}$; Mewe et al. 1997; Patterer et al. 1993): this discrepancy is likely due to calibration uncertainties in the XRT at low energies.

3.1. Trigger Spectrum

The BAT trigger spectrum could be fit with a single component model, either a thermal (APEC) model with abundances fixed to solar (Grevesse & Sauval 1998), or a power-law model. At the high temperatures returned by the APEC model ($\sim 180 \times 10^6$ K) continuum emission dominates. Both models fit the data statistically equally well; however, we favor the thermal model based on previous behavior in large stellar flares (Favata & Schmitt 1999; Pallavicini 2001; Franciosini et al. 2001) which behavior indicate the presence of high-temperature thermal plasma. Spectral fit results are given in Table 1 and shown in Figure 2.

3.2. Orbits 1 and 2

We investigated the presence of large residuals around 6.4 keV in the XRT spectrum during Orbits 1 and 2, and added a line at this energy, fixing the energy at 6.4 keV and width at the instrumental value. The right bank of panels in Figures 3 and 4 display the 5.5–9 keV region in Orbit 1 and Orbit 2 which includes this feature. We interpret this excess to be the signature of $K\alpha$ emission from neutral or low ionization states of iron, and we defer the discussion of its origin and interpretation to §4.5.

Only in two time intervals (Orbits 1 and 2) were both XRT and BAT spectra available, covering the 0.8–200 keV energy range with significant signal to noise. Our spectral fitting for these times started with a single thermal component, adding in additional thermal components to reduce the fit statistic. The large value of the second temperature component can be confirmed by examination of the 5.5–9 keV region (right bank of panels in Figures 3 and 4) which contains several line diagnostics sensitive to $40\text{--}160 \times 10^6$ K plasma. The

He-like and H-like Iron transitions at ~ 6.7 and ~ 6.9 keV are the most prominent, and their ratio constrains there to be plasma at $\approx 10^8$ K. Since the single temperature fit was not adequate to the spectra in either Orbit 1 or 2, we do not discuss it further. Temperatures near 10^8 K have also been inferred from previous large stellar flares (e.g., Maggio et al. 2000; Franciosini et al. 2001). Figure 3 shows the spectral fitting results in Orbit 1, and Figure 4 shows the spectral fitting results for Orbit 2. The left bank of panels displays the fits to the 0.8–200 keV energy range for two temperature (2T+G), three temperature (3T+G), and two temperature plus nonthermal (2T+G+NT) models (all have a Gaussian component at 6.4 keV as described above). The residuals plotted are deviations of the model from the data, calculated in units of σ . The two-temperature fit has several energy bins above 40 keV (Orbit 1) and 20 keV (Orbit 2) with significant residuals, which prompted us to add in the additional component.

In the case of three thermal components, the highest temperature component is modelled using a thermal bremsstrahlung model whose contribution in the spectrum appears mainly at high energies. The normalization of the bremsstrahlung component is given in $n_e n_I dV$, as compared to the APEC model normalization $n_e n_H dV$, n_I being the ion number density and n_H the hydrogen number density. For both orbits, the χ^2_ν statistic is minimized with three thermal components, but the temperature of the highest component, $\approx 300 \times 10^6$ K, in both Orbit 1 and 2, is very high, and we reject this model for the following reasons. At high temperatures, the conductive cooling time dominates. We can compute the ratio of the thermal relaxation time of the plasma to the timescale for conductive cooling:

$$\tau_{\text{relax}}/\tau_{\text{cond}} = 200 \frac{T_8^4}{n_{10}^2 L_9^2} \quad (1)$$

(see discussion in Benz 2002), where T_8 is the temperature in units of 10^8 K, n_{10} is the electron density in units of 10^{10} cm^{-3} , and L_9 is the loop length in units of 10^9 cm. For $T_8=3$, the timescale over which the plasma can relax to a thermal distribution at this temperature exceeds by a large factor the timescale on which the plasma would lose its energy via conductive losses, unless the density is very high and/or the length scales involved are very long. At high densities, the magnetic field required to confine the plasma becomes large, $B_{\text{conf}} = \sqrt{8\pi n_e k_B T} = 60 \sqrt{n_{10} T_8} G$. At low densities, the length scales exceed the primary stellar radius ($\sim 3R_\odot$) and the binary separation ($a \sin i = 3.4 \times 10^{11}$ cm, Strassmeier et al. 1993). There have been numerous discussions in the literature concerning the thermal or nonthermal nature of hard X-ray emission from solar flares (Vilmer 1987; Brown & Smith 1980). Because other lines of evidence exist which confirm that particle acceleration does occur during stellar flares (mostly microwave gyrosynchrotron emission), we consider a model which describes bremsstrahlung emission from suprathermal electrons. The arguments which apply to 3×10^8 thermal plasma apply also to the second temperature component found in Orbits

1 and 2 (T_2 from $1.2\text{--}1.5 \times 10^8$ in Orbit 1, T_2 from $7\text{--}9 \times 10^7$ K in Orbit 2) with only a slight easing of the physical restrictions described above. However, the line information present in the He-like and H-like iron transitions confirm the existence of this plasma, whereas the 3×10^8 component comes from continuum emission at hard X-ray energies.

Thus, we consider an additional model which contains a nonthermal component. This is based on hard X-ray emission from solar flares, which usually shows evidence of bremsstrahlung radiation from a population of nonthermal electrons (Dennis & Schwartz 1989). If the emission arises as the result of a beam of injected electrons propagating downward through the atmosphere, we expect the observed radiation spectrum to differ from the injection spectrum, being modified by collisions with the increasingly dense atmosphere. The formulation for describing such “thick-target” hard X-ray emission is described by Brown (1971), where the observed spectrum $I(\epsilon)$ has the form

$$I(\epsilon) \sim \epsilon^{-\gamma} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \quad (2)$$

where ϵ is the photon energy and γ is the photon index. Under the formalism of thick-target bremsstrahlung emission, the observed spectrum can be related to the spectrum of injected electrons, $F(E) \sim E^{-\delta} \text{ erg s}^{-1} \text{ keV}^{-1}$, where E is the electron energy, and δ is the power-law index of the electron distribution function; δ is related to γ as $\delta = \gamma + 1$. We implemented a thick-target bremsstrahlung code⁸ in XSPEC to model the behavior of the hard X-ray photons. The spectral shape is determined by the power-law index of the electron injection spectrum; the normalization depends on the total power input in accelerated electrons and the low-energy cutoff in the electron injection spectrum. We cannot constrain the cutoff with our dataset, and fix this value to an arbitrary value of 20 keV often used in solar flare analysis (Dennis & Schwartz 1989). Recent RHESSI solar flare results (Holman et al. 2003) have determined 37 keV as the highest value consistent with their data, although much lower energy cutoffs (down to a few keV) have also been determined (Sui et al. 2006). This value (20 keV) is roughly comparable with the approximate location in the spectrum where the nonthermal spectrum starts to dominate. Note that the choice of low energy cutoff has dramatic consequences for the power input in accelerated electrons: decreasing the cutoff to a lower value E_c increases the power input necessary to reproduce the spectrum by a factor $(20/E_c)^{\delta-2}$, or a factor \approx two higher for $\delta \sim 3$ and $E_c = 10$ keV.

The fact that the 3rd temperature component in Orbit 2 is also unphysically high, coupled with the large residuals above 20 keV between model and data for a two-temperature

⁸Based on the BREMTHICK code developed for analysis of RHESSI solar flare data available at <http://hesperia.gsfc.nasa.gov/hessi/modelware.htm>

fit and the χ^2_ν statistic for the 2 temperature plus nonthermal model being nearly the same as for the three temperature model, leads us to conclude that there is evidence for nonthermal emission into the decay phase of the flare. Indeed, since the thermal plasma has cooled ($T_2 \approx 8 \times 10^7 \text{K}$ in Orbit 2 compared with $T_2 \approx 1.4 \times 10^8 \text{K}$ in Orbit 1), the discrepancy between model and data for the two-temperature model shows up at smaller X-ray energies (see Figure 4). Based on either the three temperature model or the two temperature plus nonthermal model, in Orbit 1 the 0.8–10 keV flux is $6.12 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ [(6.09–6.13) $\times 10^{-9}$ 1σ uncertainty], and the 10–200 keV flux is $3.9 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ [(3.6–4.0) $\times 10^{-9}$ 1σ uncertainty]. Expressed as a fraction of the bolometric luminosity ($L_{\text{bol}} \approx 5.5 \times 10^{33} \text{ erg s}^{-1}$), these values are 0.24 (0.8–10 keV) and 0.15 (10–200 keV). In Orbit 2, the 0.8–10 keV flux is $3.62 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ [(3.61–3.64) $\times 10^{-9}$ 1σ uncertainty], and 10–200 keV flux is $1.29 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ [(1.11–1.37) $\times 10^{-9}$ 1σ uncertainty]. Expressed as a fraction of the bolometric luminosity, these values are 0.14 (0.8–10 keV) and 0.05 (10–200 keV).

3.3. Orbit 3

In the third orbit following the trigger, there was no BAT detection of the source. The XRT did collect data for an interval of ~ 535 s, which we analyzed. There is no statistical evidence indicating the need for either a power-law component at the highest energies, or for a 6.4 keV feature. The thermal component is still at a relatively high level, and the 0.8–10 keV flux is ~ 40 times higher than recorded during quiescent intervals seen with Chandra ($5.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, 0.5–12 keV; Huenemoerder et al. 2001). We conclude that the flare in soft X-rays lasted longer than the ~ 12 ks in which it was observed by Swift. Spectral fit results are listed in Table 1 and the data and model are plotted in Figure 2.

4. Discussion

The soft X-ray flux peaked during Orbit 1, with the radiated energy flux $\gtrsim 100$ times that observed during previous observations made when the system was quiescent (Huenemoerder et al. 2001). Thus, we apply the “superflare” moniker to describe this event. There have been previous detections of stellar flares in the hard X-ray band of 20–50 keV (Favata & Schmitt 1999; Pallavicini 2001; Franciosini et al. 2001; Krivonos et al. 2005), yet none have shown unambiguous evidence for nonthermal emission. Indeed, detailed spectral fitting for these flares has indicated the presence of a superhot thermal plasma component ($T > 80 \times 10^6 \text{K}$), but, with no detections above ~ 50 keV there has been no evidence of a power-law tail in the spectrum due to nonthermal emission. These results were somewhat puzzling, in that radio

observations necessitate continuous acceleration of electrons to describe the steady levels of microwave emission (Chiuderi Drago & Franciosini 1993). In addition, intense radio flares reaching 2–3 orders of magnitude enhancement over the quiescent level of microwave emission have been observed (Richards et al. 2003) which probably correspond to the “superflare” classification as well.

We estimate the peak flux during Orbit 1 as if this were a solar flare – the 1–8 Å (1.55–12.40 keV) flux at Earth would be 440 W m^{-2} for $d = 1AU$ instead of $d = 42pc$. Using the notation for X-class solar X-ray flares ($Xn = n \times 10^{-4} \text{ Wm}^{-2}$), this would correspond to $X4.4 \times 10^6$. For comparison, the largest solar flare yet observed has been $\sim X30$. Given the huge difference in radiative output, we should not expect this flare to look and behave like solar flares. The key features of this superflare are (1) its intensity in the soft X-ray band, notably the evidence for high temperature thermal emission; (2) evidence for nonthermal emission at hard X-ray energies; and (3) the presence of 6.4 keV Iron K emission. We discuss the implications of each of these for the physics of flares in the following sections.

4.1. High Temperature Thermal Emission and the Neupert Effect

High temperature plasma ($> 5 \times 10^7 \text{ K}$) is evident in all four time intervals. The hottest component, $\approx 1.8 \times 10^8 \text{ K}$, appears during the trigger, although this result is based only on 10–200 keV continuum emission. The spectral fitting to Orbits 1 and 2 involving models with two or more temperature components returns a high temperature ($\sim 70\text{--}150 \times 10^6 \text{ K}$) which is generally hotter in Orbit 1 than in Orbit 2. We have argued in a previous section (§3.2) that the temperature returned by modelling the spectra in Orbits 1 and 2 with three temperature components is not as plausible as the existence of a nonthermal thick-target bremsstrahlung emission component at hard X-ray energies, and so we will ignore the three temperature fits in favor of the nonthermal interpretation. The two temperature fit to the spectrum in Orbit 3 also reveals evidence for plasma at $\approx 5 \times 10^6 \text{ K}$. Thus, the general trend appears to be that the plasma is cooling during this progression from the trigger through Orbit 3, as deduced by the decrease in the hottest temperature component from these spectral fits, with an exponential decay time of ~ 3 hours.

The correspondence in many solar flares between thermal coronal energies and the amount and timescale of nonthermal energy deposition (the “Neupert Effect”; Neupert 1968) lends credence to the posited physical association between particle acceleration and coronal heating. Stellar flares also sometimes show evidence of the Neupert effect, although typically radio emission or other proxies for hard X-ray emission (e.g. optical white-light flares) are used to compare with soft X-ray thermal radiation (Güdel et al. 1996; Güdel et al. 2002;

Hawley et al. 1995). We have investigated the temporal relationship between the soft X-ray emission and hard X-ray emission in this flare to see if it shows the Neupert effect. In this case, the time rate of change of the thermal energy content of the corona (as revealed by soft X-ray radiation) should be roughly equivalent to the instantaneous nonthermal energy luminosity, $\dot{E}_{th} \propto L_{NT}$. The 40–101 keV energy band of the BAT spectrum appears to be dominated by power-law hard X-ray emission, so we use this light curve to describe the temporal variation in nonthermal energy deposition. The thermal coronal energy is released mainly in the 0.8–10 keV energy band, so we use this light curve to constrain the temporal evolution in the thermal energy. Figure 5 displays the correspondence between the derivative of the XRT light curve and the instantaneous nonthermal hard X-ray emission. The greatest correlation occurs during the first part of Orbit 1. We take this as suggestive of a Neupert effect relationship between the nonthermal hard X-ray emission and thermal coronal radiation, although there is complex behavior here, as the nonthermal hard X-ray emission appears to persist into the decay phase of the flare. An additional complication lies in whether the plasma heating to such high temperatures takes place concurrently with, or as a result of, the particle acceleration producing the nonthermal emission.

The Neupert effect argues for a causal relationship between particle acceleration and plasma heating. The energy dissipation which sets off the chain of events seen in a flare can heat plasma as well as accelerate particles (Dennis & Schwartz 1989); the exact proportion depends on the partition between plasma heating and particle acceleration, which is unknown. It is possible that plasma heating to the high temperatures seen during the trigger and subsequent orbits occurs before or concurrently with particle acceleration, although we cannot constrain the presence of the nonthermal component during the time of the trigger, due to poor signal-to-noise constraints, and we also cannot deduce what the pre-trigger conditions were. Benka & Holman (1994) discussed a model in which both thermal and nonthermal emissions occur and are physically linked due to electron currents both heating plasma by Joule dissipation and accelerating electrons via a runaway process. Secondary heating such as predicted by the Neupert effect is then a different effect. McTiernan et al. (1999) show that high temperature solar flare plasma ($T > 16 \times 10^6 \text{K}$) is more likely to exhibit the Neupert effect than low temperature plasma, but this assumes that the flare energy release occurs predominantly in nonthermal electrons. Li et al. (1993) computed hard and soft X-ray time profiles using models in which the hard X-ray emission was produced by either a super-hot thermal component or nonthermal thick-target bremsstrahlung, and concluded that the thermal model fails to reproduce the derivativity relationship between hard X-ray and soft X-ray emission. A situation where primary plasma heating and secondary plasma heating due to energy lost by nonthermal electrons would be more complicated. The current data appear to be consistent with a Neupert effect relationship, but a more confident

interpretation relies on knowing the times when nonthermal emission and high temperature flare emission appeared.

As discussed by Feldman et al. (1996), there appears to be a relationship between flare temperature and emission measure for solar flares and large stellar flares; “bigger” flares (more intense, larger emission measure) tend to be hotter. The high temperature component of the flare under consideration here also appears to fit with this general relation. Battaglia et al. (2005) found a correlation between nonthermal hard X-ray flux and thermal plasma parameters from a sample of solar flares, indicating that flares with large values of nonthermal emission also have higher temperatures and emission measures. Applying this result to the current flare confirms that a strong bias exists in detecting nonthermal hard X-ray emission from stellar flares, as very large and energetic (and hence rare, due to the flare frequency-energy relationship) flares are needed to achieve detections of nonthermal emission at hard X-ray energies. This problem is further compounded by the addition of the superhot thermal component, itself a consequence of the large flare, which complicates detection of the nonthermal component in the hard X-ray spectrum.

4.2. Nonthermal Hard X-ray Emission

The power F_0 in the accelerated electrons as deduced by thick-target bremsstrahlung spectral fits is $\sim 10^{37}$ erg s $^{-1}$, as listed in Table 1. As noted above, this number depends on the value of the low energy cutoff in the injected electron spectrum, which we cannot constrain. However, our somewhat arbitrary choice of 20 keV as a lower energy cutoff does fit with the region of the spectrum where nonthermal emission begins to dominate. The spectral indices of the electron distribution returned from the spectral fitting are δ of 2.8 and 3.1; these compare favorably with spectral indices inferred from solar HXR burst spectral indices (e.g., McTiernan & Petrosian 1991); significant evolution of the hard X-ray spectrum is usually observed during solar flares, but our sensitivity constraints do not permit examinations on a finer time scale.

The flare lasted for > 11000 s in the soft X-ray band, but the timescale for hard X-ray emission is shorter, ~ 7000 s, based on the nondetection by BAT in the third orbit following the trigger. The major energy loss mechanism for the nonthermal electrons will be via collisions with the ambient thermal electrons; we thus estimate the energy loss timescale as

$$\tau_{defl} = 9.5 \times 10^7 s \left(\frac{E_{keV}^{3/2}}{n_e} \right) \left(\frac{20}{\ln \Lambda} \right) . \quad (3)$$

where E_{keV} is the energy of the electron in keV, n_e is the ambient plasma density in the

region of energy loss in cm^{-3} , and $\ln \Lambda$ is the Coulomb logarithm, ≈ 10 under typical chromospheric conditions. We use n_e of $\sim 10^{10} - 10^{11} \text{ cm}^{-3}$ based on electron density measurements of II Peg’s lower transition region/upper chromosphere given in Doyle et al. (1992). Under these conditions, a 100 keV electron will lose its energy in 2–20 s. This is significantly shorter than the observed timescale for the hard X-ray emission, and thus the observations require either continuous acceleration and/or the presence of much more energetic electrons than can be diagnosed with the spectral energy coverage and sensitivity of the Swift detectors. The first option is broadly consistent with hydrodynamic stellar flare models which require continued heating (Reale et al. 1997), hence continuous particle acceleration, assuming the two processes are physically linked. It is likely that both continuous acceleration and a population of highly energetic electrons exist; radio observations of active stars indicate the presence of $\sim \text{MeV}$ electrons. We expect that had radio observations of this flare been obtained, the observations would have shown a significant enhancement above typical levels. Indeed, using the $L_X - L_R$ relationship of Güdel & Benz (1993), we would expect a centimeter-wavelength radio luminosity of $(4.5 - 45) \times 10^{17} \text{ erg s}^{-1} \text{ Hz}^{-1}$, or 0.2–2 Jy flux density, using the 0.8–10 keV X-ray luminosity during Orbit 1 ($L_X = 7.7 \times 10^{32} \text{ erg s}^{-1}$). Although, in most solar flares, particle acceleration occurs only during the impulsive phase, there is evidence for continued particle acceleration and chromospheric evaporation during the gradual phase of some flares (Cliver et al. 1986; Kai et al. 1986; Czaykowska et al. 1999), which are typically long-duration events.

4.3. Occurrence Rate

The Swift mission had been operating for roughly 9 months before this event was detected, observing $\sim 60\%$ of the sky each day. This suggests a rough frequency of occurrence for these superflares of once every 5.4 months, or roughly once in 164 days. Other flare events from active binary systems with high luminosities have been only sporadically reported in the literature. If such events follow the usual power-law dependence of flare frequency with luminosity, then this is almost certainly due to the low probability of catching such a flare during pointed observations lasting a few days or less. For the 66 days of exposure accumulated in the *Ariel-V* observations of Schwartz et al. (1981), the rate of flares in excess of $6 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (10 – 30 times the typical ‘quiescent’ X-ray flux of $2 - 6 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ since determined for this system) in the 1.5-20 keV band was inferred to be 11 per year.

Dedicated surveys obviously will have a higher probability of detecting these events. Waldram et al. (2003) have a Ryle Telescope 15 GHz light curve of II Peg (their Fig. 13)

which spans 14 months, albeit with some gaps, which shows one flare with an intensity greater than 200 mJy (≈ 100 times the quiescent radio flux density) and 2 others >100 mJy. Based on several years’ observation at centimeter wavelengths with the Green Bank Interferometer reported in Richards et al. (2003), we can also estimate the occurrence rate of radio superflares in active binary systems, using the flux data for HR 1099 and UX Arietis⁹, two analogous active binary systems to II Peg containing a K subgiant and hotter companion (but where the K subgiant, as in II Peg, is presumed to dominate in the X-ray and radio emission). Only for 0.2% of the time did flare events in HR 1099 and UX Ari reach radio luminosities in excess of $100\times$ the quiescent values, corresponding to a total of 9 flare events for these two systems. The average time between superflares is 136 days (165 days for 4 events on HR 1099 and 113 days for 5 events on UX Ari); with the usual caveat of small number statistics, the event rate for X-ray superflares and radio superflares appear to be broadly consistent, being roughly once every several months to a year.

4.4. Contribution of Thermal and Nonthermal Energies

A lower limit to the amount of thermal energy in the plasma can be obtained by determining the radiative flux from the thermal plasma over a large range of photon energies. We did this in XSPEC through the use of a “dummy” response covering 0.01–200 keV. For Orbits 1 and 2, we used the best-fit two-temperature plus Gaussian plus nonthermal model parameters listed in Table 2, and removed the Gaussian and nonthermal model components. A lower limit to the thermal energy can then be calculated as $4\pi d^2 F \Delta t$, where F is the radiative flux from 0.01–200 keV (9.5×10^{-9} erg cm⁻² s⁻¹ for Orbit 1 and 4.8×10^{-9} erg cm⁻² s⁻¹ for Orbit 2), and Δt is the duration of Orbit 1 and 2 (1535 and 2641 s, respectively). In both cases, the radiative energy estimates work out to $\approx 3\times 10^{36}$ erg, for a total of $\approx 6\times 10^{36}$ erg. The total radiated energy of the hot plasma over all wavelengths can also be computed from the radiative loss function, using the radiative losses at the temperatures returned from spectral fitting appropriate for the derived abundances, and multiplied by the emission measure at that temperature and total duration. We used the line and continuum emissivities in APEC to calculate this function. The total radiated energy calculated in this manner matches to within an order of magnitude the energy estimates above; this is due partly to the wide wavelength range considered in the “dummy” response. We note that the total radiated energy over all wavelengths from the few solar flares in which changes in total solar irradiance have been made (Woods et al. 2004) indicate that the total radiated flare energy can be larger than the radiated energy of the hot plasma by a factor of up to

⁹Obtained from <ftp://ftp.gb.nrao.edu/pub/fghigo/gbidata/gdata/gindex.html>

ten. Thus, a lower limit to the radiated energy for the flare in Orbits 1 and 2 combined can be placed at $\sim 10^{38}$ erg. This is the amount of energy the plasma loses by radiation, and ignores the effect of conductive energy losses (which will be important at high temperatures) as well as bulk kinetic energy of the plasma or any energy loss due to expansion.

We can estimate the amount of conductive energy losses by using the equation for conductive flux,

$$F_{\text{cond}} = \kappa T^{5/2} \nabla T = \frac{\kappa T^{7/2}}{L} \text{ erg cm}^{-2} \text{ s}^{-1} \quad (4)$$

where κ is the Spitzer conductivity value ($= 8.8 \times 10^{-7} \text{ erg cm}^{-1} \text{ s}^{-1} \text{ K}^{-7/2}$), and we have approximated $\nabla T \sim T/L$ where L is a characteristic length along which conductive energy is lost. The energy density per unit time can then be estimated as $F_{\text{cond}}/L \sim \kappa T^{7/2}/L^2$. Using the relationship between volume, volume emission measure, and electron density ($VEM = n_e^2 V$), and the duration of each orbit, an estimate of conductive energy losses in Orbit 1 and 2 can be estimated as

$$E_{\text{cond}} = \frac{\kappa T^{7/2} VEM \Delta t}{L^2 n_e^2} \text{ erg} . \quad (5)$$

Using the temperature and volume emission measure¹⁰ the conductive energy lost in Orbit 1 is $\sim 4 \times 10^{43} / (L_9^2 n_{10}^2)$ erg, while in Orbit 2 it is $\sim 6 \times 10^{42} / (L_9^2 n_{10}^2)$ erg, for a length in units of 10^9 cm and electron density in units of 10^{10} cm^{-3} . This is probably an upper limit on the amount of conducted energy, as evidence from solar flares indicates (Jiang et al. 2006) that the classical expression for conductive flux may overestimate the total energy decay rate.

We estimate the total energy represented by nonthermal electrons during orbits 1 and 2 by multiplying the power output by the exposure time. We cannot diagnose variations in the acceleration of electrons on shorter timescales, due to signal-to-noise limitations, so these calculations assume that electron acceleration occurs at a constant level during each orbit. In Orbit 1 $F_0 \times \Delta t = 10^{40}$ erg, and in Orbit 2 $F_0 \times \Delta t = 2 \times 10^{40}$ erg, where the low energy cutoff of 20 keV was used. In order to match the thermal energy (here assumed to be dominated by conductive energy losses) with the nonthermal energy input, we obtain a constrain on the product of electron density and length scale, $L_9 n_{10} = 60$ for Orbit 1 and $L_9 n_{10} = 20$ for Orbit 2. We have no independent constraints on either quantity. We note that the reasonable agreement between the nonthermal energy and the upper and lower limits on the thermal energy estimates add support to the nonthermal interpretation.

¹⁰ $\int n_e n_H dV$ tabulated in Table 2 can be related to the volume emission measure $n_e^2 V$ by using $n_e/n_H = 1.2$.

4.5. Iron Fluorescence

There is excess emission redward of the Fe XXV and Fe XXVI features visible in the XRT spectra of Orbit 1 and 2, visible in the right-hand bank of panels in Figures 3 and 4. We attribute this to emission from the iron $K\alpha$ feature at 6.4 keV. Both electron-impact ionization or photoionization mechanisms are capable of removing K shell electrons from neutral or near-neutral iron in the photosphere and producing the 6.4 keV spectral line (Emslie et al. 1986), although no solar $K\alpha$ line has been definitively identified with electron-impact ionization (Parmar et al. 1984). We subdivided the spectra in orbits 1 and 2 to investigate the time evolution of the 6.4 keV feature in more detail. Figure 6 displays a close-up of the 5.5–8 keV region, and Table 3 lists the results of spectral fitting for the five different time-resolved spectra.

Previous observations of $K\alpha$ emission from stars other than the Sun have been of pre-main sequence stars and have concluded that the fluoresced material is located in the circumstellar disk which is bathed in the thermal hard X-ray continuum radiation emitted by flaring plasma. Applying this interpretation to the event on II Peg poses several problems, however. The equivalent width of the 6708 Å lithium resonance line and the lithium abundance are not consistent with a pre-main sequence evolutionary state, nor is the observed C/N ratio (see discussion in Berdyugina et al. 1998). The system is therefore generally considered to be an old-disk population star. On the other hand, an infrared excess appears to have been detected in II Peg (Lazaro et al. 1987; Rodono et al. 1998) which is rather unexpected for a Pop I star. Further, the column densities returned from X-ray spectral fitting are systematically higher than previously determined interstellar values for this line of sight, suggesting the possibility of additional absorption from a circumstellar disk. However, we consider the column density returned from spectral fitting highly suspect, as we have excluded the energy range below 0.8 keV due to systematics, and there could be additional unrecognized systematics affecting the absorption column density. Thus we consider it is more plausible that the 6.4 keV signature arises from photospheric, not circumstellar, material, although we cannot at the moment rule out a face-on circumstellar disk.

4.5.1. Fluorescence

If we attribute the formation mechanism to a photoionization fluorescence mechanism, then the continuum radiation above the iron K edge, 7.11 keV, is the source of the photoionization producing the 6.4 keV feature. The luminosity and equivalent width of the feature can be used to deduce the scale height of the coronal emission above the photosphere, using equation 2 in Tsujimoto et al. (2005)

$$EW = \frac{L_{K\alpha}}{I(E_{K\alpha})} = \frac{\Delta\Omega}{4\pi} Y_{K\alpha} \frac{E_{K\alpha}}{I(E_{K\alpha})} \int n_{Fe}(s) ds \int_{\chi}^{\infty} \frac{I(E')}{E'} \sigma_{Fe}(E') dE' \quad (6)$$

where $\Delta\Omega$ is the solid angle subtended by the photosphere as seen by the flaring X-ray source. The continuum spectrum in this region is dominated by the hot thermal plasma, with a spectral shape $I(E) \propto E^{-1} \exp^{-E/kT}$. We use the fluorescence yield $Y_{K\alpha}$ of 0.342 (Bambynek et al. 1972). $E_{K\alpha}=6.4$ keV and χ is the iron K edge energy, 7.11 keV. The quantity $\sigma_{Fe}(E)$ is the photoelectric cross-section of iron; we use $\sigma_{Fe}(E) = 2 \times 10^{-20} (E/\chi)^{-3}$ cm² (Gullikson 2001). We rewrite the integral involving $n_{Fe}(s)$ as $\int (A_{Fe}) n_H ds$, where $A_{Fe} = n_{Fe}/n_H$. A comparison of coronal iron abundances (here and in Huenemoerder et al. 2001) and photospheric iron abundances does reveal chemical fractionation occurring in II Peg’s atmosphere (in a sense opposite to that seen in the Sun), yet we cannot constrain such spatial variations. The hydrogen column density in the chromosphere/photosphere is estimated using the column mass density in the atmospheric models of Short et al. (1998). Between the temperature minimum and 10⁴ K, the column mass ranges from ~ 0.001 –2 g cm⁻², or 10²¹–2×10²⁴ cm⁻² with a mean molecular weight $\mu \sim 0.6$. Since the photospheric iron abundance of II Peg is higher than the coronal abundance by factors of 2–4, and the hydrogen column density lower in the atmosphere exceeds that in the corona by orders of magnitude, we assume that the major contribution to this integral occurs in the photosphere and express the integral as $A_{Fe,phot} \int n_H ds = A_{Fe,phot} N_H$, where $A_{Fe,phot} \approx 0.4$ $A_{Fe,solar} = 1.26 \times 10^{-5}$, using the revised iron abundance of Grevesse & Sauval (1998), and the above ranges of N_H . In the solar case, the main contribution also occurs in the photosphere, due to the increasing column mass as one proceeds from the corona to the photosphere; downward propagating photons with $E > 7$ keV are optically thin to photoelectric absorption and Compton scattering (see discussion in Parmar et al. 1984), and the photospheric iron abundance being \sim one fourth that of the solar coronal iron abundance does not affect where in the atmosphere the main contribution to fluorescence occurs ¹¹.

The solid angle $\Delta\Omega$ can be expressed in terms of a height using the fraction of photons intercepted by the star, (Bai 1979),

$$\Delta\Omega(h) = 2\pi \left[1 - \frac{\sqrt{h^2 + 2R_{\star}h}}{R_{\star} + h} \right] \quad (7)$$

where h is the scale height of the flaring X-ray source; we take R_{\star} to be the radius of the primary of the system, $\approx 3R_{\odot}$ (Berdyugina et al. 1998). Figure 7 displays the relationship

¹¹Note that in the solar case, with an independent constraint on the height of the soft X-ray source from e.g. X-ray imaging telescopes, the flux of the $K\alpha$ line can be used to deduce the photospheric iron abundance (Bai 1979).

between height and column density for the measured equivalent width and plasma temperature. There is an asymptotic dependence on column density, so that the minimum column densities which can reproduce the equivalent widths are of order 10^{24} cm^{-2} . This would indicate, based on the atmospheric modelling of Short et al. (1998), that (1) the fluorescence occurred deep in the atmosphere, near the temperature minimum region, and (2) the maximum flare scale height is $0.5R_*$. There appears to be a discrepant behavior in the first sub-segment of Orbit 2, where the equivalent width shows an anomalous value compared to Orbit 2b and Orbit 1c. There are problems with this interpretation, however, due to the fact that at $N_H \sim 1/\sigma_T \sim 1.5 \times 10^{24} \text{ cm}^{-2}$, where σ_T is the Thomson cross section, photons start experiencing significant Compton scattering. In contrast with the solar photosphere, in which the temperature minimum region is reached with a lower column mass density (Vernazza et al. 1981), photons of energy 6.4 keV will also experience significant photoelectric absorption at such high column densities, decreasing the efficiency of producing fluorescence emission in such an environment. Thus we conclude that the fluorescence mechanism is probably not a valid interpretation for the formation of the 6.4 keV line.

The iron $K\alpha$ emission feature can have a great utility during stellar flares, if further observations confirm the fluorescence mechanism. With an independent constraint on the flaring loop height, say from hydrodynamic flare modelling relating the loop height to the flare evolution in the T-VEM plane (Reale et al. 1997), the equivalent width of the 6.4 keV feature can be used to constrain the photospheric Fe/H value. Line and continuum emission in the soft X-ray spectrum naturally constrain the coronal Fe/H value, allowing a simultaneous measurement of both with a single data set. This would be advantageous to studying chemical fractionation in stellar atmospheres, particularly as photospheric abundances of active stars are notoriously difficult (due to e.g. fast rotation and/or binarity).

4.5.2. Collisional Ionization

An alternative explanation raised for the production of the 6.4 keV feature seen in solar flares is the collisional ionization of K shell electrons by a beam of nonthermal electrons (Emslie et al. 1986). We used equation 11 in Emslie et al. (1986) to estimate the 6.4 keV line flux (in photons $\text{cm}^{-2} \text{ s}^{-1}$) assuming the production mechanism is collisional ionization by a beam of nonthermal electrons

$$\Phi = \frac{\omega\beta(n_{Fe}/n_H)}{4\pi d^2 K\theta} \frac{\gamma - 1}{\gamma} F_0(E_{low}) E_{low}^{\gamma-1} \times \int_x^\infty (E_0(E, N^*))^{-\gamma} EQ_I(E) dE \quad , \quad (8)$$

where ω is the fluorescence yield of iron, β is the branching ratio between $K\alpha$ and $K\beta$, =0.882 (Bambynek et al. 1972), d is the distance to the object, $K = 2\pi e^4 \Lambda / \theta^2$ with e the electronic

charge in e.s.u., Λ the Coulomb logarithm, θ the conversion from keV to erg, $= 1.6 \times 10^{-9}$, γ is the photon spectral index (related to the spectral index of the electron distribution by $\gamma = \delta - 1$). The value E_{low} is the low-energy cutoff of the electron distribution, fixed to 20 keV in our spectral fitting. The integral extends from the $K\alpha$ edge of 7.11 keV to infinity; $Q_I(E)$ is the collisional ionization cross section, obtained from the theory of Arthurs & Moiseiwitsch (1958). E_0 is the initial energy of the electron at injection, and E is its energy after collisional (thick-target) encounters. Specifically, E_0 satisfies the equation

$$E_0^3 - 3KN^*E_0 = E^3 \quad (9)$$

where N^* is the column density in the $K\alpha$ -emitting region. The results of the thick-target bremsstrahlung spectral modelling during orbits 1 and 2 are used to estimate the 6.4 keV photon flux, as there is not enough signal to subdivide the BAT spectra as was done above for the XRT spectra. For n_{Fe}/n_H we initially used the photospheric iron abundance, $A_{Fe} = 1.26 \times 10^{-5}$.

We calculate the 6.4 keV line flux relative to the underlying continuum flux (determined from the unfolded spectrum in XSPEC) to determine the equivalent width of the feature. Table 2 lists the derived values for the results from thick-target spectral modelling in Orbits 1 and 2. The right panel of Figure 7 displays the results for the thick-target model in Orbits 1 and 2 as a function of N^* . The observed equivalent widths can be reproduced for values of $N^* \leq 10^{20} \text{ cm}^{-2}$. This mechanism is effective at lower column densities than a fluorescence mechanism implies, and thus would take place higher in the atmosphere. If the abundance fractionation which is known to occur between the photosphere and corona in II Peg is happening at these column depths, the value of n_{Fe}/n_H appropriate for the calculations must consequently be lower. The equivalent widths will then be lower, by a maximum of $\sim 1/4$ the values in the Table 2, corresponding to the maximum iron depletion in the corona as found by Huenemoerder et al. (2001). We conclude that the collisional ionization mechanism is to be preferred over the fluorescence mechanism.

4.6. Loop Heights

If we assume that the flare emission originated from an ensemble of coronal loops with uniform cross section and roughly semi-circular mid-plane shape, then we can express the observed volume emission measure in terms of the loop height, density, number of loops, and loop cross section. Following Equation (5) of Huenemoerder et al. (2001), the loop height is

$$h = 0.03 \left(\frac{N}{100} \right)^{-1/3} \left(\frac{\alpha}{0.1} \right)^{-2/3} \left(\frac{VEM}{10^{53} \text{ cm}^{-3}} \right)^{1/3} \left(\frac{n_e}{10^{11} \text{ cm}^{-3}} \right)^{-2/3} R_\star, \quad (10)$$

where the volume emission measure (VEM) is rewritten as the contribution from N flaring loops, each with height h and aspect ratio α , electron density n_e . Huenemoerder et al. (2001) deduced loop heights of $0.05 R_\star$ under quiescent conditions, for $N = 100$, $\alpha = 0.1$, $VEM = 7.9 \times 10^{53} \text{ cm}^{-3}$ and $n_e \sim 10^{11} \text{ cm}^{-3}$. The peak emission measure determined here is ≈ 100 times larger than that in Huenemoerder et al. (2001); applying the same analysis to this superflare yields $h = 0.3R_\star$, for the same density, for $N = 100$. If instead only one loop is involved, h could be as much as $1.3 R_\star$. An electron density higher than the adopted value would result in more compact loops. The fluorescence analysis of the 6.4 keV feature also yields a constraint on the solid angle extended by the photosphere as seen by the continuum X-ray source, i.e. the scale height of the corona above the photosphere. The scale heights inferred in §4.5.1 are consistent with this simple scaling.

5. Conclusions

We have identified nonthermal emission as the most plausible mechanism to explain the hard X-ray emission seen during the rise and decay of a large stellar flare. This flare interestingly also displayed evidence for emission at 6.4 keV whose formation we attribute to the mechanism of collisional ionization. The increased sensitivity of the Swift BAT has enabled a detection at much higher energies than had been possible with previous hard X-ray telescopes. Nonthermal hard X-ray emission has enabled an investigation of the energetics of large stellar flares, without complication from optical depth effects and source inhomogeneities. The characteristics of this flare — a rare, intense, transient event — point to the value of triggered observations to study such flares; targeted observations would have had a very low likelihood of observing such an event during the short timescales over which the hard X-ray emission is produced. Triggered observing modes necessarily miss the preflare emissions, as the flux must pass a threshold value to warrant a telescope slew. Still, serendipitous science can be obtained, as this Swift-observed flare demonstrates. Current plans are to increase the trigger sensitivity threshold of Swift by a factor of 4.5, thus enabling more such opportunities.

Multi-wavelength observations of solar flares have revealed the dynamical response of the atmosphere to these sudden intense inputs of energy. Future observations of stellar flares like the one discussed here can benefit from the global array of telescopes which have been harnessed for gamma-ray burst studies. It will hopefully be possible to take advantage of optical telescopes to reveal the response of the lower atmosphere and radio telescopes to explore further the action of nonthermal particles. Observations of such events will allow for a comparison of particle acceleration processes in active stars and the Sun.

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Table 1. Trigger and Orbit 3 Spectral Fit Results ¹

Parameter	Trigger	Orbit 3
	T-760:T+126 ²	T+10944:T+11479 ²
N_H (10^{22} cm ⁻²)	...	0.095 (0.07–0.12)
T_1 (10^6 K)	...	15 (14–16)
$(\int n_e n_H dV)_1$ (10^{54} cm ⁻³)	...	15 (10–21)
T_2 (10^6 K)	177 (112–294)	61 (54–70)
$(\int n_e n_H dV)_2$ (10^{54} cm ⁻³)	21. (11.–39.)	32. (30.–36.)
A^a	1. fixed	0.16 (0.12–0.22)
χ^2 (dof)	23.4 (32)	521 (514)
$f(0.8\text{--}10$ keV) ^b (erg cm ⁻² s ⁻¹)	...	2.09×10^{-9} (0.08) ^c (2.08–2.12) $\times 10^{-9}$
$f(10\text{--}200.$ keV) ^b (erg cm ⁻² s ⁻¹)	1.2×10^{-9} (0.04) ^c (0.8–1.3) $\times 10^{-9}$	... ...
Δt (s)	834	535

¹Unless otherwise indicated, error ranges refer to 90% confidence intervals.

²Start and stop times of each time interval, in seconds since the trigger time of 11:21:52 UT. For the Trigger spectrum, these times refer to the BAT, for Orbit 3 the time is the XRT.

^aScaled abundance relative to solar, using solar abundances of Grevesse & Sauval (1998).

^bError ranges correspond to 68% confidence intervals.

^cNumber in italics refers to flux converted to luminosity and expressed as a fraction of the bolometric luminosity.

Table 2. Models Fit to XRT & BAT Spectra in Orbits 1 and 2¹

Parameters	1T+G ²	2T+G ²	3T+G ²	2T+G+NT ²
— Orbit 1: T+126:T+1661 ^a —				
N_H (10^{22} cm ⁻²)	0.062 (0.057–0.067)	9.8e-2 (0.09–0.1)	0.1 (0.09–0.11)	0.1 (0.09–0.11)
A ^b	0.33 (0.28–0.38)	0.33 (0.27–0.38)	0.38 (0.31–0.49)	0.34 (0.29–0.39)
T ₁ (10^6 K)	139 (134–143)	16.5 (15.0–18.4)	15.4 (14.4–17.2)	15.3 (14.4–16.0)
$(\int n_e n_H dV)_1$ (10^{54} cm ⁻³)	85 (84–86)	7.45 (5.7–9.4)	5.3 (3.8–7.0)	5.8 (4.5–7.0)
N ^c (10^{-3} photons cm ⁻² s ⁻¹)	2.4 (1.8–3.1)	2.5 (1.9–3.2)	2.6 (1.9–3.2)	2.7 (2–3.3)
EW ^d (eV)	45	48	47	51
T ₂ (10^6 K)	...	152 (146–157)	118 (102–132)	139 (133–144)
$(\int n_e n_H dV)_2$ (10^{54} cm ⁻³)	...	83 (82–84)	65 (47–77)	83 (83–84)
T ₃ (10^6 K)	...	...	306 (224–580)	...
$\int n_e n_I dV$ (10^{54} cm ⁻³)	...	...	20 (7–38)	...
δ^e	...	...	...	2.8 (2.4–3.4)
F ₀ ^f (10^{36} erg s ⁻¹)	...	...	...	8.5 (7.6–28)
χ^2 (dof)	1065 (836)	943 (834)	918 (832)	924 (832)
— Orbit 2: T+4810:T+7451 ^a —				
N_H (10^{22} cm ⁻²)	0.011 (0.0055–0.016)	0.066 (0.057–0.075)	0.067 (0.058–0.077)	0.066 (0.058–0.075)
A ^b	0.31 (0.29–0.34)	0.26 (0.24–0.29)	0.28 (0.25–0.32)	0.27 (0.25–0.30)
T ₁ (10^6 K)	67	15.5	15.3	15.4

Table 2—Continued

Parameters	1T+G ²	2T+G ²	3T+G ²	2T+G+NT ²
	(66–69)	(15.2–16.4)	(15.0–15.8)	(15.1–15.8)
$(\int n_e n_H dV)_1$ (10^{54} cm^{-3})	58	13	12	12
	(57–59)	(12–15)	(10–14)	(11–14)
N^c ($10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}$)	1.14	0.9	0.95	0.99
	(0.84–1.6)	(0.56–1.3)	(0.6–1.32)	(0.65–1.3)
EW ^d (eV)	42	33	34	34
T_2 (10^6 K)	...	86	74	83
	...	(83–90)	(67–81)	(80–86)
$(\int n_e n_H dV)_2$ (10^{54} cm^{-3})	...	51	47	51.4
	...	(50–52)	(41–50)	(50.7–51.5)
T_3 (10^6 K})	...	...	302	...
	...	...	(191–1000)	...
$\int n_e n_I dV$ (10^{54} cm^{-3})	...	...	6.3	...
	...	...	(2.5–12)	...
δ^e	...	...	...	3.1
	...	...	...	(2.2–4.1)
F_0^f ($10^{36} \text{ erg s}^{-1}$)	...	...	...	8.6
	...	...	...	(6.0–26)
χ^2 (dof)	1460 (814)	952 (812)	932 (810)	931 (810)

¹Uncertainty ranges refer to 90% confidence intervals.

²Key to model combinations: $nT = n$ thermal components, G=Gaussian at 6.4 keV, NT=nonthermal thick target bremsstrahlung model. See text for details.

^aStart and stop times of each orbit, in seconds since the trigger time of 11:21:52 UT.

^bAbundance of thermal plasma as a multiple of the solar photospheric metal abundance given in Grevesse & Sauval (1998).

^cFlux emitted in the 6.4 keV line.

^dEquivalent width of the 6.4 keV line.

^ePower-law index of accelerated electron spectrum; see text for details.

^fPower in accelerated electrons from thick target bremsstrahlung modelling above a cutoff energy of 20 keV.

Table 3. 6.4 keV Feature¹

Parameter	Orbit 1a T+144:T+650 ²	Orbit 1b T+650:T+1156 ²	Orbit 1c T+1156:T+1662 ²	Orbit 2a T+4902:T+6174 ²	Orbit 2b T+6174:T+7447 ²
N_H (10^{22} cm ⁻²)	0.086 (0.07–0.10)	0.1 (0.087–0.12)	0.11 (0.09–0.12)	0.075 (0.065–0.092)	0.048 (0.035–0.061)
A ^a	0.47 (0.36–0.58)	0.35 (0.26–0.44)	0.26 (0.17–0.35)	0.28 (0.23–0.32)	0.29 (0.24–0.33)
T_1 (10^6 K)	15.1 (12.76–18.56)	15.3 (13.57–18.7)	15.8 (14.6–18.9)	16.2 (15.1–17.4)	15.4 (14.8–16.1)
$(\int n_e n_H dV)_1$ (10^{54} cm ⁻³)	3.0 (1.7–5.1)	6.0 (3.8–8.7)	11.1 (7.4–17.7)	15.1 (12.3–18.5)	10.4 (8.7–12.8)
T_2 (10^6 K)	151 (138–173)	142 (130–155)	140 (126–169)	88 (82–95)	86 (81–91)
$(\int n_e n_H dV)_2$ (10^{55} cm ⁻³)	6.8 (6.6–6.9)	8.7 (8.5–8.8)	9.3 (9.1–9.4)	5.3 (5.1–5.5)	4.9 (4.8–5.0)
Flux in 6.4 keV feature (10^{-3} photons cm ⁻² s ⁻¹)	2.5 (1.4–3.6)	2.7 (1.5–3.9)	2.8 (1.5–4.0)	0.65 (0.08–1.1)	1.68 (1.2–2.2)
EW (eV) ^b	55	48	47	18	61
χ^2 (dof)	526 (552)	549 (538)	592 (555)	595 (579)	621 (555)

¹Error ranges refer to 90% confidence intervals.²Start and stop times in Orbits 1 and 2 during which XRT spectra were extracted, in seconds since the trigger time of 11:21:52 UT.

^aAbundance of thermal plasma as a fraction of the solar photospheric metal abundance of Grevesse & Sauval (1998).

^bEquivalent width of the 6.4 keV line.

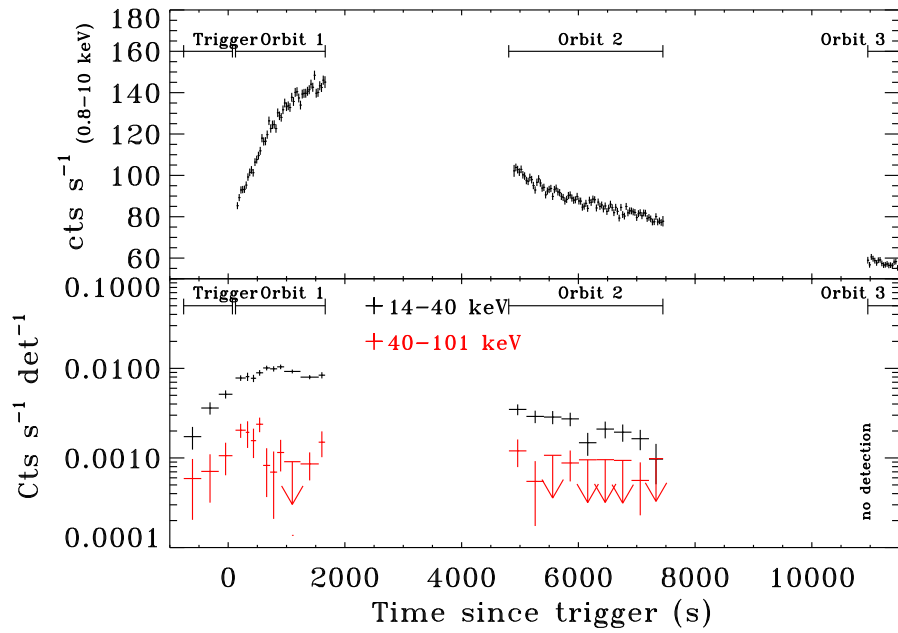


Fig. 1.— Light curves from XRT, 0.8–10 keV (top) and two hard X-ray energy bands from the BAT (14–40, 40–101 keV; bottom). Time bins where SNR < 1 are shown as downward arrows. Time is expressed referenced to the trigger of 11:21:52 UT on 16 December 2005.

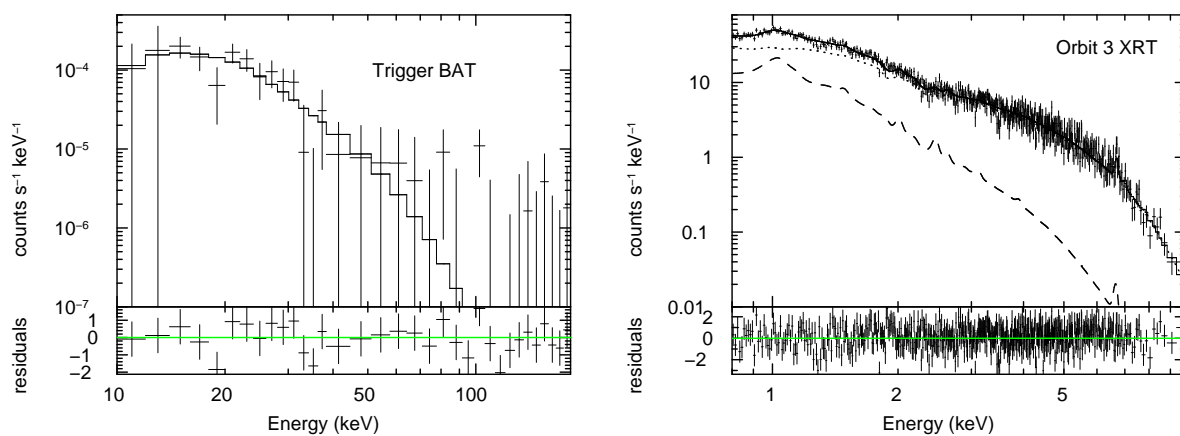


Fig. 2.— Spectral fit to BAT trigger spectrum (left) and XRT spectrum in Orbit 3 (right). For the trigger spectrum a single temperature component is fitted, while for Orbit 3 two temperature components are fitted. Data with error bars are indicated by crosses. Histogram shows final model. For Orbit 3 the contribution of the lower temperature component is shown with a dashed line, while the contribution of the higher temperature component is shown with a dotted line. Residuals are differences between data and model in units of σ . Spectral fits are tabulated in Table 1.

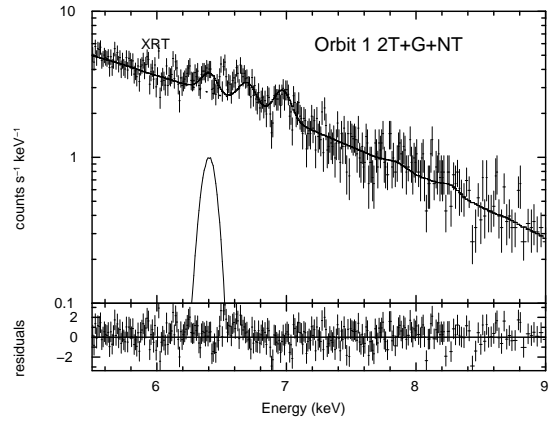
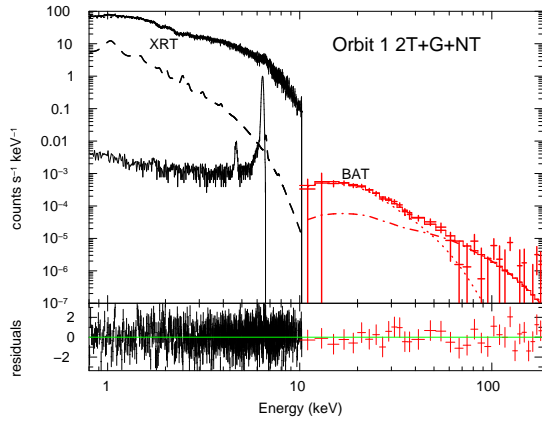
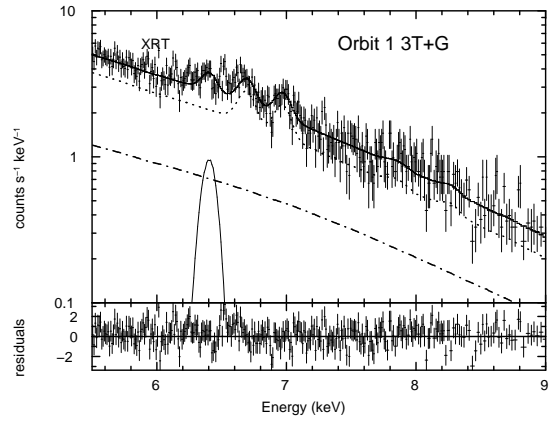
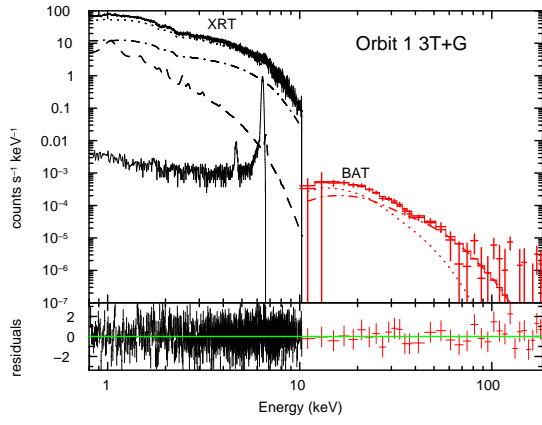
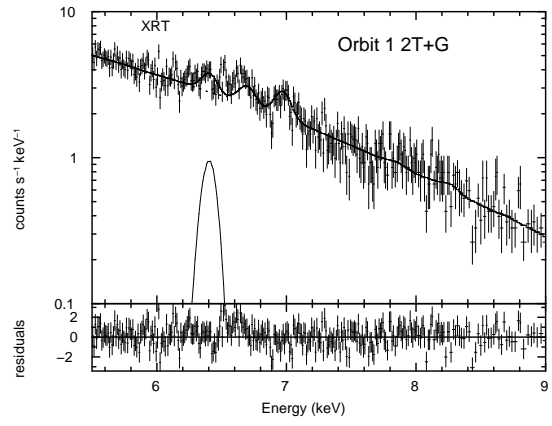
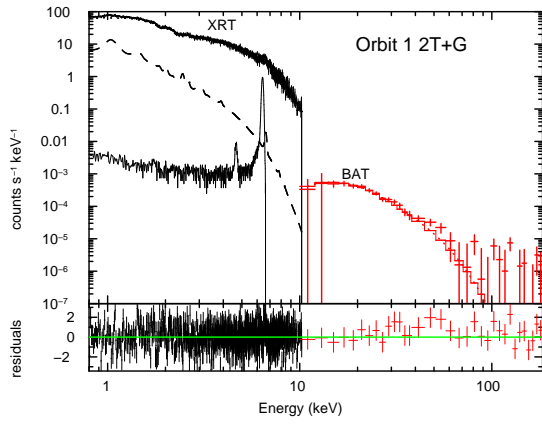


Fig. 3.— Spectral fits to XRT and BAT spectra in Orbit 1. The top panel of each sub-plot displays data and model, while the bottom panel plots the residuals between data and model. The residuals are in units of σ and are plotted with unity error bars. In the upper panel of each sub-plot, crosses show spectral data points with errors. The histogram displays the final model with all components included. The contribution of each additive component is also shown: the first temperature component is delineated by a dashed line, the second by a dotted line, and the Gaussian at 6.4 keV by the thin solid line. The large residuals above 40 keV in the two temperature fit require the addition of another model component. In models with either a third temperature component or a nonthermal component, this additive component is indicated by a dashed-dotted line. The left bank of sub-plots shows the data from 0.8–200 keV, while the right bank of sub-plots zooms in on the Fe K region. The He- and H-like transitions of Iron confirm the 2nd temperature component in all cases. See Table 2 for fit parameters.

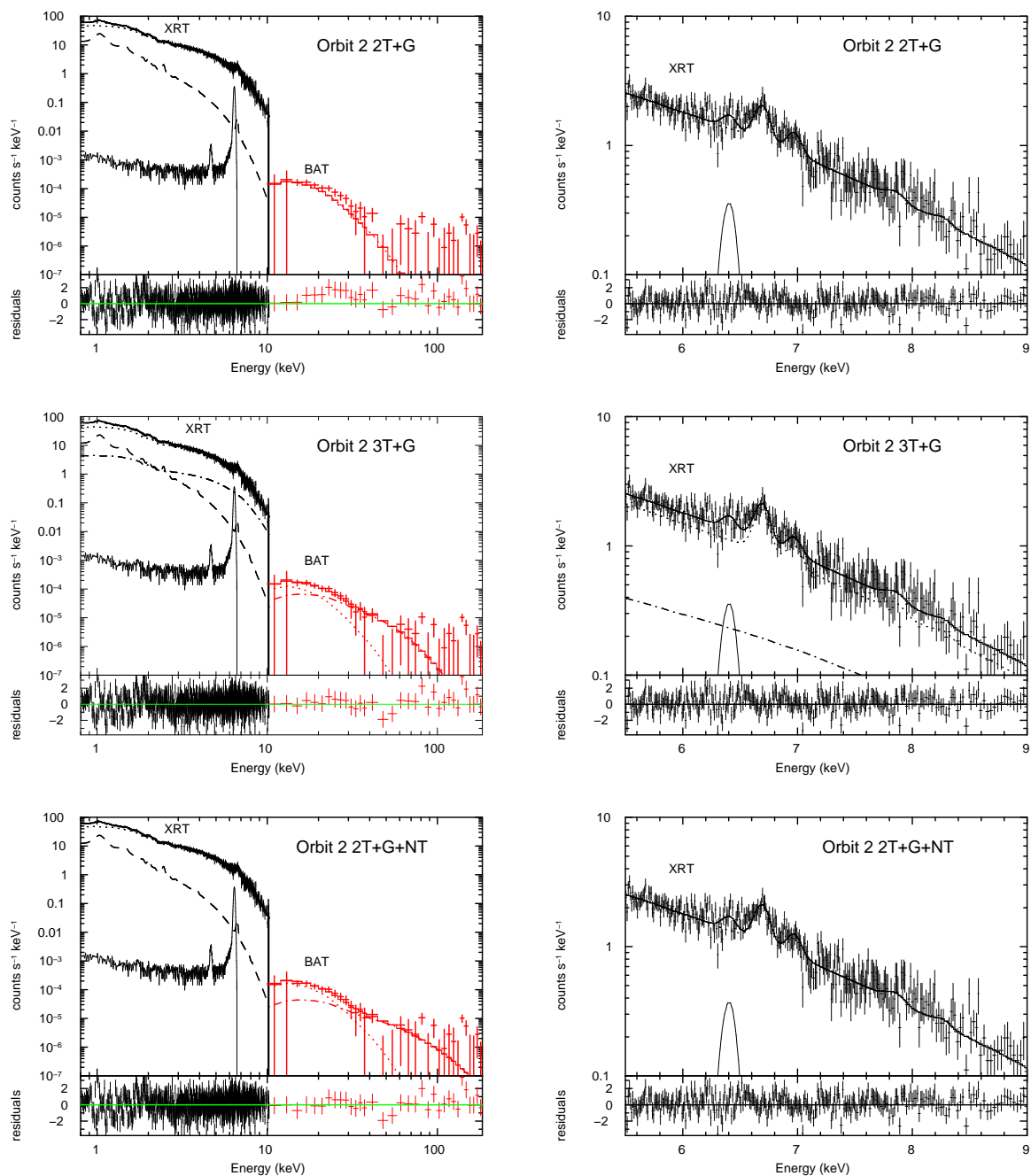


Fig. 4.— Same as Figure 3, but for Orbit 2. Note the residuals between data and model for the two temperature fit in the left-hand panel show a systematic excess above about 20 keV, which can be fit by either a third temperature or a nonthermal model.

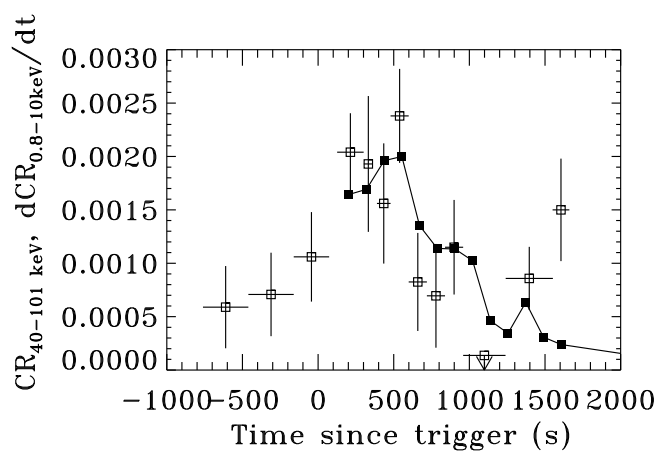


Fig. 5.— Plot of 40–101 keV BAT light curve (heavy squares with error bars), along with scaled derivative of 0.8–10 keV XRT light curve (filled squares connected by a line) for the first 2500 seconds of the flare. The XRT light curve has been rebinned to a coarser time sampling than original data. The correlation for roughly one thousand seconds after the trigger may be indicative of the Neupert effect relating energy deposition in nonthermal particles and subsequent plasma heating.

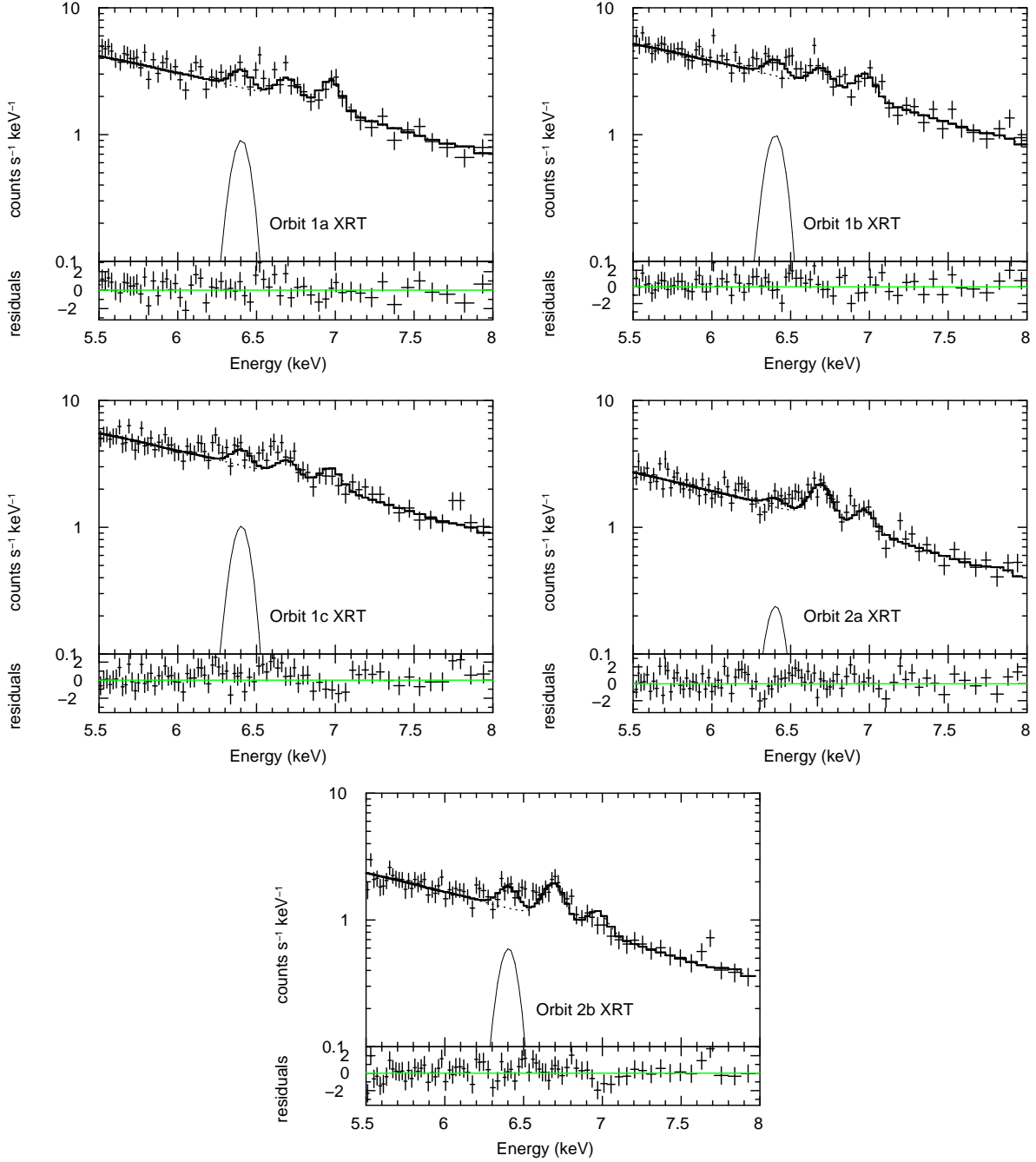


Fig. 6.— Intra-orbit variation of the spectral region around the Fe $K\alpha$ 6.4 keV feature, for three time slices in Orbit 1 and two in Orbit 2. Time intervals are listed in Table 3. Data points and errors are shown as crosses. The 6.4 keV component is drawn with a solid line, and the dotted line delineates the emission from the APEC model; the thick histogram describes the total model emission over this energy interval. The prominent features at 6.7 and 6.9 keV are the He- and H-like transitions of iron, respectively. “Resid” refers to residuals between model and data in each energy bin, in units of σ . See Table 3 for spectral fit results.

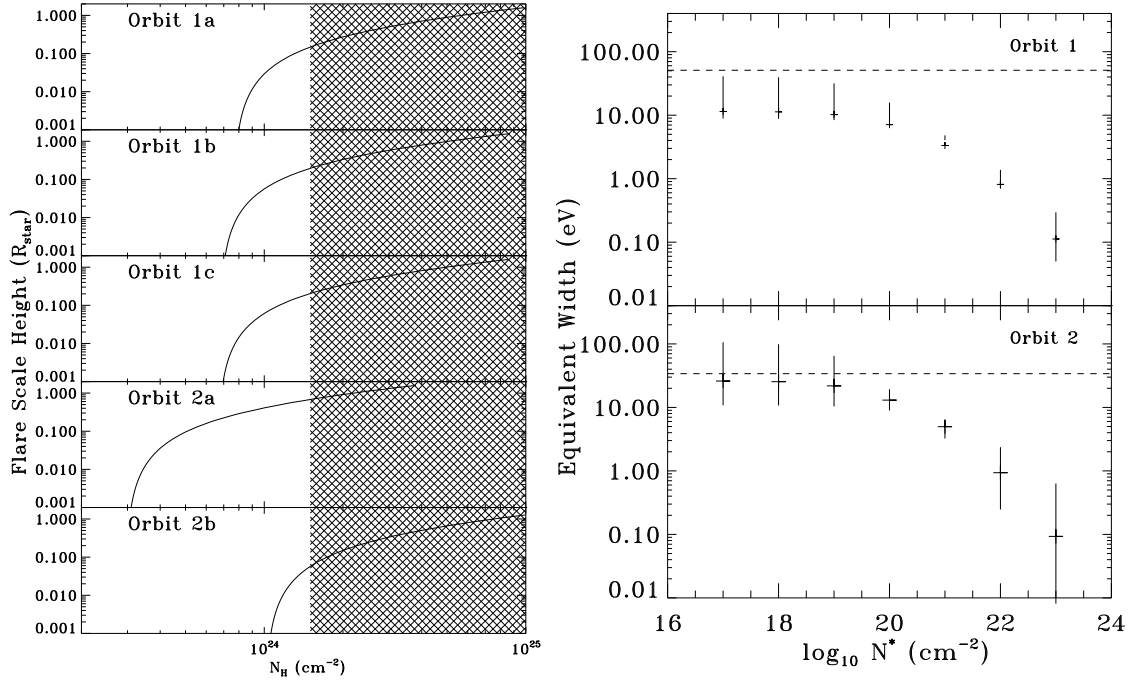


Fig. 7.— (*left*) Relationship between flare scale height and column density in the lower atmosphere of II Peg, using the plasma temperature and equivalent widths appropriate to each time slice (values listed in Table 3), for five time intervals in orbits 1 and 2. Above column densities of $N_H \sim 1.5 \times 10^{24} \text{ cm}^{-2}$, significant Compton scattering will occur and 6.4 keV emission will be reduced or eliminated; this region is indicated by the cross-hatching. See §4.5.1 for discussion. (*right*) Predicted equivalent width as a function of N^* , the atmospheric column density where $K\alpha$ emission originates, for collisional ionization formation of the 6.4 keV $K\alpha$ line. Top panel shows results for thick-target bremsstrahlung model in Orbit 1; bottom panel shows results for Orbit 2. Dashed lines indicate equivalent width measurements from Table 2. Crosses indicate values for best-fit δ , F_0 from spectral fitting (Table 2), as well as maximum and minimum values using uncertainties in δ and F_0 .