1995ApJ...446L..47K

THE ASTROPHYSICAL JOURNAL, 446:L47–L50, 1995 June 10

ENERGY RELEASE AND DISSIPATION DURING GIANT SOLAR FLARES

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Received 1994 September 21; accepted 1995 April 5

ABSTRACT

The Solar X-Ray/Cosmic Gamma-Ray Burst Experiment aboard *Ulysses* has observed 11 solar hard X-ray flares with effective peak counting rates greater than 4×10^5 counts s^{-1}. We have estimated the energy dissipated during these "giant" flares (*GOES* class > X12). The flare on 1991 June 1, probably the largest flare of the present solar activity cycle (cycle 22), may represent energy dissipation by greater than 20 keV electrons at a rate of $\sim 10^{32}$ ergs s^{-1}, a rate of energy release ~ 1000 times larger than that in the well-studied flares in 1972 August. The total energy released during the flare would then have been $\sim 10^{34}$ ergs carried by $\sim 10^{41}$ electrons with energies above 20 keV, assuming a nonthermal interpretation, or $\lesssim 2 \times 10^{33}$ ergs assuming a thermal interpretation. The energy release rate in the other giant flares could have been 10^{30}–10^{31} ergs s^{-1}. The resources of an active region seem to be inadequate for the production of these energies. It is suggested that the instability that triggers the energy release during a solar flare may affect the corona globally (rather than only locally). Although our energy estimates are subject to large uncertainties, they may be confirmed by future *Ulysses* observations.

Subject headings: Sun: flares — Sun: X-rays, gamma rays — acceleration of particles

1. INTRODUCTION

A solar flare is generally assumed to release energy at a rate less than 10^{30} ergs s^{-1}, the source of energy being the magnetic field in the vicinity of the flare (Svestka 1976, p. 300; Dennis & Schwartz 1989). The release of energy is presumably from the coronal magnetic field, details of the exact process varying from one model to another. A magnetic loop or helmet structure has been invoked for acceleration of particles and heating of plasma in the flare region (Holman, Kundu, & Kane 1989; Holman & Benka 1992). Although recent high-resolution observations of the soft and hard X-ray sources in the flare region have shown the existence of loops or looplike structures (see Masuda 1993), the basic flare process is not yet well understood. In this Letter we present *Ulysses* observations relevant to the energy and particle requirements for some of the very large flares in the current solar activity cycle (cycle 22). These observations seem to indicate that production of these flares may stretch to the limit the energy and material resources of an active region.

2. HARD X-RAY SPECTROMETER ON *ULYSSES*

The Solar X-ray/Cosmic Gamma-Ray Burst Experiment aboard the interplanetary spacecraft *Ulysses* has among its objectives the stereoscopic measurements of solar X-ray emission. The experiment has been described in detail elsewhere (Hurley et al. 1992; Kane et al. 1993). Here we present briefly the characteristics of the hard X-ray spectrometer relevant to solar flare observations. The hard X-ray sensor consists of two CsI(Tl) scintillators with an effective area of ~ 20 cm^2; the lower energy threshold, at which the detector is 10% efficient, is determined by the entrance window and is 11 keV. The instrument is designed to measure X-ray count rates and energy spectra in the nominal energy range 15–150 keV. Hard X-ray bursts from solar flares often trigger the "burst mode." In this mode 5–150 keV X-ray spectra are recorded in 16 channels using relatively slow microprocessor electronics. The time resolution is 1–16 s depending on the elapsed time after the trigger occurred. In the absence of a burst the instrument operates in the "real time mode." In this mode the integral counting rate of X-rays above a nominal ~ 25 keV threshold energy is continuously available. The time resolution is 0.25–2.0 seconds depending on the telemetry rate. These rates use a discriminator circuit which is independent of the microprocessor. The highest observed integral counting rate is $\sim 8 \times 10^4$ counts s^{-1} and is relatively independent of the incident photon spectrum. At higher photon fluxes, dead time effects cause a decrease in the recorded rate. The integral rate data presented here include appropriate corrections for the dead time effects and counter overflow and are "normalized" to the Earth's distance from the Sun.

Intense hard X-ray fluxes distort the pulse height spectrum because of pulse pile-up effects. We have studied this with a Monte Carlo program that follows the interactions of photons in the crystal. Among other things, it takes into account the photon absorption in the window, multiple photoelectric and Compton interactions in the crystal, the energy resolution of the detector, and pulse pile-up of photons arriving at random (Poisson-distributed) times. We ran this code for count rates up to 10^6 interactions s^{-1} for both power law (indices 2, 3, 4, 5, and 6) and bremsstrahlung (kT's of 1, 2, 4, and 8 keV) energy spectra. We find that it is quite possible for a 2 keV bremsstrahlung spectrum to produce pile up counts in our energy range. Indeed the fluxes recorded by *GOES* for the June 1 event, which we discuss below, are sufficiently intense to contribute substantially to our observations, although we believe that they cannot explain them entirely. Nevertheless, uncertainties exist in the Monte Carlo model, particularly in the treatment of pulse pileup, which in turn introduce uncertainties in the energy estimates which we make below, and these are discussed further in § 5.

3. OBSERVATIONS

Between 1991 January and June the *Ulysses* instrument observed 11 solar hard X-ray flares with effective peak counting rates greater than 4×10^5 counts s^{-1} (Table 1). These "giant" flares include some of the largest flares (*GOES* class > X12) ever recorded. In fact, for many of them, one or both channels of the *GOES* instrument were *saturated* (i.e., remained at a constant, maximum rate), and hence the true time and magnitude of the maximum of the soft X-ray emission is not known. A similar situation exists for hard X-ray instruments aboard most near-Earth spacecraft. However, because of the large distances (several AU) from the Sun, the X-ray flux at the *Ulysses* instrument was smaller than that at the near-Earth instruments by a factor of 3–12. Consequently, *Ulysses* could observe, without complete saturation, the integrated counting rate during these giant flares. By this we mean that the counting rate, although subject to large dead time effects, continued to vary in response to varying solar X-ray fluxes. In some cases, good photon spectra in the early phase of the flares were also measured (e.g., 14:58 to 15:01 UT for the June 1 flare), but we will concentrate on the integral rate data, since they were taken by a simple discriminator circuit independent of the PHA and microprocessor electronics capable of functioning at much higher counting rates. Most of the unocculted flares in Table 1 were associated with very intense soft X-ray and microwave radio bursts. For example, the flare on 1991 June 6 had an associated X12 soft X-ray burst and a 15.4 GHz radio burst with peak flux density of 75,000 sfu. The flares on June 21, 26, 28, and 30 are included in Table 1 although the soft X-ray emission from these flares, as observed by *GOES*, was small or undetectable. The *Ulysses* observations indicate that these flares were indeed giant. The associated soft X-ray emission was small, most probably because the flares were located behind the east limb of the Sun and hence the soft X-ray sources were partially or completely occulted from the view of the near-Earth instruments.

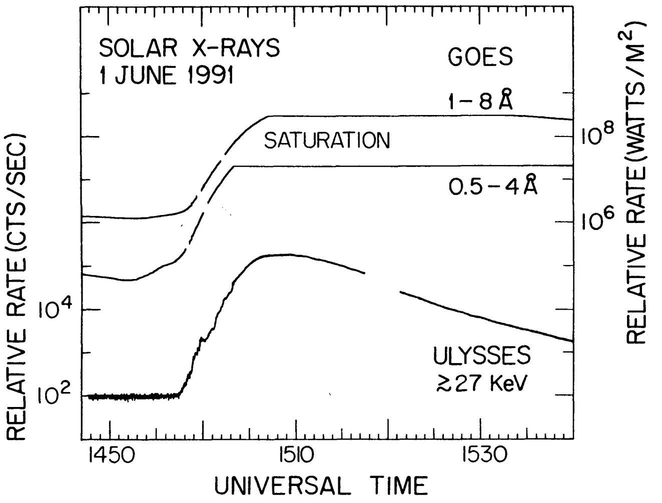

FIG. 1.—Time-rate profile for the integral counting rate of hard X-rays (>27 keV) observed by *Ulysses* and broad-band soft X-rays (1–8 Å and 0.5–4 Å) observed by *GOES* during the 1991 June 1 solar flare. Note that *GOES* rates for both channels are completely saturated because of intense soft X-ray flux.

As an example, we discuss the flare on 1991 June 1 in detail. It occurred in the active region 6659 at a location ~5°–10° behind the east limb. The X-ray, gamma ray, and microwave radiation sources in this flare were, therefore, partially occulted from the view of the near-Earth instruments. On the other hand, the hard X-ray source was in full view of the *Ulysses* instrument, which was located 22° behind the east limb at the time of the flare. It is probably the largest solar flare of this solar cycle. The light curve for X-rays greater than 27 keV observed by *Ulysses* is shown in Figure 1. The hard X-ray burst started at ~1457 UT and reached a broad maximum at ~1508 UT. For comparison, soft X-ray emission observed by *GOES* is also shown in Figure 1. The soft X-ray burst (magnitude > X12: Garcia & McIntosh 1992), started at ~1452 UT; it saturated *GOES* X-ray channel 1 starting at 15:03 and channel 2 starting at 15:07 (Solar Geophysical Data). Saturation ended at 1537 UT. At 15.4 GHz, the peak microwave emission occurred at ~1507 UT and had a flux density of ~54,000 sfu. Substantial hard X-ray/gamma-ray emission in the 100 keV–8 MeV range, with a maximum at ~1504 UT, was observed from 1457 to 1519 UT by the Phebus

TABLE 1

CHARACTERISTICS OF GIANT FLARES

			HARD X-RAYS (*ULYSSES*)								
			Rates of *Ulysses*				Hα FLARE			NON-THERMAL ELECTRONS GREATER THAN 20 keV	
						SOFT X-RAYS (*GOES*)		Location			
DATE (1991)	TIME OF MAXIMUM (UT)	MINIMUM E (keV)	Observed (counts s^{-1})	Dead Time-Corrected (counts s^{-1})	Rates at 1 AU (counts s^{-1})	Int.	Int.	Lat.	CMD	Energy (ergs s^{-1})	Number (electrons s^{-1})
25 Jan.......	0633:00	22.7	4.1×10^4	6.0×10^5	2.1×10^6	X10.8	1B	S12	E90	9.1×10^{30}	2.0×10^{38}
04 Mar......	1401:00	24.0	7.0×10^3	1.3×10^6	6.9×10^6	X7.1	...	...	E103	3.3×10^{31}	7.3×10^{38}
22 Mar......	2244:20	25.7	6.8×10^4	3.8×10^5	2.3×10^6	X9.4	3B	S26	E28	1.3×10^{31}	2.9×10^{38}
29 Apr	1401:00	31.5	4.5×10^4	6.0×10^4	4.9×10^5	...	...	...	>E90	4.5×10^{31}	1.0×10^{39}
01 Jun	1509:00	26.9	7.5×10^3	1.1×10^6	1.1×10^7	>X12.0	1F	N25	E90	6.8×10^{31}	1.5×10^{39}
04 Jun	0343:30	27.1	6.1×10^4	4.0×10^6	4.1×10^5	>X12.0	2N	N34	...	2.5×10^{31}	5.7×10^{38}
06 Jun	0106:30	27.2	6.0×10^4	1.0×10^5	1.0×10^6	>X12.0	3B	N32	E45	6.5×10^{30}	1.4×10^{38}
21 Jun	0824:15	28.0	4.8×10^4	6.5×10^4	7.3×10^5	...	...	...	>E90	4.9×10^{30}	1.1×10^{38}
26 Jun	2011:45	28.2	6.6×10^4	3.6×10^5	4.2×10^6	C2.9	...	...	>E90	2.9×10^{31}	6.5×10^{38}
28 Jun	1428:55	28.0	3.0×10^4	3.5×10^4	4.1×10^5	...	...	...	>E90	2.8×10^{30}	6.3×10^{37}
30 Jun	0256:22	28.0	5.4×10^4	7.8×10^4	9.2×10^5	...	...	...	>E90	6.4×10^{30}	1.4×10^{38}

instrument on the near-Earth spacecraft *Granat* (Barat et al. 1994). The Phebus energy range (>120 keV) is relatively immune to pulse pile-up from a soft bremsstrahlung spectrum, and the emission it observed can safely be assumed to be nonthermal. (The fact that it was observed beyond the limb may explain why the Phebus time profile is more impulsive than the *Ulysses* time profile.) We have verified that the *Ulysses* photon spectra taken from ~14:58 to ~15:01 are indeed power laws. From 15:00 to 15:01 the power-law index is ~4.1, which is the same as the Phebus count spectrum index (Barat et al. 1994). After 15:01 the spectra contain the signature of pulse pile-up, namely a turnover and a deficit of low-energy photons. Comparison with our Monte Carlo results indicates that this distortion is not what would be expected from pulse pile-up due to a soft thermal spectrum, but rather, from a power-law spectrum. Using the procedure of Thomas, Starr, & Crannell (1985) we have used the *GOES* data to track the temperature and emission measure of the thermal plasma. Just prior to saturation in channel 1 (15:03), we find these values to be $\sim 40 \times 10^6$ K and $\sim 10^{50}$ cm^{-3}, respectively. Such a spectrum could account for only 20% of the counts we observe with *Ulysses*, even when pile-up effects are included. If we assume a constant temperature and extrapolate the channel 1 rates to the point where channel 2 saturates (15:07), we find that the thermal spectrum could only account for 12% of the observed *Ulysses* counts, including pile-up. These calculations do not take into account the fact that the flare region was fully viewed by *Ulysses*, but partially occulted as viewed by *GOES*; thus *Ulysses* could have observed a more intense thermal source than *GOES*. We return to this point in § 4.

4. ENERGETIC ELECTRONS

If the observed hard X-ray emission is primarily impulsive with a power-law spectrum, as inferred above, it is expected to be thick-target bremsstrahlung produced by a nonthermal distribution of energetic electrons moving from the corona to the chromosphere. Several models for the hard X-ray source have been developed in detail (see Holman, Kundu, & Kane 1989; McTiernan & Petrosian 1990; Holman & Benka 1882).

Let the incident photon spectrum be a power law given by $j(E) = KE^{-\gamma}$ photons cm^{-2} s^{-1} keV^{-1} at 1 AU from the Sun. For an assumed $\gamma = 3.5$ (a value consistent with the *Ulysses* and Phebus observations, and common at the impulsive hard X-ray maxima of energetic flares—see Bromund, McTiernan, & Kane 1995), the observed counting rate at 1 AU, and the known response of the instrument to X-rays can be used to determine the spectral parameter K for the incident photon spectrum. For a simple thick-target model with isotropic X-ray emission (Brown 1971; Hudson, Canfield, & Kane 1978) the injection rate spectrum of energetic electrons at the Sun responsible for the power-law hard X-ray spectrum is also a power law. The rate at which the number and energy of electrons ≥ 20 keV were deposited in the hard X-ray source during different flares are presented in Table 1. It can be seen that, at the hard X-ray maximum electrons with energy ≥ 20 keV are injected in the thick target X-ray source at a rate of 10^{37}–10^{39} electrons s^{-1}. The correspondng injection rate for the energy is 10^{30}–10^{32} ergs s^{-1}. Considering the long duration (≥ 10 minutes) of these flares, the FWHM of the counting rate profile is ≥ 100 seconds. The total energy dissipated in these flares is therefore in excess of 10^{32}–10^{34} ergs carried by 10^{39}–10^{41} electrons above 20 keV.

Because *Ulysses* viewed the entire flare region, it is possible that it observed a more intense thermal component than *GOES*. If the intensity were such that the *entire Ulysses* count rates were due to thermal photons only, the total energy of the flare would still be considerable. For example, we find that it is possible that all of the *Ulysses* counts could be due to a piled-up thermal spectrum with $kT = 1.8$ keV. However, such a spectrum would have a total energy of $\sim 8 \times 10^{29}$ ergs s^{-1} *in X-rays alone*. If we assume $kT = 4$ keV, considerably more than 10^6 counts s^{-1} would be required to explain 99% of the counts by a piled-up spectrum. Our pulse pile-up simulations are not expected to be reliable above 10^6 counts s^{-1}, because multiple (rather than just double) pulses are involved. However, if we assume that 5×10^6 counts s^{-1} are required to explain the entire count rate by piled-up thermal photons (i.e., 5 times more than we estimated above) we arrive at an energy estimate $\sim 5 \times 10^{28}$ ergs s^{-1} in X-rays alone. Using the study of Canfield et al. (1980) to convert these numbers to total radiated energy, and integrating over the X-ray time history, we estimate that the total flare energy would have been between 10^{32} and 2×10^{33} ergs, still a considerable energy.

5. SOURCE OF RELEASED ENERGY AND ACCELERATED PARTICLES

Taken at face value, the observations and analysis presented here show that the giant flare on 1991 June 1 represents energy dissipation by more than 20 keV electrons at a rate of $\sim 10^{32}$ ergs s^{-1} associated with a production rate of $\sim 10^{39}$ electrons s^{-1}. The rate of energy release was thus ~2% of the solar luminosity, a fraction which is in principle measurable using irradiance monitors (Hudson & Willson 1983). The total energy released during the flare was $\sim 10^{34}$ ergs carried by $\sim 10^{41}$ electrons. This estimate does not include the energy dissipated in mass motions associated with the flare. So far, the giant flare on 1991 June 1 is the most energetic solar flare of the present solar activity cycle (cycle 22) with a rate of energy release about 100–1000 times larger than that in the well studied flares in 1972 August (Lin & Hudson 1976). The energy release in most other giant flares listed in Table 1 is somewhat smaller but still much larger than that in the so-called large flares studied in the past. There are two main sources of uncertainty in these estimates: the Monte Carlo modeling of the pulse pile-up, and the electron spectrum lower limit. We assume a conservative uncertainty for the former of an order of magnitude. If the electron energy lower limit were 50 keV, the above energy estimates would be reduced by a factor of $0.4^{2.5}$ or 0.1. Thus, these estimates should be considered to have a maximum uncertainty of two orders of magnitude.

Basic requirements of an impulsive energetic flare are (1) sufficient amount of energy available for release on timescales ≤ 1 s; (2) rapid (≤ 1 s) acceleration of particles to relativistic energies (see Kane et al. 1986) with many energetic particles reaching the corona and some energetic particles leaving the Sun; and (3) compact sources of impulsive hard X-ray/gamma-ray, EUV, and optical emissions located in the chromosphere/transition region (Kane et al. 1980; Kane et al. 1982; Dennis & Schwartz 1989; Masuda 1993; Sakao 1994). The photosphere and the convection region underlying the active region are, of course, large reservoirs of particles and energy. At present there is no general agreement on the physical process which would relate the mechanical energy in the convection zone to the energy dissipation in the corona during a flare. Among the three types of models generally considered, viz: (1) photospheric dynamo, (2) magnetic energy storage in the corona, and

(3) emerging/erupting flux tube, only the emerging flux tube model seems to be capable of producing a flare with total energy as large as $\sim 10^{33}$ ergs (McClymont & Fisher 1989). However, since the implicit time constant for accumulating such a large amount of energy is several years, the emerging flux tube model is unable to explain the production of several giant flares in a single active region within one week, as in 1991 June.

It is interesting to compare the energy and particle requirements for giant flares with the resources of an active region. For an active region with an average coronal magnetic field of $B \sim 100$ G over an area $A < 10^{20}$ cm^2, the total magnetic field energy is $\epsilon_b = A^{3/2}B^2/8\pi < 4 \times 10^{32}$ ergs. Since the total energy of the nonpotential field is less than ϵ_b, the total magnetic field energy available from an active region will be used up by the flare within a few seconds. If the average density in the corona above the active region is $n_e \sim 10^{10}$ cm^{-3}, the total number of thermal electrons in that part of the corona is $\eta_e = \eta_e A^{3/2} < 10^{40}$. Since the giant flares require 10^{39}–10^{41} energetic electrons and the efficiency of the acceleration process is likely to be less than 100%, the active region can barely supply enough electrons for acceleration during the smaller of the giant flares.

The resources of an active region thus seem to be inadequate for the production of giant flares. This is especially true if the release of energy occurs primarily in the corona. Since the flares studied here appear to be basically similar to the often observed medium-large flares, a reexamination of our present ideas about the sources of energy and particles for solar flares is indicated. It is possible, for example, that the instability that triggers the energy release during a solar flare affects the corona globally (rather than only locally) so that resources from a substantial part of the corona inside as well as outside the relevant active region are available for energy release and acceleration of particles. Thus, although the sources of impulsive hard X-ray/gamma-ray and EUV/optical emissions are compact and localized, the energy required to excite these emissions may be derived from magnetic field far from these sources. Hence, the solar flare process is considered more complex and its operation seems to be on a much larger scale than that often described in models with a simple magnetic loop or a helmet structure.

It is clear from the preceding discussion that raising the energy output of even a relatively small number of exceptional flares is not a step to be taken lightly. The *Ulysses* data set, particularly for the June 1 flare, is a unique one which cannot be verified independently. There is, however, a good chance that the *Ulysses* mission will be extended into the next solar maximum. If so, improved *GOES* detectors at that time, and *Ulysses* observations at ~ 5 AU from the Sun between 1997 and 1999, may ultimately confirm our findings.

We acknowledge discussions with H. Garcia regarding the *GOES* observations of very large flares, and numerous helpful comments from B. Dennis. The *Ulysses* Solar X-ray/GRB experiment was constructed at the CESR (Toulouse, France) with a grant from CNES, and at the Max-Plank Institute for Extraterrestrial Physics with support from FRG contracts 01 ON 088 ZA/WRK 275/4-7.12 and 01 ON 88014. We are indebted to R. Williams, C.-H. Y7, J. Callet, S. Davies, S. Vilke, and W. Wartelle for assistance in data reduction operations. K. H. acknowledges support from NASA under JPL contract 958056. S. K. and J. M. were supported by NASA through grants NAGW-2452 and NAG 5-1559 and Lockheed contract SE70A311OR, respectively.

REFERENCES

Barat, C., Trottet, G., Vilmer, N., Dezalay, J.-P., Talon, R., Sunyaev, R., Terekhov, O., & Kuznetsov, A. 1994, ApJ, 425, L109

Bromund, K., McTiernan, J., & Kane, S. 1995, ApJ, submitted

Brown, J. C. 1971, Solar Phys., 18, 489

Canfield, R., et al. 1980, in Solar Flares, ed. P. Sturrock (Boulder: Colorado Assoc. Univ. Press) 451

Dennis, B. R., & Schwartz, R. A. 1989, Solar Phys., 121, 75

Garcia, H. A., & McIntosh, P. S. 1992, Solar Phys., 141, 109

Holman, G. D., & Benka, S. G. 1992, ApJ, 400, L79

Holman, G. D., Kundu, M. R., & Kane, S. R. 1989, ApJ, 345, 1050

Hudson, H. S., Canfield, R. C., & Kane, S. R. 1978, Solar Phys., 60, 137

Hudson, H., & Willson, R. 1983, Solar Phys., 86, 123

Hurley, K., et al. 1992, A&AS, 92, 401

Kane, S. R., Chupp, E. L., Forrest, D. J., Share, G. H., & Rieger, E. 1986, ApJ, 300, L95

Kane, S. R., et al. 1980, in Solar Flares, ed. P. A. Sturrock (Boulder: Colorado Assoc. Univ. Press), 188

Kane, S. R., Fenimore, E. E., Klebesadel, R. W., & Laros, J. G. 1982, ApJ, 254, L53

Kane, S. R., Hurley, K., McTiernan, J. M., & Sommer, M. 1993, Adv. Space Res., 13, 241

Lin, R. P., & Hudson, H. S. 1976, Solar Phys., 50, 153

Masuda, S. 1993, Ph.D. thesis, Univ. Tokyo

McClymont, A. N., & Fisher, G. H. 1989, in Solar System Plasma Physics, ed. J. H. Waite, J. L. Burch, & R. L. Moore (Washington: AGU), 219

McTiernan, J. M., & Petrosian, V. 1990, ApJ, 359, 541

Sakao, T. 1994, Ph.D. thesis, Univ. Tokyo

Svestka, Z. 1976, Solar Flares (Dordrecht: Reidel)

Thomas, R., Starr, R., & Crannell, C. 1985, Solar Phys., 95, 323