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THE ROLE OF HIGH-ENERGY PROTONS AND ELECTRONS IN POWERING THE SOLAR WHITE-LIGHT FLARE EMISSION

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Abstract. The temporal histories of three intense and impulsive gamma-ray flares, for which also white-light emission had been observed, are analyzed in order to test the role of high-energy particles – electrons and protons – in powering the optical continuum. By comparing the light curves at optical wavelengths and at X-ray and gamma-ray energies, we find a good correlation of the main peaks of emission, which confirms previous findings that the continuum emission is most likely associated with the energy loss of energetic particles. The power carried by the greater-than-50 keV nonthermal electrons may be sufficient to balance the optical emission. The power residing in protons or ions with energies greater than 1 MeV depends largely on the spectral shape of the particle distribution. Only if this is similar to a power law, may the energy carried by these high-energy particles be sufficient to balance the white-light flare emission.

1. Introduction

Solar flares are observed routinely in the optical regime in Hα. In rare cases, small parts of a flare become visible in white light for a few minutes near flare maximum. The generally good temporal correlation between a white-light flare (WLF) emission and bursts in hard X-rays and microwaves points to an origin of the optical continuum that is associated with accelerated particles. One possible conclusion is that beams of energetic electrons and/or protons bombard the lower solar atmosphere and produce the continuum emission (see review by Neidig, 1989). The conclusion that nonthermal thick-target electrons can lead to solar flare optical continuum is based upon measurements which show that these electrons may carry sufficient power to balance the output in the optical continuum, and that peaks in the optical and high-energy X-ray emissions have a generally good

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temporal correlation (Neidig *et al.*, 1993; Neidig and Kane, 1993). Because flare measurements in the gamma-ray regime are much rarer than those at X-rays, the role of energetic protons or ions in powering the optical continuum is not so well established. There are, to our knowledge, only two papers that have made quantitative comparisons between optical output and the power in energetic protons as measured from nuclear gamma-ray lines (Lin and Hudson, 1976; Ryan *et al.*, 1983). In this paper we investigate three big flares that showed intense gamma-ray line emission, observed by the Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) satellite. The power carried by the energetic protons and electrons is calculated and compared to the output in white light recorded at the National Solar Observatory/Sacramento Peak.

2. Observations

2.1. OPTICAL OBSERVATIONS

The optical data were acquired with the Multi-Band Patrol (MBP) at Sacramento Peak (Neidig and Beckers, 1983) which records a six-channel sequence of photographic images at wavelengths/bandpasses (full-width, half maximum) of 3610/22, 5645/50, 6203/49, 4275/40, 5645/50, and 4957/48 Å. At the times of two of the flares described here (16 and 17 March, 1989) the MBP was operating in two channels (3610 and 4275 Å) at a full-cycle cadence of 30 s, while in the third flare (25 April, 1984) all channels were recorded at 30-s full-cycle cadence. Flare photometry was achieved using two-dimensional microphotometry and subtraction of co-registered preflare images. The absolute power output of the flare was determined by using the quiet solar background outside the active region as a calibration standard. Also, a flare spectrum extending into the near-UV and near-IR was assumed; details and method of observation are described elsewhere (Kane *et al.*, 1985; Neidig *et al.*, 1993; Neidig, Wiborg, and Gilliam, 1994). Aside from the random and systematic errors in image registration and photometric reduction, that apply over the range 3610–6203 Å and which are less than 30%, there is an additional uncertainty in the assumed near-UV and near-IR spectra of the flare which might be 50%, or possibly more, in terms of instantaneous power. An estimate of the latter uncertainty, which is model dependent, is crucial for the conclusions reached here. Although there is presently no generally-accepted atmospheric model for the WLF, we assume, based on the available observational evidence, that the emission includes a chromospheric component (hydrogen recombination series) as well as a photospheric back-warmed component (H-minus recombination) (e.g., Aboudarham and Hénoux, 1986, 1987, 1989). Under the assumption of a simple two-component model with a 10^4 K chromosphere, and the additional observational constraint provided by measurements of the flare brightness at the head of the Balmer continuum, the synthesized WLF flare spectrum will radiate about $\frac{1}{3}$

of its power between 3700 and 8200 Å (cf., Neidig *et al.*, 1993). If we make the somewhat arbitrary assumption that the remaining $\frac{2}{3}$ of the WLF power (in the W and IR) could be a factor of two larger or smaller than the $\frac{2}{3}$ fraction predicted by this two-component model, the uncertainty in the total power would then be +67 or −33%, respectively, of the calculated value based on the measurements available at visible wavelengths (note, however, that the availability of data at 3610 Å constrains to some extent the power radiated in Balmer continuum). An additional source of uncertainty originates from the variation in flare intensity with viewing angle. Consideration of the model dependency of the latter effect (cf., Neidig *et al.*, 1993) leads to an uncertainty not exceeding about $\frac{1}{3}$ of the value calculated from simple models. Our final estimate for the probable error in the total instantaneous WLF power in the visible, near-UV, and near-IR regimes, as shown in the figures here, is ±50% – a number which is itself uncertain.

2.2. ESTIMATION OF THE THICK-TARGET PROTON AND ELECTRON POWER

The proton power is deduced from the gamma-ray flux recorded by the GRS on SMM. In the gamma-ray regime the flux is a superposition of a continuum originating from high-energy electrons via bremsstrahlung and line radiation from the interaction of energetic protons or ions with the solar atmosphere. To separate the electron from the proton contribution, it is customary to extend the bremsstrahlung continuum, which can be approximated in the energy range 0.3 to 1 MeV by a power law, to higher energies. The excess above this power law can be ascribed to nucleonic interactions (Forrest, 1983; Chupp, 1984; Rieger, 1990). The energy range from 4 to 7 MeV contains the strong nuclear de-excitation lines of carbon and oxygen. Following Murphy and Ramaty (1984) and Ramaty (1986) we calculate the number of high-energy protons and the power carried by them, which will depend upon the cutoff energy. In this paper we adopt 1 MeV as the cutoff, because (1) protons with energies below about 3 MeV do not lead to nuclear excitation (Ramaty, Kozlovsky, and Lingenfelter, 1979) and (2) protons with energies below 1 MeV cannot penetrate to atmospheric layers dense enough to produce bright optical continuum (Lin and Hudson, 1976). The proton power has been calculated for two different shapes of the particle distribution: a modified Bessel-function of second order (Ramaty, 1979) whose slope steepens with energy, and a power law whose slope is constant in logarithmic representation. The electron power is deduced from measurements of one of two small X-ray detectors attached to the GRS on SMM (Forrest *et al.*, 1980; The GRS on SMM, 1991) which is sensitive from 14 to 199 keV. In order to prevent pulse pile-up effects during intense solar events it is covered by a graded shield consisting of thin plates of aluminum and iron. The energies at the channel boundaries are 14, 28, 56, 114, and 199 keV, providing four channels in addition to the readout of the 'burst-window' of the GRS, which is sensitive from 300 to 350 keV. To these data points a best-fit power law is adjusted, and the electron power is then calculated using a method developed in

Lin and Hudson (1976) and applied by Neidig *et al.* (1993) for the white-light flare of 7 March, 1989. In estimating the thick target nonthermal electron power, a lower limit of 50 keV has been chosen. Electrons with this energy have an atmospheric penetration range roughly equivalent to that of 1 MeV protons, and can reach well into the chromosphere to column densities of about 3×10^{20} cm^{-2} (Bai, 1982; Fisher, Canfield, and McClymont, 1985a). This corresponds to an atmospheric height of about 1000 km, at which substantial optical continuum emission can be produced relatively promptly (within a few seconds) via hydrogen recombination following ionization and heating by collisional degradation of the nonthermal particles (Lin and Hudson, 1976; Neidig *et al.*, 1993). Further transport of the deposited energy to even deeper layers of the atmosphere, via hydrodynamic responses to explosive heating of the chromosphere, might occur on somewhat longer time scales (up to about 10 s), resulting in deep atmospheric heating and further continuum emission (Nagai, 1980; Livshits *et al.*, 1981; Fisher, Canfield, and McClymont, 1985b). Thus our selection of 50 keV and 1 MeV as cutoff energies for electrons and protons, while somewhat arbitrary, allows for transport of flare energy via nonthermal particles to a sufficiently deep layer that intense optical continuum can be produced, and with time delays that are of the order of the time resolution of the optical data, or less.

2.3. THE FLARE EVENTS

The X3.6/2B white-light flare of 16 March, 1989 occurred in NOAA active region 5395 which produced numerous large flares during its passage across the solar disc (see NOAA Technical Memorandum ERL SEL-82). Among these events, several showed continuum emission as for instance the well-studied X1.8/2B flare of 7 March, 1989 (Neidig *et al.*, 1993). The flare of 16 March was recorded with the MBP with a temporal resolution of 30 s. Its evolution in the near ultraviolet at 3610 Å is illustrated in Figure 1. The WLF appears as a number of short-lived kernels, with maximum emission occurring around 15:25:30 UT. If the flare kernels mark the footpoints of flux tubes in the chromosphere, their multiple appearance reveals a complicated magnetic structure in the flaring region.

In Figure 2 the temporal history of the event is shown at high-energy X-rays and at gamma-rays. Concerning the emission in these energy ranges it is one of the most impulsive events that the GRS recorded in cycle 22 before it ceased to operate in the middle of November 1989. The event was not accompanied by a Coronal Mass Ejection (CME) or any other manifestation of flare activity in interplanetary space (Feynman and Hundhausen, 1994) contrary to the flare of 17 March, discussed below (see also NOAA Technical memorandum ERL SEL-82). The flare consists basically of two bursts of which the first one is very hard. This first burst is an example of an 'electron-dominated' event – a type of event which was detected previously by the GRS, and which represents an extreme case of a flare that exhibits a continuum over the whole gamma-ray range with no

1996SoPh..167..307R

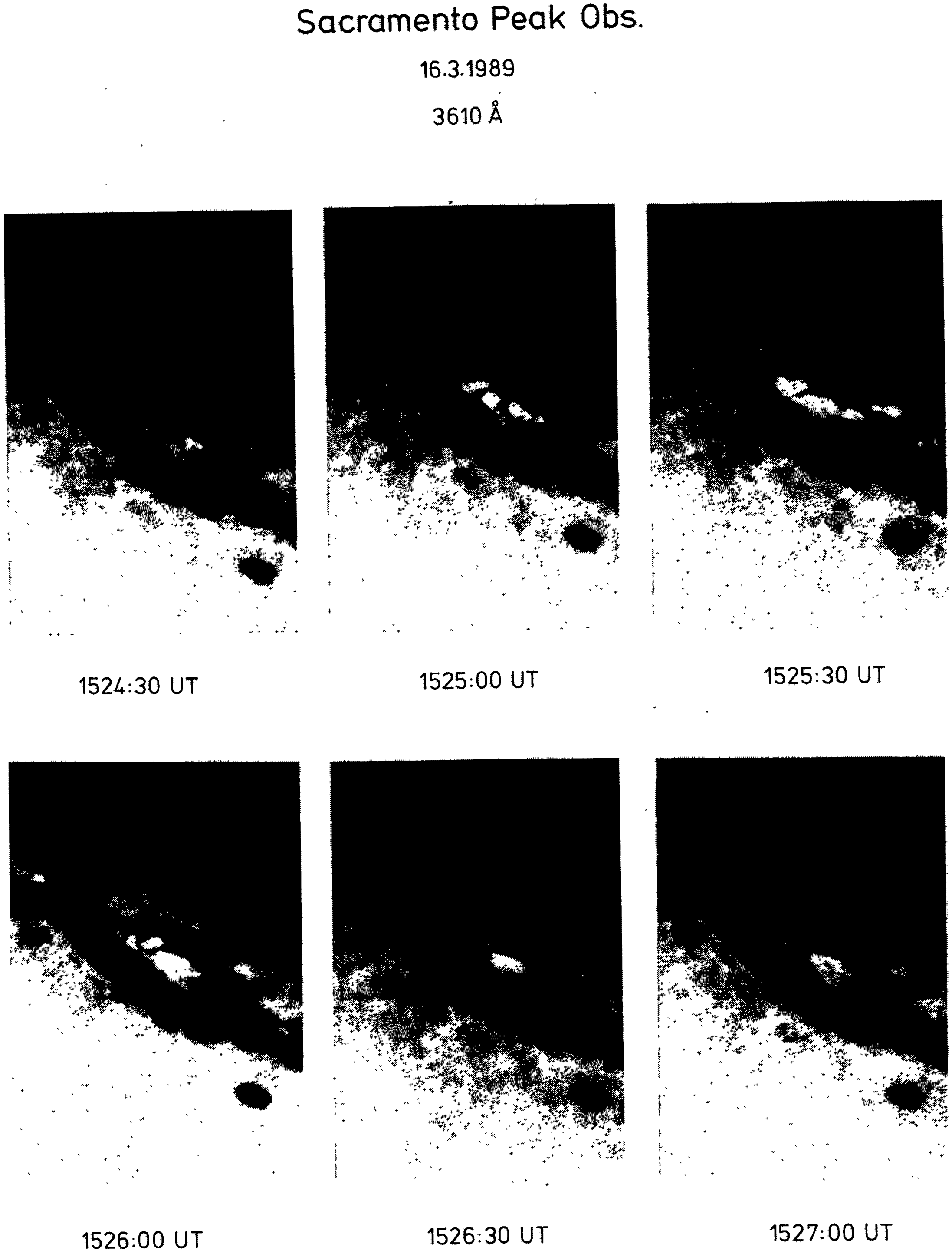

Figure 1. Temporal evolution of the WLF emission of the 16 March, 1989 flare at 3610 Å recorded by the National Observatory/Sacramento Peak.

significant appearance of gamma-ray lines (Rieger and Marschhaeuser, 1990). It is believed that these unusual events result from bremsstrahlung of highly relativistic electrons. During the second burst, which dominates at X-ray energies, nuclear lines appear in the spectrum, indicating that protons have been accelerated to MeV

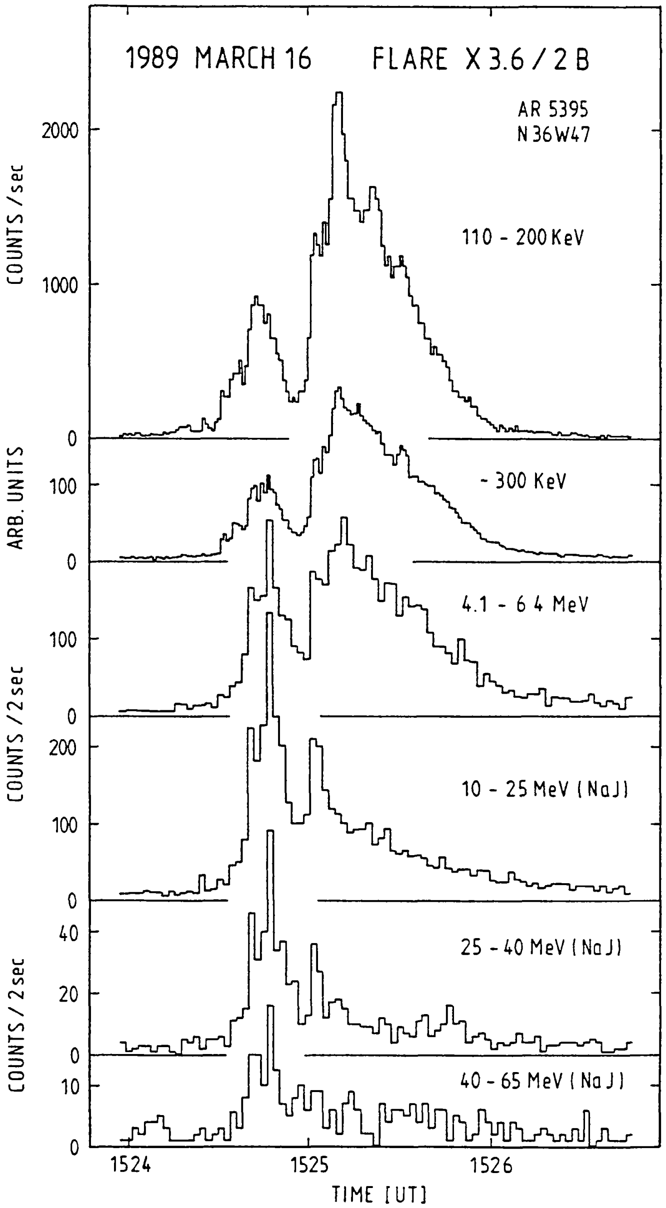

Figure 2. Temporal history of the 16 March, 1989 flare in different X-ray and gamma-ray energy bands.

energies. The line fluence, from which the number of accelerated and interacting particles can be calculated, categorizes this flare as a moderately large event.

In Figure 3 the temporal history of the flare is shown in the optical continuum, along with the power in nonthermal electrons with energies greater than 50 keV and the power in energetic protons with energies greater than 1 MeV. The latter is displayed two ways: one assuming a power law and one assuming a Bessel-function particle energy distribution. The electron power is indicated by a shaded area, reflecting the uncertainty in the best-fit power law through the spectral data. We truncated our calculation after 15:26:30 UT, because thereafter the single power-law fit becomes increasingly uncertain. For the proton power only a two-

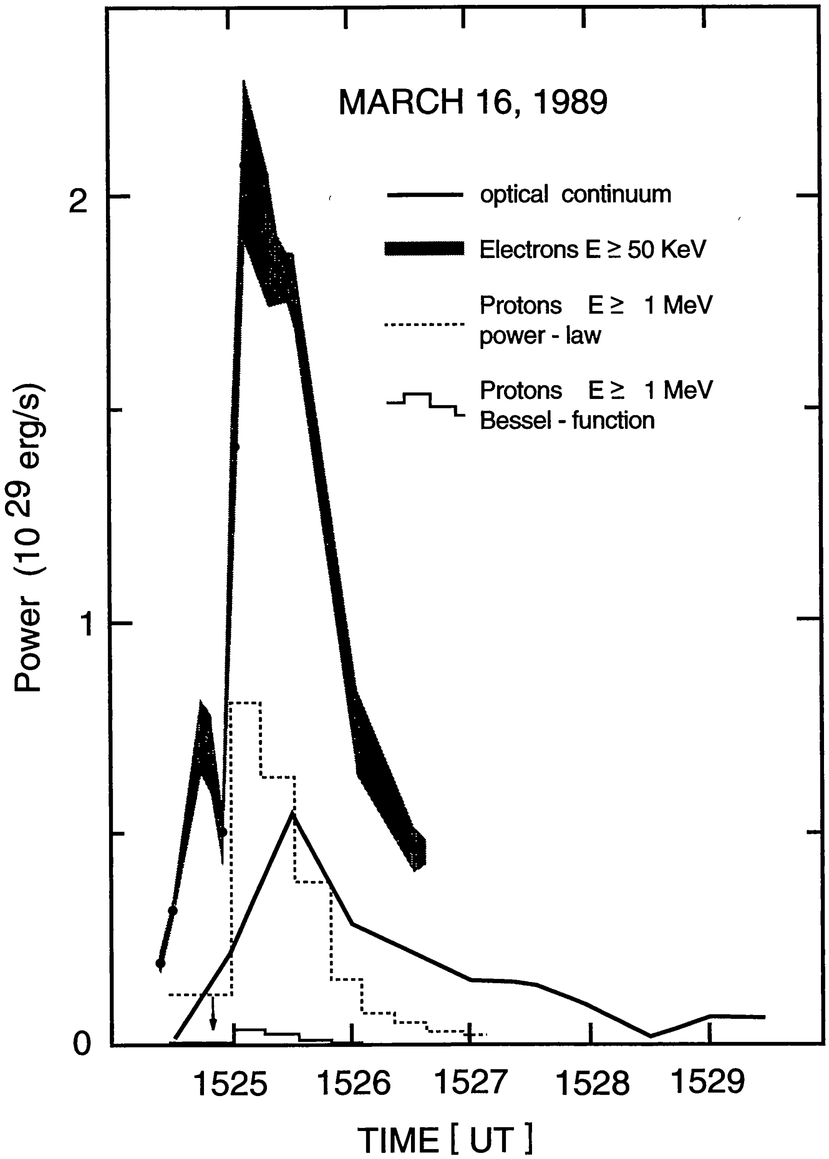

Figure 3. Power as a function of time in optical continuum (full line), in high-energy protons (histograms in dashed and full line), and in high-energy electrons (shaded area) of the 16 March, 1989 flare.

sigma upper limit can be given during the first burst. There is a delay of the peak of the optical continuum and the electron and proton power. However, due to the coarse time resolution at optical wavelengths, the amount of this delay is not precisely known. Images at 4275 Å, taken between the times of the exposures at 3610 Å, suggest that the peak power occurred between 15:25:15 and 15:25:30 UT. This would give a time lag of between 0 to 30 s, a value already observed in other white-light flares (Neidig and Kane, 1993). The first X-ray and gamma-ray burst occurred between the times of two exposures at 3610 Å. It is, therefore, not possible to check whether the impact of the very high-energy electrons led to a secondary maximum in the optical emission.

The flare of 17 March, 1989 (X6.5/2B) also originated from NOAA active region 5395. The weather conditions at Sacramento Peak, however, were less favourable than during the flare one day before, but despite this a light curve could be obtained. In Figure 4 the X-ray and gamma-ray emissions are shown versus time. This event is of an impulsive nature, too, but unlike the previous flare, the emission above 10 MeV is much less pronounced; nor does it have an electron dominated phase. Instead, the emission between 4.1 and 6.4 MeV is dominated by the carbon and oxygen de-excitation lines. In Figure 5 the temporal history of the optical continuum power (time resolution 30 s), the power carried by the non-thermal electrons and the power in high-energy protons with two different assumed spectral shapes, are shown. The power of the greater-than-50 keV electrons exhibits several peaks which stand out also in high-energy X-rays, but due to a steepening of the spectrum in the X-rays as the flare evolves, the main maxima of the electron power are shifted to later times. This is perhaps reflected in the optical data as well. The largest optical maximum occurs at about 17:36:40 UT. A second maximum in the optical continuum is evident at 17:38:10 UT, which could be associated with the electron power peak at 17:37:35 UT, but only if the time lag is unusually long.

The third flare is the exceptional event of 24 April (maximum on 25 April), 1984. It exhibited the highest flux and largest fluence in optical continuum observed so far (Neidig, 1989; Neidig, Grosser, and Hrovat, 1994). It was also one of the largest events recorded by the GRS and the X-ray spectrometers on SMM (Chupp, 1990). The light curve in optical continuum, as well as an X-ray time profile, recorded by the Hard X-ray Burst Spectrometer (HXRBS) on SMM, have already been published (Neidig, Grosser, and Hrovat, 1994). In the latter paper, however, it was not possible to calculate the thick target nonthermal electron power, because the very large X-ray fluxes associated with this event led to pulse pileup effects in the HXRBS recordings. In the present paper we estimate the electron power from measurements of one of our two X-ray detectors which, due to its small size (7.9 cm^2) and good shielding should be free from pulse pile-up. It must, however, be mentioned that scattered photons from the GRS (located in close proximity to the X-ray detector), during the most intense phase of the flare from 00:00–00:01:50 UT, may have influenced the X-ray recording (Forrest, private communication). It must also be mentioned that the nucleonic flux required a correction for gain shift, due to the intense photon flux near the threshold of the GRS (280 keV) during the same time interval. In Figure 6 the optical continuum power is compared to the power carried by the energetic electrons and protons. Again we realize a generally good correlation between the maxima of the optical continuum and the energetic particle power. However, due to the large error bars on the electron power, as well as the uncertainty in the optical power, a precise peak-to-peak coincidence to the respective curves cannot be proven.

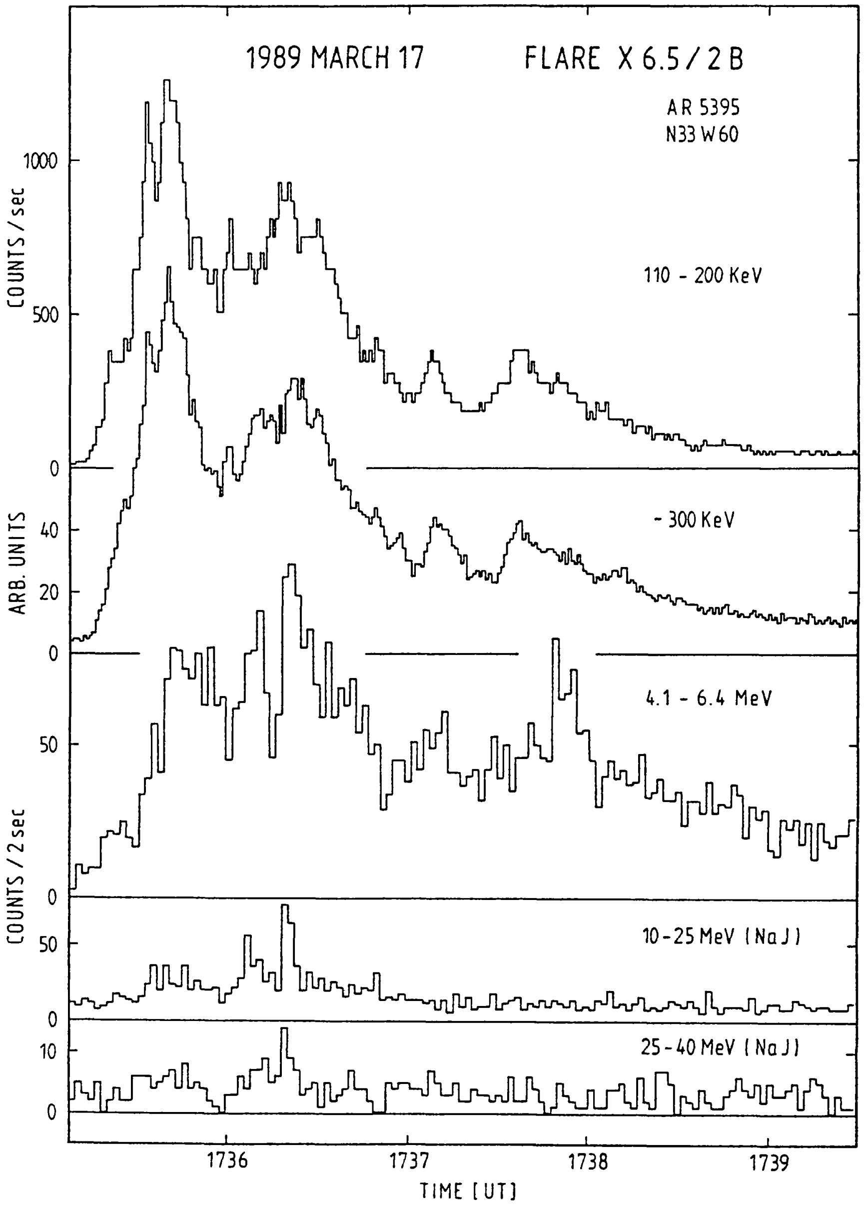

Figure 4. Temporal history of the 17 March, 1989 flare in different X-ray and gamma-ray energy bands.

3. Discussion

In order to check if high-energy protons could balance the WLF power we have used two different spectral shapes for the energetic particles: a modified Bessel function of second order and a power law. The Bessel function has an energy-dependent slope which approaches zero at low energies (Forman, Ramaty, and Zweibel, 1986) whereas the slope of the power law is constant. In the case of the flares under discussion the power law exponent is between 3.1 and 3.6 if deduced from the ratio of the 2.2 MeV neutron capture line and the 4 to 7 MeV nuclear excess fluence. This is within the range found for other gamma-ray line events (Hua

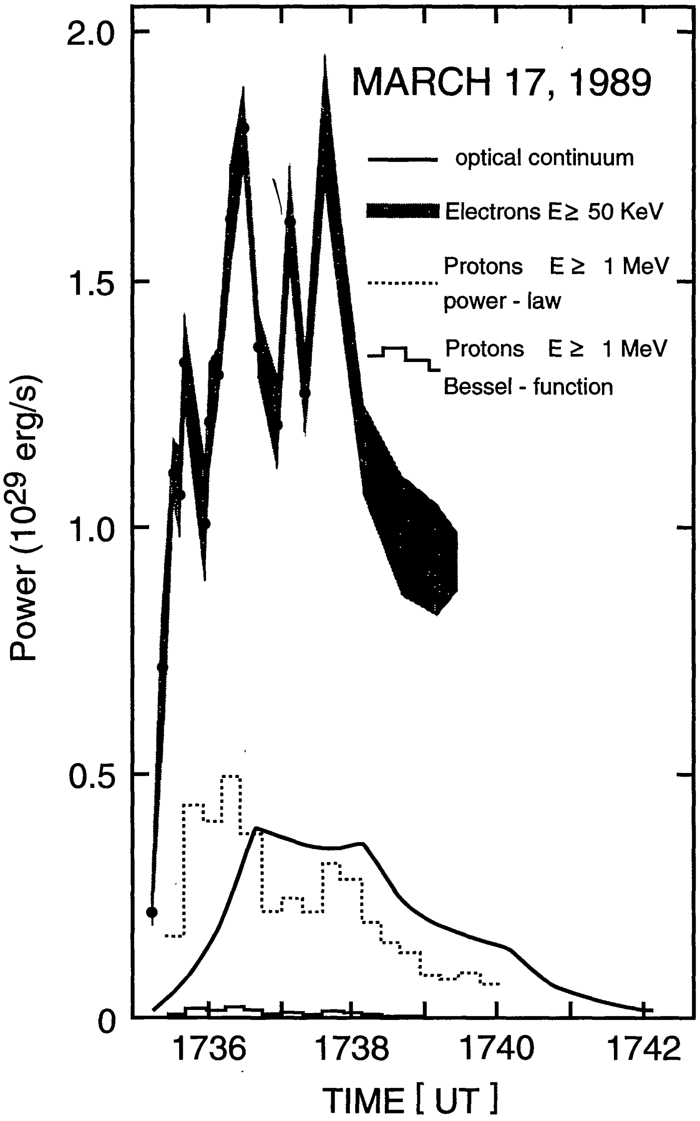

Figure 5. Power as a function of time in optical continuum, high-energy protons and electrons of the 17 March, 1989 flare.

and Lingenfelter, 1987). The calculated power is, therefore, much more dependent upon the cutoff energy of the particles, for a power law, as opposed to a Bessel function. If, for example, we lower the cutoff from 10 MeV to 1 MeV the power increases by more than an order of magnitude for the power law, and by only a factor of about two for a Bessel function. While this trend is not shown in the figures, we see that the high-energy proton power is much too low to balance the WLF output if the particle spectrum resembles a Bessel function. In the case of a power law the energy sufficiency is marginal, especially if also He^4 as a constituent of the beam is taken into account. Then, the power carried by the high-energy particles is about twice as high (Ramaty, 1995).

In order to decide which spectral form is the more probable, we would need a detector which is sensitive to photons with energies beyond 10 MeV. At these high

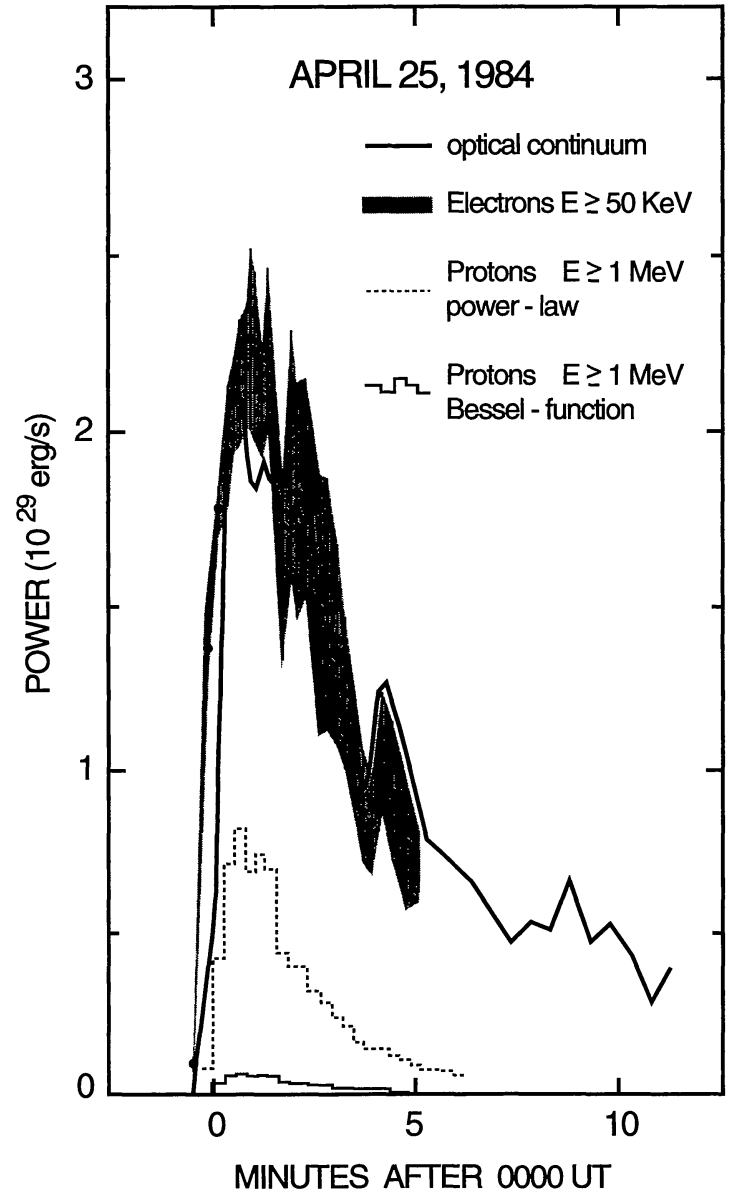

Figure 6. Power as a function of time in optical continuum, high-energy protons and electrons of the 24 (25) April, 1984 flare.

energies information can be obtained on the number of pions produced by protons with energies greater than about 150 MeV, interacting with the solar atmosphere (see Forrest *et al.*, 1985). The pion production depends crucially on the spectral form of the energetic particles, as calculations of Murphy and Ramaty (1984) have shown. According to the measurements obtained by the GRS on SMM, which is sensitive up to 140 MeV photon energies, a Bessel function, rather than a power law, is suggested for the flares discussed in this paper. In this case, the greater-than-1 MeV proton component is not a viable candidate for powering the solar white-light flare due to power insufficiency. A similar conclusion was reached by Ryan *et al.* (1983), who investigated the small gamma-ray line flare of 1 July,

1980. Recently, however, Ramaty *et al.* (1995) argue for a power law in the particle distribution at low energies down to about 1 MeV in order to fit the neon-to-oxygen ratio obtained from SMM gamma-ray line flare measurements (Share and Murphy, 1995) to values deduced from energetic particle observations in space (Reames, Meyer, and von Rosenvinge, 1994). If this somewhat artificial particle distribution – levelling off below about 1 MeV, a power law up to about 150 MeV and a cutoff at higher energies – should prevail during solar flares, then energetic protons can power the WLF emission.

Nevertheless, nonthermal electrons with energies greater than 50 keV, on the other hand, can within the limits of the experimental error, balance the WLF emission in all of the flares under discussion. For the flare of 25 April, 1984 (the most intense WLF observed so far) the electron power is approximately equivalent to the optical continuum through the white-light flare duration. In the 16 and 17 March flares the power in greater than 50 keV electrons is much greater than the power radiated in optical continuum. This disproportion is well known from other flare investigations (e.g., Neidig and Kane, 1993). In fact, there are known to have been cases of very large flares, as for instance the 6 March, 1989, X15/3B event, that are apparently devoid of detectable levels of optical continuum (Feynman and Hundhausen, 1994). While this may in part be due to a lack of sensitive detectors around the world, it may also indicate that, depending on individual circumstances, only part of the energy in high-energy electrons goes into powering the optical continuum, while the remainder goes into other wavelengths or generates mass motions (Lin and Hudson, 1976).

4. Concluding Remarks

The basic outcome of this paper is that the WLF emission cannot be powered by high-energy protons, if the particle distribution is represented by a modified Bessel function of second order. This spectral form is suggested by our GRS measurements. In this case, the power carried by protons or ions is at least an order of magnitude too small (see also a compilation of WLF's by Rieger and Gan (1993)). If, on the other hand, the particle distribution fits a power law at low energies, or there should exist a particle component below 1 MeV that contributes a substantial amount of power, then protons or ions can balance the WLF output. Such low-energy particles do not excite nuclear lines and are, therefore, not accessible to gamma-ray spectrometers. Metcalf *et al.* (1993) report the observation of about 100 keV protons by the measurement of impact polarization during a flare, but there are no flux values reported. These particles, moreover, might not have sufficient range to reach the atmospheric levels from which the WLF emission originates, so that the energy carried by them would have to be transported downward by some process subsequent to their thermalization. The concept that the WLF is powered by nonthermal thick target electrons is supported by our measurements, primarily from energetic considerations. There is a good temporal correlation, within the limits imposed by the time resolution and the time scales of the transport processes, between the maxima of the optical continuum and the high-energy X-rays. Each of the flares investigated also shows a large increase in brightness at 3610 Å, relative to 4275 Å, which suggests a Balmer jump and hence recombination emission – which, in turn, suggests that a substantial fraction of the optical continuum may be chromospheric in origin (Neidig, 1989; Fang and Ding, 1995). If, however, a sizable fraction of the continuum should originate in the upper photosphere (Neidig, Wiborg, and Gilliam, 1993; Ding *et al.*, 1994), we would require electrons with energies in excess of 900 keV (Bai, 1982; Fisher, Canfield, and McClymont, 1985a) in order to reach this dense layer directly. As the power carried by these high-energy electrons is on the order of only 10^{26} erg s^{-1} even in these large flares, they could not contribute enough energy, and we would be left with the alternative that some other mechanism must be present to transport energy from the chromosphere to the photosphere. Among the possibilities for such a mechanism are irradiation by intense chromospheric Balmer continuum (Aboudarham and Hénoux, 1986, 1987, 1989; Machado, Emslie, and Avrett, 1989; Gan *et al.*, 1992; Neidig, Wiborg, and Gilliam, 1993; Neidig, 1993; Gan and Mauas, 1994) and the propagating hydrodynamic disturbances as noted above.

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References

Aboudarham, J. and Hénoux, J. C.: 1986, *Astron. Astrophys.* **156**, 73.
Aboudarham, J. and Hénoux, J. C.: 1987, *Astron. Astrophys.* **174**, 270.
Aboudarham, J. and Hénoux, J. C.: 1989, *Solar Phys.* **121**, 19.
Bai, T.: 1982, *Astrophys. J.* **259**, 341.
Chupp, E. L.: 1984, *Ann. Rev. Astron. Astrophys.* **22**, 359.
Chupp, E. L.: 1990, *Astrophys. J. Suppl.* **73**, 213.
Ding, M. D., Fang, C., Gan, W. Q., and Okamoto, T.: 1994, *Astrophys. J.* **429**, 890.
Fang, C. and Ding, M. D.: 1995, *Astron. Astrophys. J. Suppl.* **110**, 99.
Feynman, J. and Hundhausen, A. J.: 1994, *J. Geophys. Res.* **99**, No. A5, 8451.
Fisher, G. H., Canfield, R. C., and McClymont, A. N.: 1985a, *Astrophys. J.* **289**, 414.
Fisher, G. H., Canfield, R. C., and McClymont, A. N.: 1985b, *Astrophys. J.* **289**, 434.
Forman, M. A., Ramaty, R., and Zweibel, E. G.: 1986, in P. A. Sturrock, T. E. Holzer, D. Mihalas, and R. K. Ulrich (eds.), *The Physics of the Sun*, Vol. 2, Ch. 13, D. Reidel Publ. Co., Dordrecht, Holland, p. 249.
Forrest, D. J.: 1983, in M. L. Burns, A. K. Harding, and R. Ramaty (eds.), *Positron – Electron Pairs in Astrophysics*, AIP, New York, p. 3.

Forrest, D. J. and 12 authors: 1980, *Solar Phys.* **65**, 15.

Forrest, D. J., Vestrand, W. T., Chupp, E. L., Rieger, E., Cooper, J. F., and Share, G. H.: 1985, *19th Int. Cosmic Ray Conf. Papers* **4**, 146.

Gan, W. Q. and Mauas, P. J. D.: 1994, *Astrophys. J.* **430**, 891.

Gan, W. Q., Rieger, E., Zhang, H. Q., and Fang, C.: 1992, *Astrophys. J.* **397**, 694.

Hua, X.-M. and Lingenfelter, R. F.: 1987, *Solar Phys.* **107**, 351.

Kane, S. R., Love, J. J., Neidig, D. F., and Cliver, E. W.: 1985, *Astrophys. J.* **290**, L45.

Lin, R. P. and Hudson, H. S.: 1976, *Solar Phys.* **50**, 153.

Livshits, M. E., Badalyan, O. G., Kosovichev, A. G., and Katsova, M.: 1981, *Solar Phys.* **73**, 269.

Machado, M. E., Emslie, A. G., and Avrett, E. H.: 1989, *Solar Phys.* **124**, 303.

Metcalf, T., Mickey, D., Canfield, R., and Wülser, J.-P.: 1993, in J. M. Ryan and W. Th. Vestrand (eds.), *High-Energy Solar Phenomena – A new Era of Spacecraft Measurements*, AIP, New York, p. 59.

Murphy, R. J. and Ramaty, R.: 1984, *Adv. Space Res.* **4**, No. 7, 127.

Nagai, F.: 1980, *Solar Phys.* **68**, 351.

Neidig, D. F.: 1989, *Solar Phys.* **121**, 261.

Neidig, D. F.: 1993, *Adv. Space Res.* **13**, No. 9, 317.

Neidig, D. F. and Beckers, J. M.: 1983, *Sky Telesc.* **65**, 226.

Neidig, D. F. and Kane, S. R.: 1993, *Solar Phys.* **143**, 201.

Neidig, D. F., Grosser, H., and Hrovat, M.: 1994, *Solar Phys.* **155**, 199.

Neidig, D. F., Wiborg, P. H., and Gilliam, L. B.: 1993, *Solar Phys.* **144**, 169.

Neidig, D. F., Kiplinger, A. L., Cohl, H., and Wiborg, P. H.: 1993, *Astrophys. J.* **406**, 306.

NOAA Technical Memorandum ERL SEL-82: 1994, 'Excerpts from Region 5395 of March 1989', Maj W. Cliffswallow (ed.).

Ramaty, R.: 1979, in J. Arons, C. Max, and C. McKee (eds.), *Particle Acceleration Mechanisms in Astrophysics*, AIP, New York, p. 135.

Ramaty, R.: 1986, in P. A. Sturrock, T. E. Holzer, D. Mihalas, and R. K. Ulrich (eds.), *The Physics of the Sun*, Vol. 2, Ch. 14, D. Reidel Publ. Co., Dordrecht, Holland, p. 291.

Ramaty, R.: 1995, paper given at the High Energy Solar Physics Workshop, Goddard Space Flight Center, August 16–18.

Ramaty, R., Kozlovsky, B., and Lingenfelter, R. F.: 1979, *Astrophys. J. Suppl.* **40**, 487.

Ramaty, R., Mandzhavidze, N., Kozlovsky, B., and Murphy, R. J.: 1995, *Astrophys. J.* **455**, L193.

Reames, D. V., Meyer, J. P., and von Rosenvinge, T. T.: 1994, *Astrophys. J. Suppl.* **90**, 649.

Rieger, E.: 1989, *Solar Phys.* **121**, 323.

Rieger, E.: 1990, in Ph. Durouchoux and N. Prantzos (eds.), *Gamma-Ray Line Astrophysics*, AIP, New York, p. 421.

Rieger, E. and Gan, W. Q.: 1993, *Acta Astron. Sinica* **34**, No. 4, 430.

Rieger, E. and Marschhaeuser, H.: 1990, in R. M. Winglee and A. L. Kiplinger (eds.), *Proceedings of MAX91 Workshop No. 3*, University of Colorado, Boulder, p. 68.

Ryan, J. M., Chupp, E. L., Forrest, D. J., Matz, M., Rieger, E., Reppin, C., Kanbach, G., and Share, H.: 1983, *Astrophys. J.* **272**, L61.

Share, G. H. and Murphy, R. J.: 1995, *Astrophys. J.* **450**, 933.

The GRS on SMM: 1991, Informal Comm. from SMM-Gamma-Ray Group, contact J.Gurman at SMM-Data Analysis Center, Goddard Space Flight Center, Greenbelt, Maryland.