4.1.2.7 Flares

Klaus Wilhelm

4.1.2.7.1 Flare signatures

Flares (sometimes called chromospheric eruptions) produce the hottest plasmas in the solar atmosphere. They occur, under certain conditions, in active regions (cf. Sect. 4.1.2.1). Many flares are accompanied by a coronal mass ejection (CME) treated in Sect. 4.1.2.5. Flares are generally classified according to their X-ray importance [c]. The sites of major flares follow the "butterfly diagram" pattern of sunspots [07Zha]. Spectral observations of flares can be found in, e.g., [75Dos, 80Fel, 06Jai] and in the references listed in Table 1. The spectrum extends via bremsstrahlung and annihilation processes far into the X-ray and γ-ray ranges [85Bai, p]

Lines from helium-like ions in solar spectra were reported by [69Gab1, 69Gab2]. The transitions 2s ^{3}S – 2p ^{3}P in Ne^{8+}, Na^{9+}, Mg^{10+}, and Si^{12+} have been observed in flare plasmas [00Cur]. The corresponding O VII line had been identified at 162.4 nm in an early eclipse spectrum by [71Gab, 77Fel]. X-ray and extreme-ultraviolet spectra of flares are further discussed in [06Dos] and comparisons of flare spectra with the atomic database CHIANTI[1] are presented by [g, h]. References to earlier work on solar flares are given in [c, d]. The characteristics of the solar spectra can change substantially during flares: emission lines with formation temperatures of several million kelvin appear, and lines of neutral species disappear [03Dwi].

Temperatures above 10 MK are quite common and lead to spectra with lines of highly-ionized species. Neutron and γ-ray emissions during a flare are analyzed by [07Mur]. A delay of $\approx$ 12 s between the hard X-ray and γ-ray fluxes has been reported [07Dau]. The specific features of a long-duration, gradual-hardening flare are presented by [07Tak]. In flaring regions of the corona,

Table 1. Selection of spectral observations and emission-line lists related to eruptive solar activity

Frequency, wavelength, or energy ranges[a]	Spectral resolution[b]	Solar target	Reference
1 GHz to 35 GHz	six frequencies	flares	[07Nin2]
119 nm to 173 nm	5 pm	various	[93Bre]
117.5 nm to 171 nm	5 pm	various	[86San]
97.7 nm to 193.6 nm	6 pm	flare	[78Coh]
91.4 nm to 117.7 nm	6 pm	limb, flare	[91Fel]
50 nm to 160 nm	4.4 pm, (2.2 pm)	flare	[00Fel]
46.5 nm to 160.9 nm	4.4 pm, (2.2 pm)	various	[e]
30 nm to 45 nm	20 pm to 30 pm	flare	[72Pur]
28 nm to 135 nm	160 pm	various	[78Ver]
20 nm to 50 nm	20 pm	flare	[73Cow]
17.1 nm to 63 nm	20 pm	flare	[76San]
17.1 nm to 63 nm	10 pm	flare	[78Der]
6.6 nm to 17.1 nm	11 pm	flare	[74Kas]
6.6 nm to 17.1 nm	—	flare	[75Faw]
747 pm to 1.897 nm	—	flare	[g]
3.8 keV to 10.3 keV	—	flare	[i]

[a] Not the full range is covered In some cases
[b] Not all entries fully consistent (FWHM, resolution elements, etc.; second order in parentheses)

[1] freely available at `http://www.arcetri.astro.it/science/chianti/chianti.html`

a free-free continuum can also be detected [84Syl, 03Fel]. It primarily results from bremsstrahlung interactions of electrons with hydrogen and helium. Together with emission-line observations, it can be used for plasma diagnostics.

Large Doppler shifts of spectral lines to shorter wavelengths were seen in He II and Fe XV spectra, corresponding to line-of-sight (LOS) velocities of 300 km s^{-1} to 600 km s^{-1} towards the observer [81Dos1, 82Ant, 85Mac, 94Mar]. Even higher LOS velocities were measured in a limb flare of class M7.6 [01Inn]. Typical turbulence velocities are of the order of 130 km s^{-1} during the rise phase of a flare, and 60 km s^{-1} during the decay phase. Flare shock waves can excite coronal loop oscillations [04Hud] (cf., Sect. 4.1.2.6).

Density diagnostics gave electron densities of up to 3×10^{12} cm^{-3} for a flare occurring on low-lying, pre-existing loops, see, e.g. [81Dos2, 82Che, b]. Using Fe XXI to Fe XXII line ratios in the X-ray range (0.8 nm to 1 nm), [96Phi] reported electron densities that reached $n_e = 1 \times 10^{13}$ cm^{-3} near the flare maximum.

The relationship between regions emitting hard and soft X rays has been studied by [81Zir] and between a flare eruption and a sigmoidal shape of the soft X-ray emission in active regions by [99Can]. The thermal X-ray spectrum of a flare is analyzed by [05Den] and the relation to the non-thermal contribution by [06Gri]. A purely thermal event with temperatures up to 44 MK is reported by [06Kob]. The soft X-ray emission of Fe XV during a solar flare is compared with a spectrum of Capella [06Kee]; for a discussion of other solar and stellar flares see also [91Hai]. Radio and hard X-ray observations led to the conclusion that the radio emission stems from a trapped electron population and the X rays from precipitated fluxes [06Sma]. A large number of flares observed in hard X-ray emission and 100 MHz to 4 GHz radio emission is studied by [05Ben]. Reviews of radio observations from explosive solar energy releases are given by [98Bas, 03Kun]; and studies of the morphology of a flare at 617 MHz by [06Kun]. The Neupert effect – a correlation between the hard X-ray flux and the time derivative of the soft X-ray flux – is discussed for many flares by [93Den].

Major flares dissipate an energy of more than 1×10^{27} J, such as the X20 flare on 2 April 2001 (one of the largest flares on record), down to $\approx 1 \times 10^{18}$ J, if microflares are included. The dependence of the flare occurrence rate on the energy dissipation is described by power-law indices between $|\gamma| \approx 1.9$ and ≈ 2.6, and thus the limit of two, critical for the contribution of most of the energy by small events, is still not adequately constrained, see, e.g., [97Fel, 02Ben].

During the impulsive phase of a class X3 flare, irradiance increases by a factor of ≈ 12 occurred in Si IV and C IV lines [96Bre]. A fractional flare size of 0.08 % of the solar disk was estimated with the help of Hα images leading to radiance increase at the flare site in these lines of $\approx 1.5 \times 10^4$. A similar increase was observed during a class X5.3 flare on 25 August 2001 [04Lem]. A relative increase of the total solar irradiance (TSI; cf., Sect. 4.1.1.3) of 2.7×10^{-4} was measured on 28 October 2003 during a class X17 flare [04Kop] The same flare has been studied with THEMIS[2] observations by [06Smi], and by [06Sri] using observations from many space missions. In the latter study, the characteristics of the γ-ray line at 511 keV are of particular interest. This flare also caused seismic effects on the Sun (a Sun quake) described by [06Kos], and a large increase of the total electron content in the Earth's ionosphere [05Tsu].

The ultraviolet contribution to the TSI during large flares is given in [06Woo]. Soft X-ray irradiance increases during flares are presented in [06Rod]. The "Bastille Day Flare" 1998 of class X10, one of the best-observed flares, has been described by [00Aul]. A pre-cursor phase of flares has been identified by [03Mat1]. See Table 2 for a selection of more flares that have been described in the recent literature in some detail. A catalogue of solar flares observed with the *Yohkoh* instruments has been compiled in [m].

[2]Telescopio Heliografico para el Estudio del Magnetismo y de las Inestabilidades Solares

Table 2. Observations made during selected (major) flares treated in the recent literature

Date	Class[a]	Observations[b]	Instruments[c], Spacecraft[d]	Reference
04 Jun 1991	X12	WL; Hα; Hβ	MFT	[01Zha]
13 Jan 1992	M2.0	SXR; HXR	SXT; HXT	[94Mas]
21 Feb 1992	M3.2	50 pm to 400 pm;	SXT;	
		14 keV to 23 keV	HXT	[92Tsu]
09 Jul 1996	X2.6	Sun quake	MDI	[98Kos]
25 Jul 1999	M2.4	SXR; HXR;	SXT; HXT	
		VUV	*TRACE*	[99War]
24 Nov 2000	X1.8	EUV; Hα; WL;	EIT; BBSO; MDI;	
		SXR; HXR; B	LASCO; SXT; HXT	[02Wan]
12 Apr 2001	X2.0	230 GHz; 345 GHz;	KOSMA;	
		HXR; SXR	SXT; HXT	[04Lut]
15 Apr 2002	M1.2	SXR; HXR; VUV;	*RHESSI*; NORH;	
		17 GHz; 34 GHz; WL; B	*TRACE*; LASCO; MDI	[05Sui]
16 Apr 2002	M2.5	SXR; HXR;	*RHESSI*;	
		VUV	*TRACE*; SUMER	[04Sui, 07Wan]
21 Apr 2002	X1.5	17 GHz; 34 GHz;	NORH; EIT;	
		SXR; HXR; 19.5 nm	*RHESSI*; *TRACE*	[02Gal, 04Kun]
09 Sep 2002		4.8 GHz to 9.4 GHz;	OVSA; BBSO;	
		19.5 nm; 12 keV, 25 keV	EIT; MDI; *RHESSI*	[06Hua]
27 Oct 2002		HXR;	*RHESSI*;	
		γ rays	GRS	[07Kru]
01 Aug 2003	C5.6	Hα; Ca II;	MISS; *RHESSI*;	
		1083 nm; 19.5 nm; HXR	EIT; MDI	[05Li]
21 May 2004		17 GHz; 35 GHz;	*RHESSI*;	
		HXR	NORP	[07Nin1]
14 Aug 2004	M7.4	Sun quake; Ni I; Hα;	MDI; GONG; BBSO	
		17 GHz; 34 GHz; (HXR)	*RHESSI*; NORP	[07Mar]
15 Jan 2005	X1.2	Sun quake;	MDI; *RHESSI*;	
		Ni I (676.8 nm); HXR	*TRACE*; GONG	[07Mor]
17 Jan 2005	X3.8	HXR; γ rays	*RHESSI*	[06Kon, 07Kon]

[a] X-ray flux classification [c] (as given in the reference from *GOES* observations)
[b] WL – White Light; EUV – Extreme UltraViolet (cf., Sect. 4.1.1.3); SXR – Soft X Rays (100 eV to 10 keV, cf., Sect. 4.1.1.3); HXR – Hard X Rays (10 keV to 100 keV (cf., [f]); B – Magnetic field; γ rays – $>$ 100 keV (cf., [f])
[c] MFT – Magnetic Field Telescope, Huairou; SXT – Soft X-ray Telescope on *Yohkoh*; HXT – Hard X-ray Telescope on *Yohkoh*; MDI – Michelson Doppler Imager on *SOHO*; EIT –Extreme-ultraviolet Imaging Telescope on *SOHO*; BBSO – Big Bear Solar Observatory; LASCO – Large Angle Spectroscopic COronagraph on *SOHO*; SUMER – Solar Ultraviolet Measurements of Emitted Radiation *SOHO*; KOSMA – Köln Observatory for Submillimeter and Millimeter Astronomy; NORH – NObeyama RadioHeliograph; OVSA – Owens Valley Solar Array; GRS – Gamma Ray Spectrometer on the Mars Odyssey mission; MISS – Multi-channel Infrared Solar Spectrograph; NORP – NObeyama Radio Polarimeter; GONG – Global Oscillations Network Group
[d] *GOES* – Geostationary Operational Environmental Satellites (*GOES* data at `http://www.goes.noaa.gov/`); *RHESSI* – Ramaty High-Energy Solar Spectroscopic Imager; *SOHO* – SOlar and Heliospheric Observatory; *TRACE* – Transition Region And Coronal Explorer

Conflicting results on the linear polarization of Hα emission during flares have been published by [03Kot, 05Xu, 05Bia]. In a large post-flare arcade, a number of dark, downwards moving flows could be seen in 19.5 nm images [03Dob]. Spectra of lines with formation temperatures between 2×10^4 K and 10 MK show that these flows are dark in the hottest line (Fe XXI), but not in the cooler one [03Inn]. There was no absorption in the H I Lyman continuum and, therefore, the conclusion was reached that the dark flows correspond to moving voids. Similar plasma features have earlier been seen by [99McK].

4.1.2.7.2 White-light flares

Many observations have demonstrated that the optical continuum emission of a flare is spatially and temporally related to the hard X-ray flux [75Rus, 93Nei, 94Nei, 03Mat2, 06Che]. This is generally interpreted as evidence of a heating process involving non-thermal electrons, accelerated by magnetic reconnection at relatively low altitudes (in the chromosphere). These electrons are also thought to generate most of the hard X rays via bremsstrahlung emission in the chromosphere (the thick-target assumption). However, a discrepancy between the electron range and the required heating at photospheric levels remains to be explained [99Din, 07Fle]. In addition, rather isotropic electron distributions have been deduced by [06Kon] for two flares. This casts some doubt on the general applicability of the thick-target model. Near-infrared observations by [06Xu] place the flare emission even deeper in the solar atmosphere requiring other heating mechanisms, such as, back warming [86Abo, 03Met]. An intermittend emission of the white-light radiation is reported by [06Hud].

4.1.2.7.3 Flare physics

The physics of solar flares is treated by [k, o, 89Stu, l, 02Pri]. The release of magnetic energy often occurs near the neutral line of the vertical component of the magnetic field (see, e.g., [02Wan]). A reconnection model of flares has been developed by [96Shi, 99Shi]. Fermi and betatron acceleration scenarios are compared by [05Bog]. Particle acceleration in reconnecting current sheets is treated by [93Lit]. The role of anomalous resistivity in the reconnection process is considered by [07Sin]. Reconnection inflow with an apparent speed of 5 km s^{-1} and a plasmoid ejection could be detected during a flare [01Yok]. A flare, occurring at the site of a disappearing filament, usually has a two-ribbon structure [n]. A rotation of flare loops was spectroscopically detected by [05Li].

Evidence of chromospheric evaporation with downward motion in the chromosphere and upward motion in the transition region (TR) at a site remote from the flare (identified by hard X-ray emission) is presented by [07Bro]. Observations of spectral lines with formation temperatures between 2×10^4 K and 7.9 MK above the limb during a sequence of flares indicated that the flaring plasma is heated *in situ* from ≈ 1 MK to ≈ 10 MK, possibly by compression of the coronal plasma [04Fel]. Spectral observations of solar flares over the last few decades are compiled in Table 1.

Chromospheric evaporation by precipitating of non-thermal electrons is thought to be an important process during a solar flare, cf., [85Fis1, 85Fis2]. However, the very high upflow speeds expected from such a model have not been found in recent spectroscopic observations. This might indicate that the threshold of explosive evaporation [89Fis] had not been reached. Such an observation has been described as gentle evaporation by [05Ber, 06Fal]. The dynamics of an eruptive flare was observed by [06Ter]. A multi-thread concept of a flare loop assembly has been suggested by [05War, 05Dos]. Energetic flare particle fluxes observed in the interplanetary space are often enriched in ^{3}He relative to the photosphere [94Rea], indicating that the acceleration region must be deep within the solar atmosphere (with density greater than 10^{10} cm^{-3}), cf. also [99Zha] for a theoretical treatment.

Many aspects of flares are not completely understood. Following the suggestion that double layer formation could be of importance in the solar atmosphere [67Alf], several studies, e.g., by [78Has, 88Raa, j], considered this concept without reaching a final conclusion. A comparison between a two-ribbon flare and processes in the Earth's geomagnetic tail is made by [90Mar]. The operation of an electron cyclotron maser in the flaring plasma is considered by [98Con], and coronal shock acceleration by [01Man, 03Man].

4.1.2.7.3.1 Flare particle emissions

In addition to the electromagnetic radiation, a flare produces large fluxes of high-energy atomic particles affecting both the solar atmosphere and the interplanetary space. The specific aspects and open questions concerning the particle acceleration during flares (and other transient events) are reviewed by [87Ram, 95Tsu, 98Mil, 99Rea, a, 03Ems, 04Ems]. The electron spectrum at 1 ua is given for many flare-related events by [06Sim], and the proton acceleration is studied in [06Sim]. Many coronal mass ejections (CME; cf., Sect. 4.1.2.5.6) are associated with flares [92Kah, 94Kah, 95Har, 07Har].

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