Stellar Flares: How Common? How Important?

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Abstract. Flares are often observed from a wide variety of stars that are called active by virtue of their rapid rotation, young age, and strong magnetic fields. Although the total energies of these flares cover many orders of magnitude in range, they typically follow a common pattern with impulsive and gradual stages and the distribution of energy among the different radiating channels is remarkably similar. The similar phenomenology points to a common scenario of magnetic reconnection, electron beam heating, and evaporation of the lower atmosphere followed by gradual cooling of the hot coronal plasma. The solar two-ribbon flare is often cited as the prototypical model. However, this conclusion must be viewed as tentative because the radiative response of an atmosphere to the impulsive input of energy could be the same for a variety of different energy input mechanisms.

In flagrante delicto.

Caught in the act.

I INTRODUCTION

Most stars with convective zones and strong magnetic fields show transient brightenings called *flares*. These flares are most easily detected in X-rays, ultraviolet emission lines, and at radio wavelengths where the contrast between the flare emission and the quiescent (nonflare) emission from the star is large. The low photospheric temperatures of M dwarfs allows flares to be detected easily in the optical, especially in the U band. The most energetic flares on the Sun are also detected in broad-band optical observations, a phenomena called *white light flares*. Flares on the Sun and nondegenerate stars are characterized by an enormous range of energies, 10^{22} erg solar *nanoflares* to 10^{38} – 10^{40} erg huge flares on RS CVn and premain sequence stars. Despite their 18 orders of magnitude range in energy, flares generally show similar phenomenology, suggesting a common physical origin.

At this Workshop on Cosmic Explosions, stellar flares are small firecrackers compared to supernovae and gamma ray bursts. Nevertheless, there are elements in common between the big and small explosions, and flares on nearby stars and especially the Sun can be studied with high temporal and spatial resolution, revealing some of the physical processes responsible for the explosions. Thus prudence requires that one should learn from the nearby relatively small flares at the same time as tackling the distant great events at the edge of the universe.

II FLARE PHENOMENOLOGY

Although flares on the Sun and different classes of stars vary greatly in energy, time scales, and volumes, they generally proceed through the same sequence of stages. The following is a very simplified overview of these stages of stellar flares. For a more comprehensive and detailed review of stellar flares, I call your attention to a number of excellent review papers [6,13,15,16,29,24].

Buildup: For stars with convective envelopes, convective motions below the photosphere, where the kinetic energy exceeds the magnetic energy ($\beta = P_{\rm gas}/P_{\rm mag} > 1$), displace and shuffle the footpoints of coronal magnetic fields. This footpoint motion spontaneously creates complex interlaced coronal magnetic field topologies with magnetic free energy; that is, magnetic energy over and above that of a potential field. Parker [33,35] argued that the interlaced topology of the coronal field relaxes to a static equilibrium with internal surfaces of *tangential discontinuity* (also called *current sheets*) that must eventually dissipate this free energy. The buildup phase of a flare thus describes the conversion of heat produced by nuclear reactions in the stellar core through the subsurface convective motions into the buildup of magnetic free energy in the corona awaiting a trigger to convert this energy rapidly into heat, kinetic motions, and relativistic particles.

Nanoflares: If resistive reconnection of field lines in current sheets driven by plasma inflows were inherently a continuous smooth process, then one would expect the heating of stellar coronae to be steady and uneventful. Numerical simulations and laboratory plasma experiments, however, provide a very different picture in which reconnection processes occur on very small scales ($\leq$ 1m), are irregular in both space and time, and the dissipation is episodic [34,35]. The energies of these reconnection events vary over many orders of magnitude from nanoflares [34] (10^{22} – 10^{24} erg) to the most energetic solar flares (10^{32} ergs).

Impulsive phase of large flares: The large release of energy that we call flares rather than episodic heating requires some trigger to produce an avalanche of magnetic field reconnection on a fast time scale. Theoreticians have searched for years to find the enigmatic trigger that would start the avalanche. One scenario [15,27] commonly proposed to explain the so-called *two-ribbon* flares, is the eruption of a *filament* (a magnetically confined region of cool plasma) caused by a loss of equilibrium of the mass loaded magnetic structure. These flares are long lived as they involve the disruptive opening up of large magnetic arcades over time. Whatever the cause of the eruption might be, the ejection of the filament stretches many field lines leading to enhanced field gradients at the current sheet and greatly enhanced reconnection in a large magnetic arcade. By comparison, *compact* flares involve magnetic reconnection in a few magnetic loops without disrupting a large magnetic configuration [13]. In this scenario much of the magnetic energy is converted into the acceleration of relativistic electrons and protons by the electric field. These beams then precipitate down the field lines generating gyrosynchrotron radiation as they go and hard nonthermal x-rays and ribbons of Hα emission when they impact the chromosphere. These short lived radiations characterize the *impulsive* phase of the flare.

Explosive evaporation of the lower atmosphere: A range of models has been proposed over the years to describe how energy is transmitted from the initial flare site in the corona to the dense layers of the chromosphere and upper photosphere. Possible energy transfer mechanisms include X-radiation, conduction, blast waves, and particle beams (electron or proton). At present electron beams are considered to be the most likely mechanism, so I will describe this mechanism in a little detail. Abbett and Hawley [1] modeled the response of the solar chromosphere to a high energy beam of electrons using a radiative hydrodynamic code that includes non-LTE radiative transfer in important emission lines. Initially, when the chromosphere can still radiate away the nonthermal heat input by small increases in temperature, the atmosphere remains near equilibrium with no mass motions. They refer to this stage as the *gentle phase*. When the beam heating ionizes hydrogen, the main source of radiation from the chromosphere, the atmosphere explodes with large material flows and shocks carrying away the excess energy input that radiation alone cannot accomplish. During this *explosive phase*, one observes large Doppler shifts and the *evaporation* of chromospheric gas as very hot blueshifted coronal plasma. Blue shifts with velocities up to 400 km s^{-1} are often detected in the Ca XIX lines ($T_e \geq 10^7$ K) at 3.2 Å during the first minute of solar flares, and models of beam heated evaporation predict these large upflows of the evaporated formerly chromospheric gas [2].

Gradual phase: After the initial fireworks (relativistic beams, explosive evaporation, and blast waves), the nonthermal energy thermalizes resulting in a hot corona that cools by expansion (when not confined by the magentic field), X-radiation, and thermal conduction. For solar flares the peak emission measure and temperature (often 2–3$\times 10^7$ K) of the soft X-ray emission follows the hard X-rays and 400 km s^{-1} upflows seen in the Ca XIX lines by 1–2 minutes [2], but for stellar flares the time delays are often longer [12] and the peak temperature 10^8 K or hotter [11]. During the gradual phase, the gyrosynchrotron emission from an expanding cloud of relativistic electrons can extend for hours or days in RS CVn binary systems [39,40].

III WHAT TYPES OF STARS FLARE?

A Sun

The first star observed to flare was the Sun, and the first detected flare emission was optical (white light flares and brightenings in the Balmer emission lines). The limited red sensitivity of early emulsions meant that the first photographs of solar flares were in the Hβ line. Solar flares are now routinely studied in soft and hard X-rays, ultraviolet emission lines, Hα and other emission lines observable from the ground, radio wavelengths, and even gamma rays. Relatively short duration *impulsive* or *compact* flares and the longer duration *two-ribbon* flares are generally considered as prototypes for the more energetic short and long duration flares on stars. Transition region *explosive events* observed as broad or Doppler shifted profiles in transition region lines like C IV 1549 Å are believed to be signatures of nanoflares. These nanoflares are small contributors to the heating of these layers on the Sun, but they are important contributors to the heating in active stars [42]. The solar corona is likely heated by many small magnetic reconnection events.

B dMe Stars

The first nonsolar flare was observed serendipitously on the star UV Ceti (dM6e)[1] [21] from an enhancement of both the optical line and continuum emission. Essentially all dMe stars are observed to flare and many of the less active dM stars also flare. Flares are easily detected at X-ray, UV, and radio wavelengths, and in the optical (especially in the U band and the Balmer lines) because of the large contrast with the dim stellar photosphere. Optical flares typically show very fast rise times (seconds to a few minutes in the U band) during the impulsive phase followed by exponential decay times of some tens of minutes to several hours during the decay phase [28]. Many dMe star flares with a wide variety of energies have now been observed and modelled. The properties of these flares show a remarkable consistency despite many orders of magnitude range in energy [17]. I list here some of their characteristic properties:

- The time evolution of the flare emission generally follows a similar pattern with the energy radiated during the impulsive phase (dominated by the optical and UV continuum) two to three times that of the energy radiated during the gradual phase (dominated by the Balmer and UV emission lines and the soft X-ray emission).

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[1] The letter "e" is added to the spectral type of those stars that typically show the Hα line in emission. dM stars do not show the Hα line in emission.

- Multiwavelength observing campaigns show that the total energy of a flare emitted through different channels (Balmer lines, optical and UV continuum, and X-rays) are roughly proportional over a wide range of energy. In particular, the total soft X-ray emission has about the same energy as the U band continuum, corresponding to about 1/6 of the total optical and UV continuum emission.

- The main difference between giant flares (e.g., the 1985 April 12 flare on the dM3.5e star AD Leo with a U band enhancement of 4.5 magnitudes and total flare radiated energy in excess of 10^{34} ergs [17]) and much lower energy flares is probably due to the longer duration of the heating and larger area coverage of the large flares rather than to enhanced heating per unit area and time. Thus the heating rate and magnetic recombination rate per unit area on the star appear to be roughly the same [17], indicating that the physics of magnetic field reconnection limits to within a narrow range the rate at which magnetic energy can be converted to other forms of energy.

- Since the radiative output of different flares on different stars tend to follow a consistent pattern, many authors (e.g., [12,41]) have argued that flares on dMe stars are scaled up versions of solar compact or two-ribbon flares. This conclusion must be viewed as tentative because the radiative output during a flare is the response of a stellar atmosphere to the impulsive input of energy, and the character of this radiative output may only tell us that the flaring plasmas are following the rules of hydrodynamics, atomic physics, and radiative transfer. The radiative response of the atmosphere to the impulsive input of energy could be the same for a variety of different energy input mechanisms.

- Intense radio emission is commonly detected during flares. This is usually explaned as gyrosynchrotron emission from relativistic electrons, although some radio flares are naturally explained by coherent maser or plasma emission processes [4,7]. During the 1983 February flare on YZ CMi (dM4.6e) [41], the 6 cm emission was observed to peak 7 minutes after the U band peak, and the radio emission remained bright long after the end of the U band emission.

- Although beams of nonthermal electrons cannot be observed directly, their presence can be inferred by the so-called *Neupert effect*. According to presently accepted models, magnetic field reconnection accelerates beams of relativistic electrons down into the dense chromosphere and upper photosphere. There collisions with the plasma produce hard X-rays by nonthermal bremsstrahlung, the white light continuum emission (most easily seen in the U band), and evaporation of the ambient cool plasma into the corona where it later emits soft X-rays. During the impulsive phase of solar flares, the white light emission and hard X-ray emission are coincident in space and time [19], indicating their common origin from the electron beams, but hard X-rays are difficult to observe during stellar flares. This model predicts that the soft X-ray emission during the gradual phase should equal the time integral of the hard X-ray or

U-band emission (representing the heating and evaporation up to that time). The verification of the *Neupert effect* during the 1993 March 1–3 flare of AD Leo [18], using the U-band emission as a proxy for the hard X-ray emission, provides support for electron beam heating of flares on dMe stars.

- X-ray flares on dMe stars have been observed with the Einstein, EXOSAT, ROSAT, and ASCA satellites. Typically one sees X-ray fluxes increase by a factor of 10–100 over quiescent values, flare plasma peak temperatures of roughly 3×10^7 K, and the maximum in the coronal emission measure occuring about 5 minutes after the temperature maximum as is often observed in solar flares [12]. Most authors have modelled the flare X-ray plasma using solar two-ribbon models but with much larger energies. For example, the best fit model for the 1991 May 9 flare on AD Leo observed by ROSAT has a maximum temperature of 3.5×10^7 K and a magnetic loop length about 1/7 of the stellar radius [36]. Recent analyses of X-ray emission from AD Leo and EV Lac (dM4.5e) observed with ROSAT and SAX show very high temperature plasmas, perhaps above 10^8 K, with the presence of plasma at $\log T \approx 7.6$ during a flare on EV Lac. An important, but as yet unanswered, question is whether the very hot plasma is thermal or a nonthermal power law distribution that may be the low energy tail of the MeV electrons producing the gyrosynchrotron emission.

C Brown dwarfs

Stars with mass $< 0.08 M_\odot$ are called *brown dwarfs* (spectral types L and T) because their core temperatures are too low to sustain hydrogen burning and their energy source is deuterium burning for a limited time and gravitational contraction. The lowest mass M dwarfs like VB10 have been observed to flare in the optical, ultraviolet [26], and X-rays, indicating that rapid field reconnection events, presumably driven by convective motions below the photosphere, occur in the coronae of these stars. Since brown dwarfs likely have similar internal structures and magnetic dynamos as the late-M dwarfs, they should also flare by the same process. Recently an optical flare was detected in the 2MASS object J0149090+295613 classified as M9.5V [23], and ROSAT detected an X-ray flare in a young brown dwarf in the Chamaeleon I Dark Cloud [30]. The 2MASS and DENIS surveys and infrared monitoring of young clusters will likely show that brown dwarf flares are very common events.

D RS CVn systems

These are close but detached binaries containing typically a G dwarf or subgiant and an early-K subgiant that are tidally locked. Thus the stellar rotation periods equal the obital periods, which can be as short as one day or as long as about 20 days. Systems with orbital periods longer than about 20 days tend to rotate slower than synchronous and be less active. Many powerful flares have been detected in these systems in the ultraviolet [29], x-ray [24], and radio [5]. Time sequences of ultraviolet spectra of RS CVn systems, primarily in the Mg II 2796 and 2803 Å lines, observed with the IUE satellite, show large flux enhancements with decay times typically 8–12 hours. Large mass flows in the chromosphere are indicated by very broad Mg II line profiles and Doppler shifts (typically downflows) that often exceed 100 km s^{-1}.

The total radiative energy loss (for plasma in the range $4.0 \leq \log T \leq 5.3$) can be as large as 2×10^{36} ergs and the mass flows contain comparable energy [25]. In the X-ray region the total energy losses for well studied flares lie in the range 10^{34} to a few times 10^{37} ergs, and the flares have been modelled as very energetic analogs of both solar compact and two-ribbon flares [24]. For example, the 1994 August 29 flare on UX Ari observed by ASCA and EUVE [11] showed plasma temperatures near 10^8 K and metal abundances that rise from 0.17 times solar to nearly solar during the flare, suggesting evaporation of solar abundance gas from the lower atmosphere into the flaring loop. Güdel et al. [11] modelled this flare with the Kopp and Poletto [22] two-ribbon flare model with the flaring loop covering 30% of the visible surface. If this flare on UX Ari is representative of flares on RS CVn systems, the high X-ray luminosities of RS CVn flares compared to the Sun are due to much larger loop sizes and higher densities. Analysis of 12.2 Ms of EUVE photometry of 16 RS CVn systems [31] showed that these stars show obvious flares 40% of the time. Osten and Brown [31] argued that the flares are not simply scaled-up versions of solar two-ribbon flares because the rise times are far longer than are observed in solar flares.

Very luminous radio flares are detected from the relativistic plasma that expands during a flare until it becomes as large as the binary separation. The emission process is most likely gyrosynchrotron emission as the initial brightness temperature is a few times 10^9 K and the electron energies decrease with time as a result of radiative and collisional losses [39,40].

E Algol systems

These close but detached binary systems usually contain a B- or A-type dwarf and a K giant. The Algol prototype, β Per (B8 V + K2 III), has a 2.87 day period. Using the BeppoSAX satellite, Schmitt and Favata [37] detected the giant 1997 August 31 X-ray flare on β Per with total energy 1.5×10^{37} erg in the 0.1–10 kev X-ray band. The enormous energy of the flare (about 1.2% of the K2 III star's bolometric luminosity) suggests a different flare scenario than for the relatively weak solar flares, perhaps the intertangling of the magnetic fields of both stars. However, the observation of an eclipse of the flare by the B8 V star shows that the flaring plasma was confined to a region within 0.6 radii of the surface of the K2 III star and near its rotational pole. The location of the flare close to the stellar surface, the high plasma temperature ($T \approx 1 \times 10^8$ K), and moderate strength magnetic fields (500–1000 G) suggest that even this giant flare could be a magnetic reconnection event analogous to solar flares albeit far more energetic. The 1992 August flare on Algol observed by ROSAT [32] appears to be a two-ribbon type flare with similar dimensions and temperatures to the 1997 August 31 flare, but with possible abundance variations during the flare.

F Premain sequence stars

Intense flares from very young protostars embedded in the dust and gas of their nascent clouds have been detected by X-ray satellites from many star forming regions [8]. One well studied flare is that observed by the ROSAT HRI on YLW15, a class I protostar about 10^5 years old in the ρ Oph cloud [9]. The X-ray luminosity of the flare was in the range 10^{34} to 10^{36} erg, depending on the value of the extinction that is very large. This enormous energy corresponds to 1–100 times the bolometric luminosity of the star. The total X-ray energy of the flare, which had an e-folding decay time of five hours must have exceeded 10^{38} ergs and could have been as large as 10^{40} ergs! Grosso et al. [9] estimated that the flare dimension was 0.02–0.3 AU, much larger than the star. The very large volume and extreme energy of this flare and the somewhat less energetic flares detected on other premain sequence stars are strong arguments that these flares are not scaled up solar two-ribbon flares. They are more likely magnetic reconnection events that occur when the fields of the protostar and the accretion disk shear and interconnect as forced by the different rotation rates of the protostar and accretion disk to which the flux tubes are anchored and gas flows from the disk to the protostar along interconnecting field lines [38].

G Single giants

Evolved single giants of spectral type G–M are not expected to flare because they are slow rotators and likely do not have strong magnetic fields. A few radio transients have been reported from single dish radio telescopes, but modern interferometers like the VLA have not detected any flares from such stars. A search of the ROSAT observations of apparently single late-type giants [14,20] revealed only a handful of flares, but these flares could be due to previously unknown binary companions. A more compelling case is that of μ Vel A, a G6 III star crossing the Hertzsprung gap for the first time. A large flare (5×10^{35} ergs) with a decay time of 1.5 days was observed by EUVE on 1998 March 10. Ayres et al. [3] argue that the flare was not due to the F dwarf companion located 2 arcseconds away, but there is a remote possibility that μ Vel A has a previously unknown late-type dwarf companion that flared. If the flare is actually from the G6 III star, then flares may play a major role in the loss of angular momentum from these rapidly evolving stars.

IV SUMMARY

Flares are often observed from a wide variety of stars that are called active by virtue of their rapid rotation, young age, and strong magnetic fields. Although the total energies of these flares cover many orders of magnitude in range (see Table 1), they typically follow a common pattern with an impulsive stage followed by a gradual stage, and the distribution of energy among the different radiating channels is remarkably similar. The similar phenomenology points to a common scenario of magnetic reconnection, electron beam heating, and evaporation of the lower atmosphere followed by gradual cooling of the hot coronal plasma. The solar two-ribbon flare is often cited as the prototypical model. However, this conclusion must be viewed as tentative because the radiative output during a flare is the response of a stellar atmosphere to the impulsive input of energy. The character of this radiative output may only tell us that the flaring plasmas are following the rules of hydrodynamics, atomic physics, and radiative transfer. The radiative response could be the same for a variety of different energy input mechanisms.

While flares on most active stars may be explicable by the two-ribbon flare model, premain sequence stars are probably the exceptions. For these stars the extreme energy and large volume point to a very different model in which magnetic reconnection events occur when the fields of the protostar and the accretion disk shear and interconnect as forced by the different rotation rates of the protostar and accretion disk to which the flux tubes are anchored and gas flows from the disk to the protostar along interconnecting field lines. New observations are need to test this model.

Flares are often thought of as isolated transient events, but there is evidence that low energy flares, often called nanoflares, occur all the time and are responsible for most of the heating in the coronae and transition regions of the most active stars. Chandra, XMM, and future very large area X-ray telescopes may be able to measure the distribution function of flares down to very low energies and thus tie together the large flares and nanoflares.

How important are stellar flares? They are essential in removing strong magnetic fields that are created by the dynamos operating in most late-type stars. In the process of reconnecting these fields, the observed energetic flares and the far more numerous nanoflares are probably responsible for most of the energy that heats the coronae of late-type stars. The high temperature and pressure of these coronae accelerate winds that replenish the interstellar medium with chemically processed matter and carry away angular momentum that decelerates the stellar rotation. In active stars like the young Sun, flares produced strong ultraviolet radiation that impacted the atmosphere of the young Earth and may have played a role in forming the organic molecules out of which life formed. Perhaps flares are important.

Finally, this Workshop on Cosmic Explosions serves to tie together transient events in astrophysics from the low energy flares on stars to the highest energy events, the γ ray bursts. The study of stellar flares shows that similar phenomenology and likely a common series of physical processes involving tangled magnetic

TABLE 1. Comparison of characteristics of Stellar Flares and Gamma Ray Bursts.

Property	Stellar Flares	Gamma Ray Bursts
Energy (ergs)	Sun: 10^{22} – 10^{32} dMe: 10^{31} – 10^{34} RS CVn: 10^{34} – 10^{38} PMS: 10^{36} – 10^{40}	10^{51} – 10^{54}
Time scale	Sun: ms$\rightarrow$ 1 hour dMe: s$\rightarrow$ hours RS CVn: hours$\rightarrow$ days PMS: hours	ms$\rightarrow$ 1000 s
Energy peak	X-ray: $\geq$ 10 keV Radio: $\geq$ 1 MeV	MeV range
Primary energy source	convection	gravity
Jet energy source	magnetic field	gravity and rotation
Jet direction	downward to photosphere	outward from supernova
Observed "explosion"	thermal instability when jet hits chromosphere	blast wave when jet reaches "photosphere"

fields, small scale instabilities, hydrodynamics, particle acceleration, and radiation can explain most stellar flares and even coronal heating. While we understand much of the phenomenology of flares, we do not yet have good models for the physics of rapid magnetic field reconnection or a detailed understanding of the observed correlation between the thermal X-ray emission and nonthermal radio emission of stars while flaring and outside of obvious flares [10]. Studies of transients elsewhere in astrophysics will eventually reveal their physical processes. We may then find that there is much in common among these physical principles, although the observed transient phenomena occur on very different spatial and temporal scales.

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