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Solar and stellar flares

T. G. Forbes

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Solar and stellar flares and stellar flag
By T. G. Forbes

EOS Institute, The University of New Hampshire, Durham, NH 03824, USA

New observations by space telescopes during the last ten years have led to significant advances in understanding the nature of solar flares. X-ray and UV imaging of flare New observations by space telescopes during the last ten years have led to significant
advances in understanding the nature of solar flares. X-ray and UV imaging of flare
emissions have confirmed that flares are powered by New observations by space telescopes during the last ten years have led to significant
advances in understanding the nature of solar flares. X-ray and UV imaging of flare
emissions have confirmed that flares are powered by advances in understanding the nature of solar flares. X-ray and UV imaging of flare
emissions have confirmed that flares are powered by the sudden release of magnetic
energy associated with currents flowing in the solar at emissions have confirmed that flares are powered by the sudden release of magnetic
energy associated with currents flowing in the solar atmosphere. Although many dif-
ferent processes have been suggested as possible trigge energy associated with currents flowing in the solar atmosphere. Although many different processes have been suggested as possible trigger mechanisms, the one which seems to fit the observations best is a loss of ideal-MHD ferent processes have been suggested as possible trigger mechanisms, the one which
seems to fit the observations best is a loss of ideal-MHD equilibrium, or stability,
combined with magnetic reconnection. An ideal-MHD proc combined with magnetic reconnection. An ideal-MHD process by itself has the drawwith magnetic reconnection, this drawback is eliminated. Stellar flares are very likely back that it releases a very small amount of magnetic energy, but when it is coupled
with magnetic reconnection, this drawback is eliminated. Stellar flares are very likely
to be fundamentally similar to solar flares in th with magnetic reconnection, this drawback is eliminated. Stellar flares are very likely
to be fundamentally similar to solar flares in that they involve the sudden release
of magnetic energy associated with currents flowin to be fundamentally similar to solar flares in that they involve the sudden release
of magnetic energy associated with currents flowing in their coronae. However, it
is unlikely that they all involve exactly the same type of magnetic energy associated with currents flowing in their coronae. However, it
is unlikely that they all involve exactly the same type of field configuration or the
same type of trigger mechanism. What these mechanisms is unlikely that they all involve exactly the same type of field configuration or the same type of trigger mechanism. What these mechanisms might be will be difficult to determine without further information on the structu

without further information on the structure of stellar mag
Keywords: solar flares; stellar flares; magnetohydrodynamics;
magnetic fields: reconnection: flare models Keywords: solar flares; stellar flares; magnetohydrodynamics;
magnetic fields; reconnection; flare models

1. Introduction

1. Introduction
In the solar atmosphere there are three different types of large-scale eruptive phe-
nomena which are all thought to be manifestations of a single physical process In the solar atmosphere there are three different types of large-scale eruptive phenomena which are all thought to be manifestations of a single physical process.
These phenomena are *flares, coronal mass ejections* (CMEs) In the solar atmosphere there are three different types of large-scale eruptive phenomena which are all thought to be manifestations of a single physical process.
These phenomena are *flares*, *coronal mass ejections* (CME nomena which are all thought to be manifestations of a single physical process.
These phenomena are *flares, coronal mass ejections* (CMEs) and *prominence eruptions*. What they have in common is that they all involve a di These phenomen
tions. What they
magnetic field.
If the disruption tions. What they have in common is that they all involve a disruption of the coronal magnetic field.
If the disruption occurs in an active region (i.e. a region with sunspots), then it

magnetic field.
If the disruption occurs in an active region (i.e. a region with sunspots), then it
creates the bright patches of emission on the surface which traditionally define a
flare (The emissions called *flare rib* If the disruption occurs in an active region (i.e. a region with sunspots), then it
creates the bright patches of emission on the surface which traditionally define a
flare. (The emissions, called *flare ribbons*, are bes creates the bright patches of emission on the surface which traditionally define a flare. (The emissions, called *flare ribbons*, are best seen in $H\alpha$, and they occur in the chromosphere, the layer lying just above the flare. (The emissions, called *flare ribbons*, are best seen in H α , and they occur in the chromosphere, the layer lying just above the photosphere.) If the disruption occurs outside an active region, the surface emissi chromosphere, the layer lying just above the photosphere.) If the disruption occurs
outside an active region, the surface emissions may be too weak to be considered
a standard flare, and usually such disruptions go unnotic outside an active region, the surface emissions may be too weak to be considered
a standard flare, and usually such disruptions go unnoticed, unless they lead to an
ejection of mass into interplanetary space, known as a CM a standard flare, and usually such disruptions go unno
ejection of mass into interplanetary space, known as
always produce a CME, but small flares rarely do so.
More than half of all CMEs are associated with the ection of mass into interplanetary space, known as a CME. Large flares almost
ways produce a CME, but small flares rarely do so.
More than half of all CMEs are associated with the eruption of large *quiescent*
ominences

In always produce a CME, but small flares rarely do so.
More than half of all CMEs are associated with the eruption of large *quiescent*
prominences. These prominences are dense clouds of cool partly ionized plasma which
a More than half of all CMEs are associated with the eruption of large *quiescent* prominences. These prominences are dense clouds of cool partly ionized plasma which are supported against gravity by a coronal magnetic field prominences. These prominences are dense clouds of cool partly ionized plasma which
are supported against gravity by a coronal magnetic field which is locally horizontal
in the vicinity of the prominence. In order for a ho are supported against gravity by a coronal magnetic field which is locally horizontal
in the vicinity of the prominence. In order for a horizontal field to exist, strong
currents must flow within the corona itself, and it in the vicinity of the prominence. In order for a horizontal field to exist, strong currents must flow within the corona itself, and it is the disruption of these currents which leads to the eruption of a prominence. CMEs which leads to the eruption of a prominence. CMEs not associated with a prominence
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eruption probably occur in regions where the coronal current does not have sufficient
strength or the right orientation to support a prominence. eruption probably occur in regions where the coronal current
strength or the right orientation to support a prominence.
For reasons discussed in $\S 5$, stellar flares are thought to **IATHEMATICAL,
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rength or the right orientation to support a prominence.
For reasons discussed in $\S 5$, stellar flares are thought to involve the same f

strength or the right orientation to support a prominence.
For reasons discussed in $\S 5$, stellar flares are thought to involve the same fun-
damental process as that occurring in solar flares, namely the release of magn For reasons discussed in §5, stellar flares are thought to involve the same fun-
damental process as that occurring in solar flares, namely the release of magnetic
energy stored in a star's atmosphere. However, as more da damental process as that occurring in solar flares, namely the release of magnetic
energy stored in a star's atmosphere. However, as more data are obtained about flare
stars, it seems increasingly likely that the field con stars, it seems increasingly likely that the field configurations involved may be quite different. This is almost a foregone conclusion for binary systems where interaction stars, it seems increasingly likely that the field configurations involved may be quite
different. This is almost a foregone conclusion for binary systems where interaction
between the fields of both stars are involved, an different. This is almost a foregone conclusion for binary systems where interaction
between the fields of both stars are involved, and it is also likely to be true for the
classic dMe and dKe flare stars. (The names refer classic dMe and dKe flare stars. (The names refer to their spectral type.) These are rapidly rotating red dwarfs which may have rotation periods as small as 10 h and whose magnetic field structure may, therefore, be more like Jupiter's than the Sun's. pidly rotating red dwarfs which may have rotation periods as small as 10 h and
nose magnetic field structure may, therefore, be more like Jupiter's than the Sun's.
One can speculate that the difference in the flare process

whose magnetic field structure may, therefore, be more like Jupiter's than the Sun's.
One can speculate that the difference in the flare process from one star to another
is as varied as the process which creates auroral ma One can speculate that the difference in the flare process from one star to another
is as varied as the process which creates auroral magnetic substorms in the different
planetary magnetospheres of our solar system. In the is as varied as the process which creates auroral magnetic substorms in the different
planetary magnetospheres of our solar system. In the case of Jupiter, such substorms
are caused by the disruption of the current sheet c planetary magnetospheres of our solar system. In the case of Jupiter, such substorms are caused by the disruption of the current sheet created by Jupiter's rapid 10 h rotation (Zimbardo 1993), but in the case of the Earth, are caused by the disruption of the current sheet created by Jupiter's rapid 10 h
rotation (Zimbardo 1993), but in the case of the Earth, they are caused by the
disruption of the *geomagnetic-tail* current sheet created by rotation (Zimbardo 1993), but in the case of the Earth, they are caused by the disruption of the *geomagnetic-tail* current sheet created by the drag of the solar wind on the terrestrial magnetic field (Hones 1973). In bot is the release of stored magnetic energy, but the differences in the field structures involved make it impossible for a single theoretical model to describe them both.

2. Magnetic energy storage

2. Magnetic energy storage
One of the most important aspects of solar and stellar flares is that they occur in a
plasma environment dominated by magnetic fields. In the solar atmosphere, magnetic One of the most important aspects of solar and stellar flares is that they occur in a
plasma environment dominated by magnetic fields. In the solar atmosphere, magnetic
energy is the only source of energy that is canable o One of the most important aspects of solar and stellar flares is that they occur in a
plasma environment dominated by magnetic fields. In the solar atmosphere, magnetic
energy is the only source of energy that is capable o plasma environment dominated by magnetic fields. In the solar atmosphere, magnetic energy is the only source of energy that is capable of producing the radiative and kinetic energy output of large flares. Before the onset energy is the only source of energy that is capable of producing the radiative and
kinetic energy output of large flares. Before the onset of a solar flare the magnetic
energy density $(B^2/(2\mu_0))$, where μ_0 is the per kinetic energy output of large flares. Before the onset of a solar flare the magnetic
energy density $(B^2/(2\mu_0))$, where μ_0 is the permeability of free space) of a 100 G
 (10^{-2} T) coronal field is *ca*. 40 J m⁻³ **MATHEMATICAL,
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SCIENCES** energy density $(B^2/(2\mu_0))$, where μ_0 is the permeability of free space) of a 100 G (10⁻² T) coronal field is *ca*. 40 J m⁻³. By comparison, the thermal energy density (nkT) , where k is Boltzman's constant) is *c* (*nkT*, where k is Boltzman's constant) is ca. 0.01 J m⁻³, since the coronal particle density, n, and temperature, T, are ca. 10^{15} m⁻³ and 10^6 K, respectively. Finally, the (nkT , where k is Boltzman's constant) is $ca. 0.01 \text{ J m}^{-3}$, since the coronal particle
density, n, and temperature, T, are $ca. 10^{15} \text{ m}^{-3}$ and 10^6 K , respectively. Finally, the
kinetic energy density $(\frac{1}{2}m$ density, *n*, and temperature, *T*, are *ca*. 10^{15} m^{-3} and 10^6 K , respectively. Finally, the kinetic energy density $(\frac{1}{2}m_pnv^2)$, where m_p is the proton rest mass) in the corona is *ca*. 10^{-6} J m^{-3} is ca. 10^{-6} J m⁻³ assuming that the velocity, v, is of the order of 1 km s^{-1} —the $\frac{1}{\text{avitational}}$
) is of the
 $\frac{1}{\text{m}}$ Thus convective velocity imparted by flows at the photospheric level. The gravitational energy density $(m_p ngh)$, where g is the solar surface gravity of 247 m s⁻²) is of the order of 0.04 J m⁻³ assuming that the average mas convective velocity imparted by flows at the photospheric level. The gravitational
energy density $(m_p ngh)$, where g is the solar surface gravity of 247 m s⁻²) is of the
order of 0.04 J m⁻³ assuming that the average mas order of 0.04 J m⁻³ assuming that the average mass height, h, is ca. 10⁸ m. Thus,
the magnetic energy density is about three orders of magnitude greater than any
of the other types. Since large flares typically have a \geq the magnetic energy density is about three orders of magnitude greater than any the magnetic energy density is about three orders of magnitude greater than any
of the other types. Since large flares typically have an energy of 10^{25} J (10^{32} erg)
and a volume in the range $10^{24}-10^{25}$ m³, a of the other types. Since large flares typically have an energy of 10^{25} J (10^{32} erg) and a volume in the range $10^{24} - 10^{25}$ m³, an average energy density of $1-10$ J m⁻³ is required. Only the magnetic ener and a volume in the rang
required. Only the magn
of flares are ruled out.
Sunspots and other m is quired. Only the magnetic energy density is in this range, so non-magnetic models
flares are ruled out.
Sunspots and other magnetic features in the solar photosphere are unaffected by
e-occurrence of flares. This is becau

of flares are ruled out.
Sunspots and other magnetic features in the solar photosphere are unaffected by
the occurrence of flares. This is because the plasma in the photosphere is almost 10^9
times denser than the plasm Sunspots and other magnetic features in the solar photosphere are unaffected by
the occurrence of flares. This is because the plasma in the photosphere is almost 10^9
times denser than the plasma in the corona where fla the occurrence of flares. This is because the plasma in the photosphere is almost 10^9
times denser than the plasma in the corona where flares originate, so it is very difficult
for disturbances in the tenuous corona to times denser than the plasma in the corona where flares originate, so it is very difficult
for disturbances in the tenuous corona to affect the extremely massive plasma of the
photospheric layer. Field lines mapping from t for disturbances in the tenuous corona to affect the extremely massive plasma of the photospheric layer. Field lines mapping from the corona to the photosphere are said to be inertially line-tied to the photosphere, meanin photospheric layer. Field lines mapping from the corona to the photosphere to be inertially line-tied to the photosphere, meaning that the foot field lines are effectively stationary over the time-scale of a flare. field lines are effectively stationary over the time-scale of a flare.
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The time-scale for the onset of solar flares is very rapid. From observations it has
en estimated that as much as 10^{25} J (10^{32} erg) is generated in the form of thermal The time-scale for the onset of solar flares is very rapid. From observations it has
been estimated that as much as 10^{25} J (10^{32} erg) is generated in the form of thermal
and kinetic energy during the first few min **INEERING**
IES The time-scale for the onset of solar flares is very rapid. From observations it has
been estimated that as much as 10^{25} J (10^{32} erg) is generated in the form of thermal
and kinetic energy during the first few min and kinetic energy during the first few minutes after onset. This is an extremely short time-scale for an organized process to be occurring over a region whose size is short time-scale for an organized process to be occurring over a region whose size is
of the order of 10^5 km (about 10 times larger than the diameter of the Earth), and it
implies dynamic velocities of the order of 100 of the order of 10^5 km (about 10 times larger than the diameter of the Earth), and it of the order of 10^5 km (about 10 times larger than the diameter of the Earth), and it
implies dynamic velocities of the order of 100 to 1000 km s⁻¹—close to the speed at
which magnetic and acoustic waves propagate in which magnetic and acoustic waves propagate in the corona. The implication of such a large energy output in so short a time is that $ca. 10\%$ of the available magnetic which magnetic and acoustic waves propagate in the corona. The implication of such
a large energy output in so short a time is that $ca.10\%$ of the available magnetic
energy in a volume of 10^{15} km³ is converted to t a large energy output in so short a time is that $ca.10\%$ of the available magnetic
energy in a volume of 10^{15} km³ is converted to thermal and kinetic energy within
a few wave travel times. In other words, flares re a few wave travel times. In other words, flares require an onset mechanism which processes magnetic energy with an efficiency of the order of 10% on a time-scale which is only a few times greater than the wave travel time. This combination of \bigcirc efficiency and speed is not easy to explain theore which is only a few times greater than the wave travel time. This combination of

3. Trigger mechanism

3. Trigger mechanism
At the present time, the most generally accepted explanation for the cause of flares is
that they are produced by a loss of instability or equilibrium in the coronal magnetic At the present time, the most generally accepted explanation for the cause of flares is
that they are produced by a loss of instability or equilibrium in the coronal magnetic
field. The continual emergence of new flux from At the present time, the most generally accepted explanation for the cause of flares is
that they are produced by a loss of instability or equilibrium in the coronal magnetic
field. The continual emergence of new flux from that they are produced by a loss of instability or equilibrium in the coronal magnetic
field. The continual emergence of new flux from the convection zone and the shuffling
of the footpoints of closed coronal field lines c $\overline{5}$ of the footpoints of closed coronal field lines causes stresses to build up in the coronal field. Eventually, the stress exceeds a threshold beyond which a stable equilibrium cannot be maintained, and the field erupts. The eruption releases the magnetic energy stored in the stressed field, so models based on this mechanism are sometimes referred to as *storage models*.

If the flare produces a CME, magnetic field lines mapping from the ejected plasma to the photosphere are stretched outwards to form an extended open-field structure. If the flare produces a CME, magnetic field lines mapping from the ejected plasma
to the photosphere are stretched outwards to form an extended open-field structure.
This opening of the field creates an apparent paradox, s to the photosphere are stretched outwards to form an extended open-field structure.
This opening of the field creates an apparent paradox, since the stretching of the
field lines implies that the magnetic energy of the sy This opening of the field creates an apparent paradox, since the stretching of the field lines implies that the magnetic energy of the system is increasing, whereas storage models require it to decrease (Sturrock *et al.* field lines implies that the magnetic energy of the system is increasing, whereas
storage models require it to decrease (Sturrock *et al.* 1984). Barnes & Sturrock (1972)
argued that this paradox does not occur, because t storage models require it to decrease (Sturrock *et al.* 1984). Barnes & Sturrock (1972) argued that this paradox does not occur, because the relaxation of the stressed field which exists prior to the eruption releases mo argued that this paradox does not occur, because the relaxation of the stressed field
which exists prior to the eruption releases more magnetic energy than is consumed
in stretching the field lines. In other words, the mag which exists prior to the eruption releases more magnetic energy than is consumed
in stretching the field lines. In other words, the magnetic energy required to open
the field should be less than the free magnetic energy in stretching the field lines. In other words, the magnetic energy required to open
the field should be less than the free magnetic energy stored in the corona. Following
this line of thought, Kopp & Pneuman (1976) propos the field should be less than the free magnetic energy stored in the corona. Following
this line of thought, Kopp & Pneuman (1976) proposed a scenario for a three-stage
model of an eruptive flare. Prior to the eruption, en this line of thought, Kopp & Pneuman (1976) proposed a scenario for a three-stage model of an eruptive flare. Prior to the eruption, energy is stored in a force-free arcade or flux rope. (A force-free field is one with th model of an eruptive flare. Prior to the eruption, energy is stored in a force-free
arcade or flux rope. (A force-free field is one with the current flowing in the direction
of the magnetic field.) Eventually the field eru arcade or flux rope. (A force-free field is one with the current flowing in the direction
of the magnetic-field.) Eventually the field erupts outwards to form a fully opened
magnetic-field configuration. Finally, the open of the magnetic field.) Eventually the field erupts outwards to form a fully opened
magnetic-field configuration. Finally, the opened configuration reconnects to form a
closed, nearly current-free, field. According to Bar magnetic-field configuration. Finally, the opened configuration reconnects to form a closed, nearly current-free, field. According to Barnes & Sturrock (1972) the evolution from the first stage to the second would be an id closed, nearly current-free, field. According to Barnes & Sturrock (1972) the evolution
from the first stage to the second would be an ideal-MHD process occurring on the
Alfvén time-scale, while the evolution from the seco General form the first stage to the second would be an ideal-MHD process occurring on the Californian-scale, while the evolution from the second stage to the third would be a resistive-MHD process occurring on the slower \bullet a resistive-MHD process occurring on the slower reconnection time-scale. Thus the level. ddle stage would constitute a metastable state at an intermediate magnetic energy
el.
Aly (1984, 1991) and Sturrock (1991) have shown that the above scenario is ener-
tically impossible. Using quite general arguments they

level.
Aly (1984, 1991) and Sturrock (1991) have shown that the above scenario is ener-
getically impossible. Using quite general arguments they prove that the fully opened
field configuration must always have a higher mag Aly (1984, 1991) and Sturrock (1991) have shown that the above scenario is energetically impossible. Using quite general arguments they prove that the fully opened field configuration must always have a higher magnetic ene getically impossible. Using quite general arguments they prove that the fully opened
field configuration must always have a higher magnetic energy than the correspond-
ing force-free magnetic field as long as the field is *Phil. Trans. R. Soc. Lond.* A (2000)

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 $T. G.$ Forbes caused consternation among some theorists because it seems to imply that eruptive caused consternation among some theorists because it seems to imply that eruptive
flares are energetically impossible. However, as Aly and Sturrock have noted, there
are several ways to avoid this predicament. First, the m **IATHEMATICAL,
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: ENGINEERING
CIENCES** caused consternation among some theorists because it seems to imply that eruptive
flares are energetically impossible. However, as Aly and Sturrock have noted, there
are several ways to avoid this predicament. First, the m are several ways to avoid this predicament. First, the magnetic fields may not be simply connected but contain X points and O points; second, an ideal-MHD eruption can still extend field lines as long as it does not open t ply connected but contain X points and O points; second, an ideal-MHD eruption ply connected but contain X points and O points; second, an ideal-MHD eruption
can still extend field lines as long as it does not open them all the way to infinity;
and finally, an ideal-MHD eruption is possible if it onl can still extend field lines as long as it does not open and finally, an ideal-MHD eruption is possible if it only field lines (Wolfson & Low 1992; Low & Smith 1993).
One type of storage model that has received much d finally, an ideal-MHD eruption is possible if it only opens a portion of the closed
ld lines (Wolfson & Low 1992; Low & Smith 1993).
One type of storage model that has received much attention tries to create an
uption b

field lines (Wolfson & Low 1992; Low & Smith 1993).
One type of storage model that has received much attention tries to create an
eruption by shearing the footpoints of an arcade of loops (Mikić *et al.* 1988; Martinell 1990; Steinolfson 1991; Inhester *et al*. 1992; Aly 1994; Kusano *et al*. 1995; Amari *et* eruption by shearing the footpoints of an arcade of loops (Mikić *et al.* 1988; Martinell 1990; Steinolfson 1991; Inhester *et al.* 1992; Aly 1994; Kusano *et al.* 1995; Amari *et al.* 1996). In two-dimensional force-free 1990; Steinolfson 1991; Inhester *et al.* 1992; Aly 1994; Kusano *et al.* 1995; Amari *et al.* 1996). In two-dimensional force-free configurations with translational symmetry, shearing causes the arcade to expand smoothly al. 1996). In two-dimensional force-free configurations with translational symmetry, shearing causes the arcade to expand smoothly outwards towards a fully opened state without ever producing an eruption. It is not yet kno shearing causes the arcade to expand smoothly outwards towards a fully opened state
without ever producing an eruption. It is not yet known whether this is true for all
three-dimensional configurations.
Even if shearing an without ever producing an eruption. It is not yet known whether this is true for all

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SOCIETY three-dimensional configurations.
Even if shearing an arcade does not produce an ideal loss of equilibrium or stability, it is still possible to create a rapid eruption by invoking a resistive instability.
For example, she Even if shearing an arcade does not produce an ideal loss of equilibrium or stability, it is still possible to create a rapid eruption by invoking a resistive instability.
For example, shearing an arcade may lead to the fo bility, it is still possible to create a rapid eruption by invoking a resistive instability.
For example, shearing an arcade may lead to the formation of a current sheet which
can undergo reconnection (Somov 1992). If the For example, shearing an arcade may lead to the formation of a current sheet which
can undergo reconnection (Somov 1992). If the reconnection occurs rapidly, say at a
rate which is of the order of a few Alfvén time-scales can undergo reconnection (Somov 1992). If the reconnection occurs rapidly, say at a
rate which is of the order of a few Alfvén time-scales, then a rapid eruption occurs
(Mikić & Linker 1994). In order for this mechanism to \overline{O} rate which is of the order of a few Alfvén time-scales, then a rapid eruption occurs (Mikić & Linker 1994). In order for this mechanism to work, the reconnection rate must undergo a sudden transition. Prior to the eruptio (Mikić & Linker 1994). In order for this mechanism to work, the reconnection rate must undergo a sudden transition. Prior to the eruption it must be slow compared with the time-scale of the photospheric motions, so that e must undergo a sudden transition. Prior to the eruption it must be slow compared
with the time-scale of the photospheric motions, so that energy can be stored in the
coronal currents. After the eruption it must be fast, so with the time-scale of the photospheric motions, so that energy can be stored in the coronal currents. After the eruption it must be fast, so that energy can be released rapidly. Thus, a complete model of the eruption proc coronal currents. After the eruption it must be fast, so that energy can be released
rapidly. Thus, a complete model of the eruption process must explain why the recon-
nection rate suddenly changes at the time of the erup rapidly. Thus, a complete model of the eruption process must explain why the reconnection rate suddenly changes at the time of the eruption. There are several possible mechanisms which could do this. For example, if the cu nection rate suddenly changes at the time of the eruption. There are several possible
mechanisms which could do this. For example, if the current sheet is subject to the
tearing-mode instability, then reconnection will no mechanisms which could do this. For example, if the current sheet is subject to the tearing-mode instability, then reconnection will not occur until the length of the current sheet becomes longer than about 2π times it tearing-mode instability, then reconnection will not occur until the length of the current sheet becomes longer than about 2π times its width (Furth *et al.* 1963). Alternatively, as the current sheet builds up, its cu current sheet becomes longer than about 2π times its width (Furth *et al.* 1963).
Alternatively, as the current sheet builds up, its current density may exceed the threshold of a microinstability which creates an anoma Alternatively, as the current sheet builds up, its current density may exceed the threshold of a microinstability which creates an anomalous resistivity (Heyvaerts $\&$ Priest 1976). The anomalous resistivity subsequently threshold of a microinstabili
Priest 1976). The anomalous
the ejection of a flux rope.
Sheared arcades can also b iest 1976). The anomalous resistivity subsequently triggers rapid reconnection and
e ejection of a flux rope.
Sheared arcades can also be formed by the emergence of a flux rope from below the
otosphere as long as the centr

the ejection of a flux rope.
Sheared arcades can also be formed by the emergence of a flux rope from below the photosphere as long as the central axis of the rope lies on or below the photosphere. Sheared arcades can also be formed by the emergence of a flux rope from below the photosphere as long as the central axis of the rope lies on or below the photosphere.
However, if the flux-rope axis lies above the photosph photosphere as long as the central axis of the rope lies on or
However, if the flux-rope axis lies above the photosphere, then
a flux rope whose field lines are anchored only at its ends.
Figure 1 shows a two-dimensional f by the flux-rope axis lies above the photosphere, then the arcade will contain
flux rope whose field lines are anchored only at its ends.
Figure 1 shows a two-dimensional flux-rope model which loses equilibrium when
the p

a flux rope whose field lines are anchored only at its ends.
Figure 1 shows a two-dimensional flux-rope model which loses equilibrium when
the photospheric sources of the field approach one another (Forbes & Priest 1995). Figure 1 shows a two-dimensional flux-rope model which loses equilibri
the photospheric sources of the field approach one another (Forbes & Price
The configuration is obtained by solving the Grad-Shafranov equation
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solving the Grad–Shafranov equation
\n
$$
\nabla^2 A + \frac{1}{2} \frac{d B_z^2}{d A} = 0
$$
\n(3.1)

 $\nabla^2 A + \frac{1}{2} \frac{dB_z^2}{dA} = 0$ (3.1)
in the semi-infinite xy-plane with $y \ge 0$, where B_z is the field perpendicular to the
xy-plane and $A(x, y)$ is the flux function defined by in the semi-infinite xy-plane with $y \ge 0$, where B_z is the xy -plane and $A(x, y)$ is the flux function defined by xy-plane and $A(x, y)$ is the flux function defined by

the flux function defined by
\n
$$
(B_x, B_y, B_z) = \left[\frac{\partial A}{\partial y}, -\frac{\partial A}{\partial x}, B_z(A)\right].
$$
\n(3.2)

The surface at $y = 0$ corresponds to the photosphere. Equation (3.1) is used to construct an evolutionary sequence of force-free equilibria by assuming that changes

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Figure 1. Ideal-MHD evolution of a two-dimensional arcade containing an unshielded flux rope.
(a)–(c) The flux rope and arcade jumps upwards when the two photospheric field sources are
pushed too close to one another (d) Figure 1. Ideal-MHD evolution of a two-dimensional arcade containing an unshielded flux rope.
(a)–(c) The flux rope and arcade jumps upwards when the two photospheric field sources are
pushed too close to one another. (d) (a) – (c) The flux rope and arcade jumps
pushed too close to one another. (d) In the equilibrium containing a current sheet.

equilibrium containing a current sheet.
in the photospheric boundary conditions occur more slowly than the Alfvén time-
scale in the corona in the photospheric $\frac{1}{16}$
scale in the corona.
Figure 1*a* shows the scale in the corona.
Figure 1a shows the equilibrium flux-rope height as a function of the source sepa-

scale in the corona.
Figure 1a shows the equilibrium flux-rope height as a function of the source separation (2λ) for $a_0 = 0.1\lambda_0$. The S-shaped curve is characteristic of cusp-type catas-
trophes, where the highest Figure 1a shows the equilibrium flux-rope height as a function of the source separation (2 λ) for $a_0 = 0.1\lambda_0$. The S-shaped curve is characteristic of cusp-type catastrophes, where the highest and lowest branches are ration (2 λ) for $a_0 = 0.1\lambda_0$. The S-shaped curve is characteristic of cusp-type catas-
trophes, where the highest and lowest branches are stable, but the middle branch is
unstable (Poston & Stewart 1978). If one star trophes, where the highest and lowest branches are stable, but the middle branch is unstable (Poston $&$ Stewart 1978). If one starts with a configuration corresponding to unstable (Poston & Stewart 1978). If one starts with a configuration corresponding to
a point on the lower branch, as shown in figure 1b, and then move the source regions
towards each other, a catastrophe will occur when a point on the lower branch, as shown in figure 1b, and then move the source regions
towards each other, a catastrophe will occur when λ reaches the point where the
lower and middle branches of the equilibrium curve me towards each other, a catastrophe will occur when λ reaches the point where the lower and middle branches of the equilibrium curve meet. At this point the configuration (figure 1c) loses magnetic equilibrium, and the f

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Figure 2. Comparison of (a) the two-dimensional flux-rope model with (b) a more realistic three-dimensional configuration. Several turns of the field are shown for illustrative purposes. Figure 2. Comparison of (a) the two-dimensional flux-rope model with (b) a more realistic three-dimensional configuration. Several turns of the field are shown for illustrative purposes, but in reality the number of tur three-dimensional configuration. Several turns of the field are shown for illustrative purposes, but in reality, the number of turns is probably between one and two.

but in reality, the number of turns is probably between one and two.
by the imbalance which develops between the magnetic compression and tension
forces acting on it (Van Tend & Kuperus 1978: Yeh 1983: Martens & Kuin 1989 by the imbalance which develops between the magnetic compression and tension forces acting on it (Van Tend & Kuperus 1978; Yeh 1983; Martens & Kuin 1989; van Ballegooijen & Martens 1989). by the imbalance which develop
forces acting on it (Van Tend & 1
Ballegooijen & Martens 1989).
What happens after the loss forces acting on it (Van Tend & Kuperus 1978; Yeh 1983; Martens & Kuin 1989; van Ballegooijen & Martens 1989).
What happens after the loss of equilibrium depends on the dynamics. If one

Ballegooijen & Martens 1989).
What happens after the loss of equilibrium depends on the dynamics. If one
assumes that there is no reconnection, and all the kinetic energy released by the
loss of equilibrium is dissinated, What happens after the loss of equilibrium depends on the dynamics. If one assumes that there is no reconnection, and all the kinetic energy released by the loss of equilibrium is dissipated, then the flux rope restabiliz assumes that there is no reconnection, and all the kinetic energy released by the loss of equilibrium is dissipated, then the flux rope restabilizes at the upper equilibrium shown in figure $1d$. On the other hand, if thi loss of equilibrium is dissipated, then the flux rope restabilizes at the upper equilibrium shown in figure $1d$. On the other hand, if this energy is not dissipated, then the flux rope oscillates up and down between the From shown in figure 1d. On the other hand, if this energy is not dissipated, then
the flux rope oscillates up and down between the lower equilibrium at the catas-
trophe point and a height somewhere above the height of t the flux rope oscillates up and down between the lower equilibrium at the catastrophe point and a height somewhere above the height of the upper equilibrium.
Finally, if reconnection does occur, then the flux rope continue trophe point and a height somewhere above the height of the upper equilibrium.
Finally, if reconnection does occur, then the flux rope continues to move upwards
indefinitely, although its upward motion may be slowed once i indefinitely, although its upward motion may be slowed once its altitude exceeds the definitely, although its upward motion may be slowed once its altitude exceeds the
per equilibrium height.
Because the model shown in figure 1 is two dimensional, it does not take into
nsideration what happens if the ends

upper equilibrium height.
Because the model shown in figure 1 is two dimensional, it does not take into
consideration what happens if the ends of the flux rope are anchored to the photo-
sphere (i.e. line-tied) as is almos Because the model shown in figure 1 is two dimensional, it does not take into consideration what happens if the ends of the flux rope are anchored to the photosphere (i.e. line-tied), as is almost certain to be the case i consideration what happens if the ends of the flux rope are anchored to the photo-
sphere (i.e. line-tied), as is almost certain to be the case in reality. When the ends are
anchored, as shown in figure 2, only the central sphere (i.e. line-tied), as is almost certain to be the case in reality. When the ends are anchored, as shown in figure 2, only the central portion of the flux rope has the possibility to move upwards. Consequently, the t anchored, as shown in figure 2, only the central portion of the flux rope has the pos-
sibility to move upwards. Consequently, the two-dimensional model corresponds to
the onset of an *external kink* (as opposed to an *int* sibility to move upwards. Consequently, the two-dimensional model corresponds to
the onset of an *external kink* (as opposed to an *internal kink*, which leaves the outer
surface of the flux rope unmoved). Hood (1990) has the onset of an *external kink* (as opposed to an *internal kink*, which leaves the outer surface of the flux rope unmoved). Hood (1990) has shown that the line-tying of the ends of a flux rope at a surface helps to stabilize it against kinking, but if the flux rope contains more than a couple of turns, line-tying alone can no longer stabilize it. Thus, an eruption can still occur, at least in principle, in a three-dimensional flux rope whose ends are anchored in the photosphere. it. Thus, an eruption can still occur, at least in principle, in a three-dimensional flux
rope whose ends are anchored in the photosphere. Unfortunately, the two-dimensional
model cannot be quantitatively applied to the th rope whose ends are anchored in the photosphere. Unfortunately, the two-dimensional

4. Solar flare loops

The opening of the field lines in an active region by a large flare leads to the formation The opening of the field lines in an active region by a large flare leads to the formation
of flare ribbons and loops which can last for more than 10 h. These structures appear
to move through the chromosphere and corona, The opening of the field lines in an active region by a large flare leads to the formation
of flare ribbons and loops which can last for more than 10 h. These structures appear
to move through the chromosphere and corona, of flare ribbons and loops which can last for more than 10 h. These structures appear
to move through the chromosphere and corona, and they provide some of the best
evidence for reconnection in the solar atmosphere. Dopple to move through the chromosphere and corona, and they provide some of the best
evidence for reconnection in the solar atmosphere. Doppler-shift measurements show
conclusively that the motions of the flare loops and ribbons evidence for reconnection in the solar atmosphere. Doppler-shift measurements show
conclusively that the motions of the flare loops and ribbons are not due to mass
motions of the solar plasma, but rather to the upward pro conclusively that the motions of the flare loops and ribbons are not due to mass
motions of the solar plasma, but rather to the upward propagation of an energy
source in the corona (see, for example, Schmieder *et al.* 198 motions of the solar plasma, but rather to the upward propagation
source in the corona (see, for example, Schmieder *et al.* 1987). Such
exactly what one expects for a reconnection model of the flare loops.
Flare loops ra Flare loops range from temperatures of 10^4 to 3×10^7 K, with the cooler loops range from temperatures of 10^4 to 3×10^7 K, with the cooler loops sted below the hotter loops. They have traditionally been calle

exactly what one expects for a reconnection model of the flare loops.
Flare loops range from temperatures of 10^4 to 3×10^7 K, with the cooler loops, nested below the hotter loops. They have traditionally been calle nested below the hotter loops. They have traditionally been called 'post'-flare loops, *Phil. Trans. R. Soc. Lond.* A (2000)

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but this is a misnomer since the energy release continues throughout their lifetime.
Remarkably, the loops at the low temperature are two orders of magnitude cooler
than the surrounding coronal plasma. These super-cool loo EFRING ATHEMATICAL but this is a misnomer since the energy release continues throughout their lifetime.
Remarkably, the loops at the low temperature are two orders of magnitude cooler
than the surrounding coronal plasma. These super-cool loo than the surrounding coronal plasma. These super-cool loops are formed from the hot loops by a radiative thermal instability ($Cox 1972$), which is possible in the solar atmosphere because of its non-black-body behaviour (

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than the surrounding coronal plasma. These super-cool loops are for
hot loops by a radiative thermal instability (Cox 1972), which is possil
atmosphere because of its non-black-body behaviour (Parker 1953).
The outermost e t loops by a radiative thermal instability (Cox 1972), which is possible in the solar mosphere because of its non-black-body behaviour (Parker 1953).
The outermost edges of the hot X-ray loops map to the outer edge of the The outermost edges of the hot X-ray loops map to the outer edge of the chromo-
spheric flare ribbons (Schmieder *et al.* 1996), while the inner edges of the cool $H\alpha$ The outermost edges of the hot X-ray loops map to the outer edge of the chromo-
spheric flare ribbons (Schmieder *et al.* 1996), while the inner edges of the cool H α
loops map to the inner edge of the ribbons (Rust & B spheric flare ribbons (Schmieder *et al.* 1996), while the inner edges of the cool H α loops map to the inner edge of the ribbons (Rust & Bar 1973). During the course of a flare, the separation between the ribbons incre time. a flare, the separation between the ribbons increases, and the loops grow larger with time.
Magnetic reconnection (for a review see Priest $\&$ Forbes 1999) is thought by most

time.
Magnetic reconnection (for a review see Priest $\&$ Forbes 1999) is thought by most
researchers to be the only mechanism which can account for the motion of the flare
loops and ribbons. Simple expansion of the loops Magnetic reconnection (for a review see Priest $\&$ Forbes 1999) is thought by most researchers to be the only mechanism which can account for the motion of the flare loops and ribbons. Simple expansion of the loops due t loops and ribbons. Simple expansion of the loops due to outward motion of the plasma from the flare site has been ruled out by Doppler-shift measurements of the $H\alpha$ loops. Doppler shifts in the $H\alpha$ line show that the plasma from the flare site has been ruled out by Doppler-shift measurements of the plasma from the flare site has been ruled out by Doppler-shift measurements of the $H\alpha$ loops. Doppler shifts in the $H\alpha$ line show that the plasma in the cool loops flows downward at speeds of 100 to 500 km s⁻¹ durin $\overline{H}\alpha$ loops. Doppler shifts in the H α line show that the plasma in the cool loops flows downward at speeds of 100 to 500 km s⁻¹ during the time that the loops appear to be expanding (see, for example, Schmieder downward at speeds of 100 to 500 km s⁻¹ during the time that the loops appear to be expanding (see, for example, Schmieder *et al.* 1987). Thus, the loop motions are not due to mass motions of the plasma, but rather to be expanding (see, for example, Schmieder *et al.* 1987). Thus, the loop motions are not due to mass motions of the plasma, but rather to the continual propagation of \circ an energy source onto new field lines.
Although l t due to mass motions of the plasma, but rather to the continual propagation of
energy source onto new field lines.
Although loop and ribbon motions are strong evidence for reconnection (Kopp
Pneuman 1976), the evidence th

an energy source onto new field lines.
Although loop and ribbon motions are strong evidence for reconnection (Kopp
& Pneuman 1976), the evidence they provide is circumstantial. In principle, X-ray
telescopes of sufficient Although loop and ribbon motions are strong evidence for reconnection (Kopp $\&$ Pneuman 1976), the evidence they provide is circumstantial. In principle, X-ray telescopes of sufficient spatial resolution and sensitivity telescopes of sufficient spatial resolution and sensitivity should be able to provide direct evidence by imaging the reconnection site itself as it moves upwards in the corona. However, the ability to determine whether or not there is a reconnection site in the corona depends very much on theoretical expect corona. However, the ability to determine whether or not there is a reconnection site corona. However, the ability to determine whether or not there is a reconnection site
in the corona depends very much on theoretical expectations of what such a site
should look like. During the last few years, high-resolu in the corona depends very much on theoretical expectations of what such a site
should look like. During the last few years, high-resolution images obtained from
the X-ray telescopes on the Japanese satellite Yohkoh show s should look like. During the last few years, high-resolution images obtained from
the X-ray telescopes on the Japanese satellite Yohkoh show several features that
are highly suggestive of a reconnection site in the corona the X-ray telescopes on the Japanese satellite Yohkoh show several features that
are highly suggestive of a reconnection site in the corona. These features include:
a hard X-ray source located above the soft X-ray loops (S are highly suggestive of a reconnection site in the corona. These features include:
a hard X-ray source located above the soft X-ray loops (Sakao *et al.* 1992; Masuda
1994; Bentley *et al.* 1994); cusp structures suggesti a hard X-ray source located above the soft X-ray loops (Sakao *et al.* 1992; Masuda 1994; Bentley *et al.* 1994); cusp structures suggestive of either an X-type or a Y-type neutral line (Acton *et al.* 1992; Tsuneta 1993; are highly suggestive of a reconnection site in the corona. These teatures include:
a hard X-ray source located above the soft X-ray loops (Sakao *et al.* 1992; Masuda
della 1994; Bentley *et al.* 1994); cusp structures su neutral line (Acton *et al.* 1992; Tsuneta 1993; Doschek *et al.* 1995); bright features at the top of the soft X-ray loops (Tsuneta *et al.* 1992; McTiernan *et al.* 1993); and high-temperature plasma along the field lin at the top of the
and high-tempera
(Tsuneta 1996).
Some of the cus d high-temperature plasma along the field lines mapping to the tip of the cusp-
Some of the cusp-shaped loops observed by Yohkoh have a linear trunk-like feature
aich extends from the top of the cusp all the way down to th

(Tsuneta 1996).
Some of the cusp-shaped loops observed by Yohkoh have a linear trunk-like feature
which extends from the top of the cusp all the way down to the inner arch of the flare
loop system. The hottest regions in t which extends from the top of the cusp all the way down to the inner arch of the flare \succ loop system. The hottest regions in the loop system do not lie in the trunk feature but along the edges of the cusp formed by the outermost loop (Tsuneta 1996), and loop system. The hottest regions in the loop system do not lie in the trunk feature is both cooler and denser than the plasma surrounding it.
Figure 3 shows a theoretical model which explains the loop structures in terms It along the edges of the cusp formed by the outermost loop (Tsuneta 1996), and
e trunk feature is both cooler and denser than the plasma surrounding it.
Figure 3 shows a theoretical model which explains the loop structure

the trunk feature is both cooler and denser than the plasma surrounding it.
Figure 3 shows a theoretical model which explains the loop structures in terms of
the processes of reconnection and *chromospheric evaporation* (i Figure 3 shows a theoretical model which explains the loop structures in terms of
the processes of reconnection and *chromospheric evaporation* (i.e. the ablation of the
chromosphere by heat conduction and energetic parti the processes of reconnection and *chromospheric evaporation* (i.e. the ablation of the chromosphere by heat conduction and energetic particles). The figure incorporates the early ideas of Carmichael (1964), Sturrock (196 Conformal Conduction and energetic particles). The figure incorporates
the early ideas of Carmichael (1964), Sturrock (1968), Hirayama (1974), Kopp &
Pneuman (1976) and Cargill & Priest (1982). However, most of the detail the early ideas of Carmichael (1964), Sturrock (1968), Hirayama (1974), Kopp & Pneuman (1976) and Cargill & Priest (1982). However, most of the details of the figure come from the results of various simulations of reconne Pneuman (1976) and Cargill & Priest (1982). However, most of the details of the figure come from the results of various simulations of reconnection (Forbes & Malherbe 1991), evaporation (Nagai 1980; Somov *et al.* 1982; C *al.* 1983; Pallavicini *et al.* 1983; Fisher *et al.* 1982; Pheng 1983; Doschek *et al.* 1983; Pallavicini *et al.* 1983; Fisher *et al.* 1985) and condensation (Antiochos & Sturrock 1982). According to this model, flare herbe 1991), evaporation (Nagai 1980; Somov *et al.* 1982; Cheng 1983; Doschek *et al.* 1983; Pallavicini *et al.* 1983; Fisher *et al.* 1985) and condensation (Antiochos & Sturrock 1982). According to this model, flare lo *Phil. Trans. R. Soc. Lond.* A (2000)

Figure 3. Schematic of a flare loop system formed by reconnection in the supermagnetosonic Figure 3. Schematic of a flare loop system formed by reconnection in the supermagnetosonic
regime. This regime is most likely to occur in the early phase of a flare when the reconnecting
fields are strong Solid curves indi Figure 3. Schematic of a flare loop system formed by reconnection in the supermagnetosonic
regime. This regime is most likely to occur in the early phase of a flare when the reconnecting
fields are strong. Solid curves ind fields are strong. Solid curves indicate boundaries between various plasma regions, while dashed ones indicate magnetic-field lines.

evaporation on field lines mapping to slow-mode shocks in the vicinity of the neutral evaporation on field lines mapping to slow-mode shocks in the vicinity of the neutral
line (Forbes & Malherbe 1986). These slow shocks are similar to those proposed orig-
inally by Petschek (1964), except that the conducti evaporation on field lines mapping to slow-mode shocks in the vicinity of the neutral
line (Forbes & Malherbe 1986). These slow shocks are similar to those proposed orig-
inally by Petschek (1964), except that the conducti line (Forbes & Malherbe 1986). These slow shocks are similar to those proposed originally by Petschek (1964), except that the conduction of heat along the field lines causes them to dissociate into isothermal shocks and c in ally by Petschek (1964), except that the conduction of heat along the field lines causes them to dissociate into isothermal shocks and conduction fronts, as shown in figure 3. The shocks annihilate the magnetic field in causes them to dissociate into isothermal shocks and conduction fronts, as shown
in figure 3. The shocks annihilate the magnetic field in the plasma flowing through
them, and the thermal energy which is thus liberated is c in figure 3. The shocks annihilate the magnetic field in the plasma flowing through
them, and the thermal energy which is thus liberated is conducted along the field to
the chromosphere. This in turn drives an upward flow the chromosphere. This in turn drives an upward flow of dense heated plasma back
towards the shocks and compresses the lower regions of the chromosphere downward.

In order for strong slow shocks to form on the field lines below the neutral line, towards the shocks and compresses the lower regions of the chromosphere downward.
In order for strong slow shocks to form on the field lines below the neutral line,
the outflow from it must be supermagnetosonic with respec In order for strong slow shocks to form on the field lines below the neutral line,
the outflow from it must be supermagnetosonic with respect to the fast-mode wave
speed. If the magnetic fields are sufficiently strong, the speed. If the magnetic fields are sufficiently strong, the outflow from the neutral line produces two supermagnetosonic jets, one directed upward and the other downward. Because of the obstacle presented by the closed field lines attached to the photosphere, the lower jet terminates at a fast-mode shock a ward. Because of the obstacle presented by the closed field lines attached to the ward. Because of the obstacle presented by the closed field lines attached to the photosphere, the lower jet terminates at a fast-mode shock after travelling a short distance (Forbes 1986). Below the termination shock the photosphere, the lower jet terminates at a fast-mode shock after travelling a short
distance (Forbes 1986). Below the termination shock the flow is deflected along the
field, and only weak field-aligned slow-mode shocks ar field, and only weak field-aligned slow-mode shocks are present. Consequently, the magnetic energy released below the termination shock is relatively small. ld, and only weak field-aligned slow-mode shocks are present. Consequently, the agnetic energy released below the termination shock is relatively small.
When the magnetic field is relatively strong, the fast-mode Mach numb

magnetic energy released below the termination shock is relatively small.
When the magnetic field is relatively strong, the fast-mode Mach number of the
jets is about two, but, as the field decreases, the Mach number decre When the magnetic field is relatively strong, the fast-mode Mach number of the
jets is about two, but, as the field decreases, the Mach number decreases and the
jets eventually become submagnetosonic (Forbes 1986). The tr jets is about two, but, as the field decreases, the Mach number decreases and the jets eventually become submagnetosonic (Forbes 1986). The transition occurs when the plasma β in the X-ray loops exceeds approximately the plasma β in the X-ray loops exceeds approximately $(3 - \gamma)/\gamma$, where γ is the *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 4. Optical and X-ray light curves for a flare on the red dwarf UV Ceti (23 December 1995). The optical curve is for emissions in the V-band (after de Jager *et al*. 1989).

1995). The optical curve is for emissions in the V-band (after de Jager *et al.* 1989).
ratio of specific heats. For $\gamma = \frac{5}{3}$ this gives $\beta = \frac{4}{5}$, which for typical loop parameters
corresponds to a field strength ratio of specific heats. For $\gamma = \frac{5}{3}$ this gives $\beta = \frac{4}{5}$, which for typical loop corresponds to a field strength of a few gauss (Soward & Priest 1982). % corresponds to a field strength of a few gauss (Soward & Priest 1982).
 $\,$ 5. Stellar flares

The analysis of stellar flares relies heavily upon the assumption that they are basically The analysis of stellar flares relies heavily upon the assumption that they are basically
similar to solar flares except that they are more energetic (see, for example, Gershberg
1983: Poletto *et al.* 1988). Flare stars The analysis of stellar flares relies heavily upon the assumption the
similar to solar flares except that they are more energetic (see, for ϵ
1983; Poletto *et al.* 1988). Flare stars can release 10^4 to 10^6 tip
e hat they are basically
r example, Gershberg
times the amount of
increases in magnetic similar to solar flares except that they are more energetic (see, for example, Gershberg 1983; Poletto *et al.* 1988). Flare stars can release 10^4 to 10^6 times the amount of energy released by a large solar flare, b 1983; Poletto *et al.* 1988). Flare stars can release 10^4 to 10^6 tirenergy released by a large solar flare, but it requires only modest in field strengths and scale sizes to account for this extra amount.
Many diffe energy released by a large solar flare, but it requires only modest increases in magnetic
field strengths and scale sizes to account for this extra amount.
Many different types of stars produce flares (see Pettersen (1989)

field strengths and scale sizes to account for this extra amount.
Many different types of stars produce flares (see Pettersen (1989) for a review),
but the classical flare stars are red dwarfs. These stars constitute *ca* Many different types of stars produce flares (see Pettersen (1989) for a review),
but the classical flare stars are red dwarfs. These stars constitute $ca. 65\%$ of the total
number of stars in our galaxy, and of these $ca.$ but the classical flare stars are red dwarfs. These stars constitute $ca.65\%$ of the total
number of stars in our galaxy, and of these $ca.75\%$ are flare stars (Rodonò 1986),
including our nearest stellar neighbour, Proxi number of stars in our galaxy, and of these $ca.75\%$ are flare stars (Rodonò 1986),
including our nearest stellar neighbour, Proxima Centauri. These flare stars are also
known as UV Ceti stars (the classic prototype) and including our nearest stellar neighbour, Proxima Centauri. These flare stars are also
known as UV Ceti stars (the classic prototype) and dMe or dKe stars. As their
name implies, red dwarfs are small stars, having masses o known as UV Ceti stars (the classic prototype) and dMe or dKe stars. As their
hame implies, red dwarfs are small stars, having masses of $0.08{\text -}0.8M_{\odot}$ and radii of
 $0.15{\text -}0.85R_{\odot}$, which means they are intrinsi name implies, red dwarfs are small stars, having masses of $0.08-0.8M_{\odot}$ and radii of

noticeable in the blue continuum, where the contrast with the star's red photospheric The optical radiation produced by a dMe red dwarf during a flare is especially
noticeable in the blue continuum, where the contrast with the star's red photospheric
light is greatest. There are also Balmer-line enhancement noticeable in the blue continuum, where the contrast with the star's red photospheric
light is greatest. There are also Balmer-line enhancements which precede the rise in
the blue continuum, but once the continuum appears light is greatest. There are also Balmer-line enhancements which precede the rise in
the blue continuum, but once the continuum appears it dominates the emission lines
(Haisch 1989). The emission lines remain enhanced afte the blue continuum, but once the continuum appears it dominates the emission lines (Haisch 1989). The emission lines remain enhanced after the continuum fades. As figure 4 shows, the time profile of the continuum is very i (Haisch 1989). The emission lines remain enhanced after the continuum fades. As
figure 4 shows, the time profile of the continuum is very impulsive, which suggests
that the continuum radiation is the stellar counterpart of figure 4 shows, the time profile of the continuum is very impulsive, which suggests that the continuum radiation is the stellar counterpart of white-light emission in solar flares. Although solar flares rarely emit any whi that the continuum radiation is the stellar counterpart of white-light emission in solar

(Neidig 1989). Similarly, the blue continuum in dMe flares is also associated with the
impulsive phase and originates at the star's surface (Van den Oord *et al.* 1996). (Neidig 1989). Similarly, the blue continuum in dMe flares is also associated with the impulsive phase and originates at the star's surface (Van den Oord *et al.* 1996).
Since the mid 1970s, soft X-rays have been detected **MATHEMATICAL,
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Since the mid 1970s, soft X-rays have been detected in numerous flar

1996). Since the mid 1970s, soft X-rays have been detected in numerous flare stars (Haisch 1996). These X-ray emissions occur in the star's corona after the impulsive burst of the optical radiation and are cotemporal with Since the mid 1970s, soft X-rays have been detected in numerous flare stars (Haisch 1996). These X-ray emissions occur in the star's corona after the impulsive burst of the optical radiation and are cotemporal with long-l

the optical radiation and are cotemporal wit
The X-rays are thermal in origin and often ex-
X-rays in solar flares, as shown in figure 4.
Red dwarfs that produce flares are typical ne X-rays are thermal in origin and often exhibit the same temporal profile as soft
rays in solar flares, as shown in figure 4.
Red dwarfs that produce flares are typically fast rotators with deep convection
nes. Periods a

X-rays in solar flares, as shown in figure 4.
Red dwarfs that produce flares are typically fast rotators with deep convection
zones. Periods as short as 10 h (compared with 26 days for the Sun) are not unusual,
and stars Red dwarfs that produce flares are typically fast rotators with deep convection
zones. Periods as short as 10 h (compared with 26 days for the Sun) are not unusual,
and stars of less than $0.2M_{\odot}$ are thought to be con zones. Periods as short as 10 h (compared with 26 days for the Sun) are not unusual,
and stars of less than $0.2M_{\odot}$ are thought to be convective throughout (Haisch $\&$ Schmitt 1996). The fast rotation, combined with and stars of less than $0.2M_{\odot}$ are thought to be convective throughout (Haisch & Schmitt 1996). The fast rotation, combined with the deep convection zone, greatly enhances dynamo activity in these stars, although the Schmitt 1996). The fast rotation, combined with the deep
enhances dynamo activity in these stars, although the nation
eration in fully convective stars is still an open question.
Flares also occur in early pre-main-sequenc enhances dynamo activity in these stars, although the nature of magnetic-field generation in fully convective stars is still an open question.
Flares also occur in early pre-main-sequence stars known as T-Tauri stars. Thes

eration in fully convective stars is still an open question.
Flares also occur in early pre-main-sequence stars known as T-Tauri stars. These
stars have solar-like masses but are only 10^5 to 10^7 years old. Many are Flares also occur in early pre-main-sequence stars known as T-Tauri stars. These
stars have solar-like masses but are only 10^5 to 10^7 years old. Many are also rapid
rotators (Montmerle & Casanova 1996), but the feat stars have solar-like masses but are only 10^5 to 10^7 years old. Many are also rapid
rotators (Montmerle & Casanova 1996), but the features which make T-Tauri stars
especially intriguing are their accretion discs and rotators (Montmerle & Casanova 1996), but the features which make T -Tauri stars especially intriguing are their accretion discs and outflow jets. The jets emanate from the star's polar regions and are fed by the mass in $\overline{0}$ 1994).

Close binaries form another important class of flare star. They include the RS 1994).
Close binaries form another important class of flare star. They include the RS
Canum Venaticorum (RS CVn) systems, Algol-type binaries and W Ursa Majoris
(W Uma) systems, all of which have components that are separa Close binaries form another important class of flare star. They include the RS
Canum Venaticorum (RS CVn) systems, Algol-type binaries and W Ursa Majoris
(W Uma) systems, all of which have components that are separated by Canum Venaticorum (RS CVn) systems, Algol-type binaries and W Ursa Majoris (W Uma) systems, all of which have components that are separated by no more than a few stellar radii. The orbital period of these systems ranges fr (W Uma) systems, all of which have components that are separated by no more than
a few stellar radii. The orbital period of these systems ranges from 0.5 to 50 days
(Catalano 1996), and, because the components are tidally a few stellar radii. The orbital period of these systems ranges from 0.5 to 50 days (Catalano 1996), and, because the components are tidally locked, the rotation periods of both stars are the same as the orbital period. Th (Catalano 1996), and, because the components are tidally locked, the rotation periods of both stars are the same as the orbital period. Thus, as in the case of the dMe stars, close binaries are rapid rotators with strong of both stars are the same as the orbital period. Thus, as in the case of the dMe stars, close binaries are rapid rotators with strong magnetic dynamos. RS CVn systems consist typically of K and G subgiants located on the consist typically of K and G subgiants located on the main sequence, while the Algolconsist typically of K and G subgiants located on the main sequence, while the Algoltype binaries consists of a primary star of A or B type with an evolved K subgiant secondary that has overflowed its Roche lobe and is in type binaries consists of a primary star of A or B type with an evolved K subgiant
secondary that has overflowed its Roche lobe and is in the process of transferring
mass to the primary. The W Uma systems are very short-pe secondary that has overflowed its Roche lobe and is in the promass to the primary. The W Uma systems are very short-period contact binaries where both components fill their Roche lobes.
Table 1 compares observed quantities mass to the primary. The W Uma systems are very short-period (less than one day) contact binaries where both components fill their Roche lobes.
Table 1 compares observed quantities for coronal emission (primarily X-rays) f

contact binaries where both components fill their Roche lobes.
Table 1 compares observed quantities for coronal emission (primarily X-rays) from
solar and stellar flares. Two separate solar classes are listed, one for comp Table 1 compares observed quantities for coronal emission (primarily X-rays) from
solar and stellar flares. Two separate solar classes are listed, one for compact flares
and one for large flares of long duration. The latte and one for large flares of long duration. The latter are often referred to as long-
duration events, and they are the large-scale two-ribbon flares which produce CMEs. and one for large flares of long duration. The latter are often referred to as long-
duration events, and they are the large-scale two-ribbon flares which produce CMEs.
In table 1, Lu is the peak luminosity, W_r is the t duration events, and they are the large-scale two-ribbon flares which produce CMEs.
In table 1, Lu is the peak luminosity, W_r is the total radiative energy from the flare, integrated over its lifetime, τ_{rise} and In table 1, Lu is the peak luminosity, W_r is the total radiative energy from the flare, integrated over its lifetime, τ_{rise} and τ_{decay} are the rise and decay times of the luminosity curve, T_{max} is the max flare, integrated over its lifetime, τ_{rise} and τ_{decay} are the rise and decay times of the luminosity curve, T_{max} is the maximum temperature, E_{m} is the volumetric emission measure, R_* is the stellar luminosity curve, T_{max} is the maximum temperature, E_{m} is the volumetric emission
measure, R_* is the stellar radius, h is the height of the flare loops (for solar flares
only) and n_d is the plasma density d measure, R_* is the stellar radius, h is the height of the flare loops (for solar flares
only) and n_d is the plasma density deduced from the ratio of density diagnostic lines.
(The value of n_d for dMe stars is highly Iy) and n_d is the plasma density deduced from the ratio of density diagnostic lines.
The value of n_d for dMe stars is highly uncertain, but is given for completeness.)
The flare luminosity (Lu) is directly proportion

(The value of n_d for dMe stars is highly uncertain, but is given for completeness.)
The flare luminosity (Lu) is directly proportional to E_m times a function which
depends only on the temperature (T). Thus, if two fl The flare luminosity (Lu) is directly proportional to E_m times a function w
depends only on the temperature (T) . Thus, if two flares have the same temperat
but different luminosities, the difference is due to the emis depends only on the temperature (T) . Thus, if two flares have the same temperature,
but different luminosities, the difference is due to the emission measure (E_m) .
For the most part, the stellar flares in table 1 are co

For the most part, the stellar flares in table 1 are considerably more energetic For the most part, the stellar flares in table 1 are considerably more energetic
than their solar counterparts, although there is an overlap between the smallest dMe
flares and the largest solar flares. The flares occurrin than their solar counterparts, although there is an overlap between the smallest dMe
flares and the largest solar flares. The flares occurring in T-Tauri stars and RS CVn
binaries are the largest, with radiative energy out *Phil. Trans. R. Soc. Lond.* A (2000)

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 $\label{eq:3} Solar \ and \ stellar \ flares$
 Table 1. *Observed quantities for stellar and solar flares in MKS units*

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(The densities (n_d) are based on density-sensitive line-ratios. The RS CVn values are from Byrne
(1995), while the dMe value is from Schrijver *et* (1995), while the dMe value is from Schrijver *et al.* (1995). Solar flare values are from Cook *et* al. (1995). Dashes indicate no available data. $1 \text{ J} = 10^7 \text{ erg.}$)

Figure 5. Schematic for AB Doradus showing the relationship between the drift rate of a prominence and its distance from the surface (from Cameron 1996).

prominence and its distance from the surface (from Cameron 1996).
magnitude greater than the largest solar flares. Since the densities and temperatures
of the stellar flares are comparable to solar flares, the larger energ magnitude greater than the largest solar flares. Since the densities and temperatures
of the stellar flares are comparable to solar flares, the larger energy output of the
stellar flares must be due to the involvement of l magnitude greater than the largest solar flares. Since the densities
of the stellar flares are comparable to solar flares, the larger en-
stellar flares must be due to the involvement of larger volumes.
Recent studies have of the stellar flares are comparable to solar flares, the larger energy output of the stellar flares must be due to the involvement of larger volumes.
Recent studies have also revealed the existence of unusually large prom

some rapidly rotating flare stars (Cameron 1996; Byrne *et al.* 1996). Figure 5 shows the geometry of these prominences inferred from $H\alpha$ observations of the K-dwarf

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 $T. G.$ Forbes
AB Doradus. The prominences lie between three and nine stellar radii from the AB Doradus. The prominences lie between three and nine stellar radii from the rotation axis, beyond the star's corotation radius at 2.6 stellar radii. Tension in the magnetic loops connecting from the prominences to the st AB Doradus. The prominences lie between three and nine stellar radii from the rotation axis, beyond the star's corotation radius at 2.6 stellar radii. Tension in the magnetic loops connecting from the prominences to the st rotation axis, beyond the star's corotation radius at 2.6 stellar radii. Tension in the
magnetic loops connecting from the prominences to the stellar surface counterbal-
ances the centrifugal pull of the star's rotation an magnetic loops connecting from the prominences to the stellar surface counterbal-
ances the centrifugal pull of the star's rotation and prevents the prominences from
escaping. In contrast to the Sun, the magnetic field hel ances the centrifugal pull of the star's rotation and prevents the prominences from escaping. In contrast to the Sun, the magnetic field helps to hold the prominences down against the rotation rather than holding them up a nences last for several stellar rotations and the amount of mass contained in them down against the rotation rather than holding them up against gravity. The prominences last for several stellar rotations and the amount of mass contained in them approaches 10^{15} kg—a hundred times greater than the ma nences last for several stellar rotations and the amount of mass contained in them
approaches 10^{15} kg—a hundred times greater than the mass in a solar prominence.
Jeffries (1993) has noted that the stress exerted by t Jeffries (1993) has noted that the stress exerted by the rotating prominences on the field may be the predominant mechanism for storing magnetic energy in the star's Jeffries (1993) has noted that the stress exerted by the rotating prominences on the field may be the predominant mechanism for storing magnetic energy in the star's corona. If so, the mechanism for triggering flares on AB field may be the predominant mechanism for storing magnetic energy in the star's
corona. If so, the mechanism for triggering flares on AB Doradus may be closely
related to the mechanism which generates auroral substorms in corona. If so, the mechanism for triggering flares on AB Doradus may be closely
related to the mechanism which generates auroral substorms in Jupiter's magne-
tosphere. Like AB Doradus, the Jovian magnetosphere is dominate related to the mechanism which generates auroral substorms in Jupiter's magne-
tosphere. Like AB Doradus, the Jovian magnetosphere is dominated by a rapidly
rotating field, and it is the rotational stressing of this field tosphere. Like AB Doradus, the Jovian magnetosphere is dominar
potating field, and it is the rotational stressing of this field which is
ply the magnetic energy for auroral substorms (Zimbardo 1993). ply the magnetic energy for auroral substorms (Zimbardo 1993).
 \bullet . Conclusions

6. Conclusions
There is a general consensus among researchers that both solar and stellar flares
are caused by the sudden release of magnetic energy stored in a star's atmosphere There is a general consensus among researchers that both solar and stellar flares
are caused by the sudden release of magnetic energy stored in a star's atmosphere.
However, the specific mechanisms which cause energy to be There is a general consensus among researchers that both solar and stellar flares
are caused by the sudden release of magnetic energy stored in a star's atmosphere.
However, the specific mechanisms which cause energy to be are caused by the sudden release of magnetic energy stored in a star's atmosphere.
However, the specific mechanisms which cause energy to be stored and then released
may be very different. Even for solar flares alone, it i However, the specific mechanisms which cause energy to be stored and then released
may be very different. Even for solar flares alone, it is not yet clear whether there is
just one mechanism involved or several. It is also may be very different. Even for solar flares alone, it is not yet clear whether there is
just one mechanism involved or several. It is also quite likely that physical processes
such as magnetic reconnection and chromospher just one mechanism involved or several. It is also quite likely that physical processes such as magnetic reconnection and chromospheric evaporation occur in both solar and stellar flares, but again, the way in which they o such as magnetic reconnection and chromospheric evaporation occur in both solar

two categories, namely ideal and non-ideal. In the ideal category are those processes, The various mechanisms which have been proposed for flares can be divided into
two categories, namely ideal and non-ideal. In the ideal category are those processes,
like the MHD kink instability or loss of MHD equilibrium two categories, namely ideal and non-ideal. In the ideal category are those processes,
like the MHD kink instability or loss of MHD equilibrium, which do not involve
dissipation or diffusion of the magnetic field. In the n like the MHD kink instability or loss of MHD equilibrium, which do not involve
dissipation or diffusion of the magnetic field. In the non-ideal category are those
processes which do. The advantage of ideal processes is tha dissipation or diffusion of the magnetic field. In the non-ideal category are those
processes which do. The advantage of ideal processes is that they occur on a time-
scale which is fast enough to account for the rate of e processes which do. The advantage of ideal processes is that they occur on a time-
scale which is fast enough to account for the rate of energy release at the onset of a
flare. However, they must at some stage lead to nonscale which is fast enough to account for the rate of energy release at the onset of a
flare. However, they must at some stage lead to non-ideal processes in order for the
plasma to be heated. This heating can be accomplis flare. However, they must at some stage lead to non-ideal processes in order for the plasma to be heated. This heating can be accomplished by the formation of shocks and current sheets produced by the large-scale motions t In the near future, new observations of solar flares are likely to reveal much about the near future, new observations of solar flares are likely to reveal much about we magnetic reconnection operates in the solar corona.

and current sheets produced by the large-scale motions triggered by the ideal process.
In the near future, new observations of solar flares are likely to reveal much about
how magnetic reconnection operates in the solar co In the near future, new observations of solar flares are likely to reveal much about
how magnetic reconnection operates in the solar corona. Although the Japanese satel-
lite Yohkoh has detected X-ray emissions from the si how magnetic reconnection operates in the solar corona. Although the Japanese satellite Yohkoh has detected X-ray emissions from the site of reconnection in the corona, it remains for future satellite missions to determine lite Yohkoh has detected X-ray emissions from the site of reconnection in the corona, it remains for future satellite missions to determine if the reconnection process works as any of the existing theories predict.

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Discussion

Discussion
R. ROSNER (*The University of Chicago, USA*). In your model of long-enduring
events, which is two dimensional, all the energy release is due to reconnection. When Events, ROSNER (*The University of Chicago, USA*). In your model of long-enduring
events, which is two dimensional, all the energy release is due to reconnection. When
you discussed the realistic case, you appealed to thre R. ROSNER (*The University of Chicago, USA*). In your model of long-enduring
events, which is two dimensional, all the energy release is due to reconnection. When
you discussed the realistic case, you appealed to three dim events, which is two dimensional, all the energy release is due to reconnection. When
you discussed the realistic case, you appealed to three dimensions, and to an ideal
MHD instability which drove reconnection (and fixed you discussed the realistic case, you appealed to three dimensions, and to an ideal MHD instability which drove reconnection (and fixed the short time-scale). In this latter case, which process dominates the release of fre latter case, which process dominates the release of free energy: the ideal instability or reconnection?

reflections and the two-dimensional model is
T. G. FORBES. Actually, the driving mechanism in the two-dimensional model is
an ideal-MHD loss of equilibrium and not reconnection, and in this two-dimensional T. G. FORBES. Actually, the driving mechanism in the two-dimensional model is
an ideal-MHD loss of equilibrium and not reconnection, and in this two-dimensional
model only ca 5% of the stored magnetic energy is released T. G. FORBES. Actually, the driving mechanism in the two-dimensional model is
an ideal-MHD loss of equilibrium and not reconnection, and in this two-dimensional
model only *ca*. 5% of the stored magnetic energy is released an ideal-MHD loss of equilibrium and not reconnection, and in this two-dimensional model only $ca.5\%$ of the stored magnetic energy is released by the ideal process, while 95% is released by the reconnection process wh model only $ca.5\%$ of the stored magnetic energy is released by the ideal process, while 95% is released by the reconnection process which follows it. Although there is no quantitative three-dimensional model as of yet while 95% is released
is no quantitative thre
values to be similar.

is no quantitative three-dimensional model as of yet, I would expect the percentage
values to be similar.
Y. UCHIDA (*University of Tokyo, Japan*). We have found that there exist connections
from the top of the candle flam Y. UCHIDA (*University of Tokyo, Japan*). We have found that there exist connections
from the top of the candle flame type arcade back to the photosphere on both sides.
These, together with some other features, cannot be e If from the top of the candle flame type arcade back to the photosphere on both sides.
These, together with some other features, cannot be explained by a 'bipolar' model
of flares. Together with the energy problem you ment These, together with some other features, cannot be explained by a 'bipolar' model These, together with some other features, cannot be explained by a 'bipolar' model
of flares. Together with the energy problem you mentioned as the Aly–Sturrock
paradox, we are proposing a 'quadrupole source model', in whi of flares. Together with the energy problem you mentioned as the Aly–Stu
paradox, we are proposing a 'quadrupole source model', in which the neutral
pre-exists in the pre-event configuration, and can avoid the energy diffi pre-exists in the pre-event configuration, and can avoid the energy difficulty.
T. G. FORBES. It should not be assumed because I showed a model for a dipole

pre-exists in the pre-event comiguration, and can avoid the energy difficulty.
T. G. FORBES. It should not be assumed because I showed a model for a dipole
configuration that the basic idea of the model will not work if th T. G. FORBES. It should not be assumed because I showed a model for a dipole configuration that the basic idea of the model will not work if the configuration is other than dipolar. In fact, Eric Priest and I have shown th configuration that the basic idea of the model will not work if the configuration is
other than dipolar. In fact, Eric Priest and I have shown that the model actually
works better (in the sense that it releases more energy other than dipolar. In fact, Eric Priest and I have shown that the model actually works better (in the sense that it releases more energy) if the dipole is replaced by a quadrupole. It is only because the dipole is simpler works ł
quadru_l
on it.

quadrupole. It is only because the dipole is simpler to discuss that I have concentrated
on it.
R. E. PUDRITZ (*McCaster University, Canada*). T-Tauri stars are known to exhibit
strong flare-like X-ray activity whose origi Str. E. PUDRITZ (*McCaster University, Canada*). T-Tauri stars are known to exhibit
strong, flare-like X-ray activity whose origin is still unclear. Have you any thoughts
on the applicability of solar flare models to T-Tau R. E. PUDRITZ (*McCaster University, Canada*). T-Tauri starstrong, flare-like X-ray activity whose origin is still unclear. I
on the applicability of solar flare models to T-Tauri stars? *Phil. Trans. R. Soc. Lond.* A (2000)

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Solar and stellar flares 727
T. G. FORBES. The T-Tauri systems are so complex that I hesitate even to speculate
about the nature of flows in these systems. However, it does seem safe to argue that T. G. FORBES. The T-Tauri systems are so complex that I hesitate even to speculate about the nature of flows in these systems. However, it does seem safe to argue that the volumes involved are probably larger by several or T. G. FORBES. The T-Tauri systems are so complex that I hesitate even to speculate
about the nature of flows in these systems. However, it does seem safe to argue that
the volumes involved are probably larger by several or about the nature of flows in these systems. However, it does seem safe to argue that
the volumes involved are probably larger by several orders of magnitude than those
for the Sun or red dwarfs. This could be a sign that m for the Sun or red dwarfs. This could be a sign that magnetic interactions between the star and its accretion disc are occurring.

L. Harra (*Mullard Space Science Laboratory, University College London, UK*). I. HARRA (*Mullard Space Science Laboratory*, *University College London*, *UK*).
You mentioned the cusp-shaped structures in solar flares as an indication of recon-
nection/eruptive behaviour. In many cases, the cusp stru L. HARRA (*Mullard Space Science Laboratory, University College London, UK*).
You mentioned the cusp-shaped structures in solar flares as an indication of recon-
nection/eruptive behaviour. In many cases, the cusp structur You mentioned the cusp-shaped structures in solar flares as an indication of r nection/eruptive behaviour. In many cases, the cusp structure connects to a active region/bright point. Does this change the interpretation in

nection/eruptive benaviour. In many cases, the cusp structure connects to a small
active region/bright point. Does this change the interpretation in any way?
T. G. FORBES. I don't think the basic interpretation that reconn T. G. FORBES. I don't think the basic interpretation that reconnection occurs will
change, but the details of what the flow and thermal structures look like should
change. It is also good to keep in mind that the models ar change, but the details of what the flow and thermal structures look like should change. It is also good to keep in mind that the models are two dimensional and highly symmetric in order to simplify the mathematics and not because we think
this is the way flares are on the Sun. Perhaps when you see field lines radiating out
of the top of a cusp curving back down toward the surface highly symmetric in order to simplify the mathematics and not because we think
this is the way flares are on the Sun. Perhaps when you see field lines radiating out
of the top of a cusp curving back down toward the surface this is the way flares are on the Sun. Perhaps when you see field
of the top of a cusp curving back down toward the surface, only
long open arcade actually does this and not the whole arcade.

of the top of a cusp curving back down toward the surface, only a small region of a
long open arcade actually does this and not the whole arcade.
N. O. WEISS (*University of St Andrews, UK*). Thank you very much. I think t N. O. WEISS (*University of St Andrews, UK*). Thank you very much. I think that's
a word of warning: we should bear in mind that on the one hand there are remark-
able similarities between the Sun and the range of middle-N. O. WEISS (*University of St Andrews, UK*). Thank you very much. I think that's a word of warning: we should bear in mind that on the one hand there are remarkable similarities between the Sun and the range of middle-age a word of warning: we should bear in mind that on the one hand there are remarkable similarities between the Sun and the range of middle-aged stars like it (with extensions to much more active stars and to binary stars), b able similarities between the Sun and the rare
extensions to much more active stars and to be there might also be fundamental differences.

extensions to much more active stars and to binary stars), but, on the other hand,
there might also be fundamental differences.
E. R. PRIEST (*University of St Andrews, UK*). I would like to thank all our speakers
today fo E. R. PRIEST (*University of St Andrews, UK*). I would like to thank all our speakers today for demonstrating in no uncertain terms just how vibrant solar research is at the present time how many fundamental discoveries a E. R. PRIEST (*University of St Andrews, UK*). I would like to thank all our speakers today for demonstrating in no uncertain terms just how vibrant solar research is at the present time, how many fundamental discoveries today for demonstrating in no uncertain terms just how vibrant solar research is
at the present time, how many fundamental discoveries are being made and how
significant they are for other stars and indeed for astrophysics