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A Test to Confirm the Source of Energy for Solar Flares

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Abstract: A test of the hypothesis that flares derive their energy from large scale current systems inferred from active region vector magnetograms is proposed. The test involves a statistical comparison of the flare-related change in coronal magnetic energy (based on the magnetohydrodynamic virial theorem) and an independent measure of the energy of the flare. A simulation suggests that — assuming the hypothesis is correct — the test requires around 50 flares with energy greater than 5×10^{23} J to return a significant result. Existing archives of vector magnetograms should provide sufficient data for such a study.

Keyword: Sun: flares

1 Introduction

Solar flares are powerful explosions in the corona (the Sun's outer atmosphere) that produce intense heating, bulk motions, and accelerate particles. Large flares can involve the release of as much as 10^{26}–10^{27} J of energy (Kane et al. 1995), and associated coronal mass ejections may have even larger energy budgets.

It is generally believed that solar flares derive their energy from coronal magnetic fields in and around active regions (regions surrounding sunspots). In particular flare energy is attributed to that part of the magnetic field associated with electric currents flowing in the corona. In spite of the magnitude of energy release involved, the observational evidence in favour of the hypothesis that electric currents in active regions are the source of energy for flaring remains circumstantial at best. For example Sammis, Tang, & Zirin (2000) recently confirmed that almost all very large flares occur in active regions with the magnetic classification $\beta\gamma\delta$, which denotes bipolar spots with mixed polarities, including a penumbra enclosing umbrae of both polarities. Such complex magnetic configurations presumably indicate currents in the field structure.

The presence of currents in active regions may be inferred from vector magnetograph measurements. Vector magnetographs measure the polarisation state of light in a narrow range of frequencies in a photospheric spectral line, which is affected by the magnetic field in the solar atmosphere according to the Zeeman effect. Based on modelling of radiative transport in the magnetised solar atmosphere, these measurements may be converted into maps of the magnetic field along and transverse to the line of sight (vector magnetograms). The transverse field is obtained only up to a 180 degree ambiguity in its direction. Provided this ambiguity is resolved by some means (e.g. Metcalf 1995), the three components of the magnetic field parallel and perpendicular to the photosphere, B_x, B_y, and B_z (here z is assumed to be the direction of the upward normal from the photosphere) may be obtained. Finite differencing of the components of the field parallel to the photosphere (B_x and B_y) gives, via Ampere's law, the normal component of the electric current density, J_z. Figure 1 illustrates the results of this procedure applied to a vector magnetogram of AR 5747 observed on 21 October 1989 (Wheatland 2000a). The greyscale image is the normal component of the magnetic field, with light shading indicating $B_z > 0$ and dark shading $B_z < 0$. The thin dark line is the neutral line, indicating the boundary between regions with $B_z > 0$ and $B_z < 0$. Regions with a normal component of current density above the 3σ level are shown as white contours (solid contours indicate $J_z > 0$, and dashed contours indicate $J_z < 0$). A large, X-class flare occurred in AR 5747 on the following day, close to the central current systems shown in the figure (Leka et al. 1993).

Analyses of the type illustrated by Figure 1 establish that flares occur near to large-scale current systems in active regions, as originally pointed out by Moreton & Severny in 1968. Melrose (1991; 1995; 1997) has stressed the importance of studies of current systems inferred from vector magnetogram studies for the understanding of the flare phenomenon. However, the association of observed current systems with flaring, and even the reality of the observed currents, is not universally accepted (e.g. Parker 1996). In response to recent criticisms, Semel & Skumanich (1998) pointed out that the observed currents are not an artifact of the method of resolving the 180 degree ambiguity. A growing body of independent evidence confirms the reality of the current systems. For example, currents observed at the footpoints of soft X-ray coronal loops agree with the observed twistedness of the loops (Pevstov, Canfield, & McClymont 1997), and the locations of currents are consistent with the sites of coronal currents inferred from microwave measurements (Lee et al. 1997).

The proximity of magnetogram currents and flaring provides circumstantial evidence in favour of the hypothesis that the observed currents power solar flares. It is more difficult to obtain direct evidence to this effect. Many authors have looked for changes in vector magnetic field measurements taken before and after flares,

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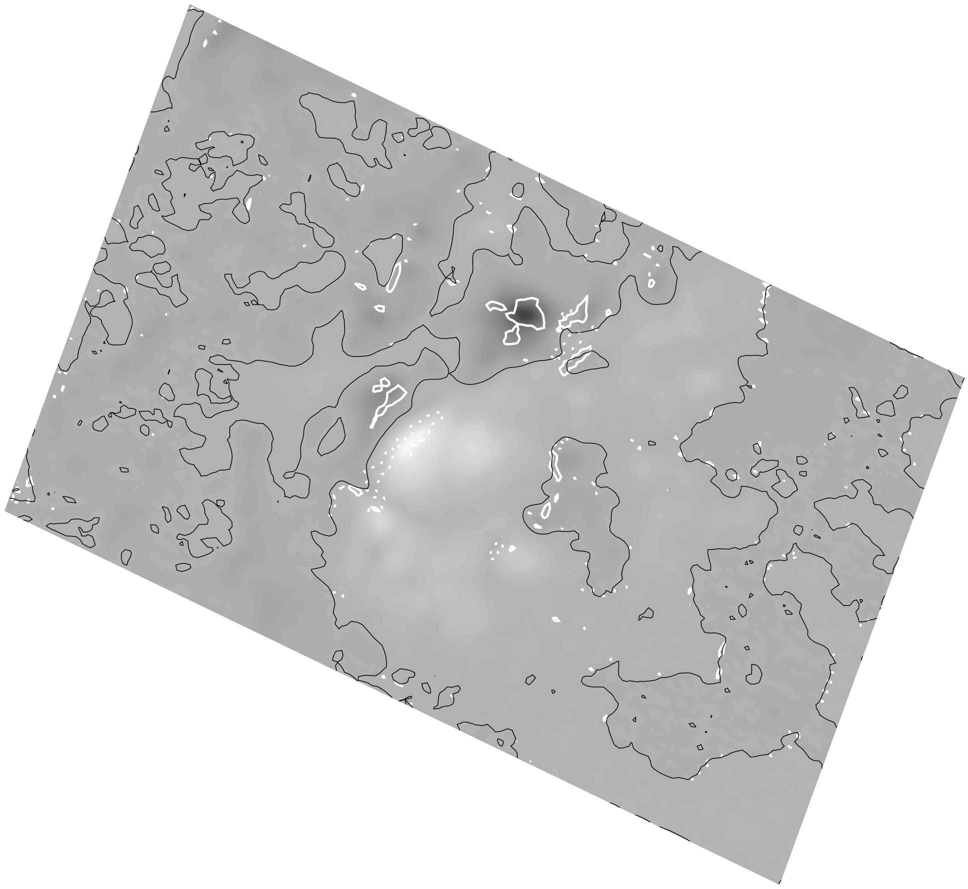

Figure 1 Vector magnetogram for AR 5747, observed on 21 October 1991. (See text for details.)

and have reported varying results (Švestka 1976). More recent investigations have shown, for example, an apparent decrease in currents (Sakurai et al. 1992), localised changes in the direction of magnetic field along the neutral line (Wang et al. 1994), a decrease in the small-scale structure of J_z (Abramenko, Yurchishin, & Carbone 1998), and localised changes in polarisation for flares observed near the limb (Cameron & Sammis 1999). Ideally, it should be demonstrated that the magnetic energy present in the corona decreases when a flare occurs.

The magnetohydrodynamic (MHD) virial theorem allows the estimation of the total magnetic energy in the corona, $E_{\rm vir}$, based on photospheric field measurements (e.g. Low 1982):

$$E_{\rm vir} = \frac{1}{\mu_0} \int_{z=0} (xB_x + yB_y) B_z \, dx dy. \qquad (1)$$

Equation (1) assumes that the magnetic field is force-free above the level of the measurements (i.e. that the current density is parallel to the magnetic field), that the active region is sufficiently small that a plane parallel approximation may be adopted, with the photosphere at the height $z = 0$, and that the magnetic field decays sufficiently rapidly with distance (faster than $r^{-3/2}$, where r is the distance from the region of interest). The assumptions about the extent of the magnetic field and its decay with distance are likely to be satisfied for most active regions, excepting those with appreciable magnetic connectivity to neighbouring regions, and those involving large-scale helmet streamers extending into the solar wind. The assumption that the field is everywhere force-free is more problematic, because there are significant non-magnetic forces at the photospheric level in active regions (Metcalf et al. 1995). A second difficulty in the application of equation (1) is the large errors in vector magnetic field measurements, which translate to large uncertainties in estimates of $E_{\rm vir}$. Klimchuk, Canfield, & Rhoads (1992) estimate that under favourable conditions, virial energy estimates based on vector magnetograms should be accurate to about 30%. Granted these uncertainties, and assuming that magnetic flares do in fact derive their energy from magnetic fields in active regions, the virial energy provides an upper limit on the free energy available for flaring.

In this paper a test of the hypothesis that flares derive their energy from the observed large scale current systems in active regions is proposed, based on equation (1). The basic idea is that although errors in individual measurements may be too large to reveal a flare-related change in virial energy estimates, the change should become apparent for a statistical sample of flares. This idea does not appear to have been suggested previously in the literature.

The structure of the paper is as follows. In Section 2 the methodology of the proposed test is presented. A simulation incorporating the expected errors in virial

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energy estimates is used to determine the number of flares required for the study. Observed rates of flaring are used to demonstrate that sufficient observations should be available in existing archives. In Section 3 the prospects for performing the test are discussed and conclusions are drawn.

2 The Test

A statistical study of flare-related changes in the virial energies of active regions should be able to overcome the problem of large errors in individual vector magnetic field measurements. The suggested procedure is as follows. A statistical sample of vector magnetograms for active regions taken before and after large flares will be obtained. These will be reduced following the same procedures used in an earlier study (Wheatland 2000a), including resolution of the 180 degree ambiguity via the Metcalf (1995) method. Virial estimates of the AR energies [equation (1)] before and after each flare will be differenced to give the change in virial energy, $\Delta E_{\rm vir}$. For each flare the total energy of the flare $E_{\rm fl}$ will be estimated from available hard or soft X-ray observations. The quantities $\Delta E_{\rm vir}$ and $E_{\rm fl}$ will be plotted against one another for all of the active regions/flares in the study. The linear correlation between the two quantities will be calculated. If flare energy derives from the observed currents, then a linear correlation is expected. The correlation should be detectable, for a sufficiently large number of points in the plot, even though the relationship is obscured by noise in any individual pair of measurements. The motivation for this claim is that the significance[1] of a correlation between points (which are related) decreases faster than exponentially with an increase in the number of points, assuming Gaussian errors (Press et al. 1992). A simulation has been performed to estimate how many flares are needed to reveal a significant correlation.

First N flare energies $E_{{\rm fl}i}$ $(i = 1, 2, \ldots, N)$ were generated above a threshold energy $E_{\rm th}$ according to a power law distribution matching the observed frequency–energy distribution $\mathcal{N}(E) \sim E^{-\gamma}$, where $\gamma \approx 1.5$ (Crosby, Aschwanden, & Dennis 1993). It is assumed that the flares are produced by a large active region, with total energy $E_{\rm AR} = 10^{26}$ J. The estimate of a 30% error in virial energy values (Klimchuk et al. 1992) is adopted. Hence the uncertainty in $\Delta E_{\rm vir}$ is about $\sigma_{\rm vir} = 0.3(E_f^2 + E_i^2)^{1/2} \approx 0.3\sqrt{2}E_{\rm AR}$, where E_i and E_f are the initial and final virial energies ($E_i \approx E_f \approx E_{\rm AR}$). Based on this estimate, N virial energy estimates $\Delta E_{{\rm vir},i}$ were generated as normally distributed random numbers with mean $E_{{\rm fl},i}$ and standard deviation $\sigma_{\rm vir}$. Next N simulated hard X-ray energy (HXR) estimates were made. Determinations of energy from HXR observations are limited by knowledge of the lower cutoff in the distribution of electrons producing the hard X-ray. A conservative estimate of this error is that the energy estimates are accurate to about a factor of 10 (Kane et al. 1995). This may be interpreted as meaning that if the best estimate of the energy is U, the true value is most likely in the range $0.1U$ to $10U$, and is equally likely to lie either side of U. A simple model incorporating these two assumptions is that the logarithm of the hard X-ray energies is normally distributed, with standard deviation unity. Hence N HXR energy estimates U_i were constructed by assuming that $\log U_i$ is normally distributed, with mean equal to $\log E_{{\rm fl},i}$, and standard deviation unity. The rank correlation of the quantities $\Delta E_{{\rm vir},i}$ and U_i (and the significance of the correlation) was then calculated. The whole procedure was repeated 1000 times, and the median significance of the 1000 simulations determined (the significance of the correlation is smaller than this number in 50% of trials). Figure 2 shows the results. The solid curve shows the median significance versus the number of flares $N = 25, 50, 75, 100$ for a threshold energy $E_{{\rm th},1} = 1 \times 10^{23}$ J (a moderate flare). The dashed curve is for $E_{{\rm th},2} = 5 \times 10^{23}$ J. We see that the significances decrease rapidly with increasing N, and also with increased size of events. The simulation indicates that a median significance of less than 5% can be obtained for as few as 50 events, for the higher threshold.

The higher threshold ($E_{{\rm th},2} = 5 \times 10^{23}$ J) is sufficiently low that flares above this energy occur relatively often. Recently Wheatland (2000b) determined the average rate of occurrence of soft X-ray flares above C1 class (averaged over three solar cycles) to be $\lambda_{\rm C1} \approx 5 \times 10^{-5}\,{\rm s}^{-1}$. A C1 flare is expected to correspond roughly to an energy $E_1 = 10^{20}$ J (Hudson 1991). Using the observed frequency–energy distribution for flares, we can then estimate the rate of occurrence λ_2 of flares above $E_2 = E_{{\rm th},2}$ to be $\lambda_2 = (E_2/E_1)^{-\gamma+1}\lambda_{\rm C1} \approx 7 \times 10^{-7}\,{\rm s}^{-1}$. This rate corresponds to more than 20 flares per year, averaged over the solar cycle. A number of observatories have magnetograms recorded over at least the last two solar cycles.

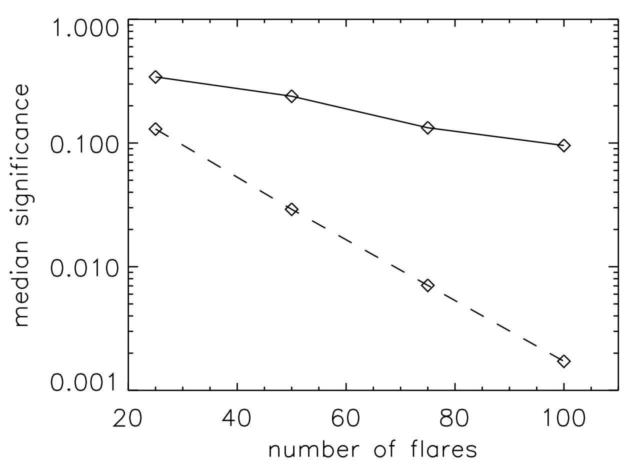

Figure 2 Results of simulation: median significance of correlation versus number of flares. (See text for details.)

[1]Significance is here used in the conventional statistical sense, i.e. the significance of a correlation is the probability of obtaining the correlation coefficient observed assuming the 'null hypothesis' that the points are in fact unrelated. A small significance is argued to be a basis for rejecting the null hypothesis, i.e. evidence for a correlation.

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Hence it is expected that there will be sufficient magnetogram measurements in available archives, even given the incomplete coverage of flare occurrence at individual observatories.

3 Conclusions

A test of the hypothesis that flares derive their energy from observed large scale current systems in solar active regions is proposed. The idea is to look for a correlation between the change in the magnetogram virial energy before and after a flare and an independent measure of the energy of the flare, for a statistical sample of active regions. A simulation incorporating the expected errors in the different energy estimates suggests that, if the hypothesis is correct, the correlation should become significant in a study involving around 50 flares with energy above 5×10^{23} J. Flares of this size occur sufficiently frequently for vector magnetogram data in existing archives to allow a meaningful test of the hypothesis.

The simulation described above is simplistic, and intended only to give an idea of the number of flares needed for the test. For example, all active regions have been assumed to have a fixed energy $E_{\rm AR} = 10^{26}$ J. This should be replaced by an appropriate distribution of active region energies, but unfortunately this distribution is not known. Also, the estimates of the errors in $\Delta E_{{\rm vir},i}$ and U_i are crude. Again, the problem is that the real uncertainties are not well characterised.

There are other possible problems with the suggested test. In particular, as mentioned in Section 1, the virial energy formula assumed the field is in a force-free state, but this is not strictly the case at the photospheric level where the spectral lines used for magnetograms are formed (Metcalf et al. 1995). For individual magnetograms, the degree of departure from the force-free state may be estimated from the data itself. This effect leads to an additional source of error in the virial energy estimates (other than those already incorporated in the simulation presented), and it is difficult to gauge the importance of this effect without detailed modelling.

In summary, the test presented here appears promising, and will be tried in the near future. If successful, this test will provide the most direct evidence yet presented for electric currents in solar active regions as the source of energy for flaring. It will also demonstrate the importance of vector magnetogram measurements for understanding the flare phenomenon, as argued by Melrose (1991; 1995; 1997).

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References

Abramenko, V. I., Yurchishin, V. B., & Carbone, V. 1998, A&A, 334, L57
Cameron, R., & Sammis, I. 1999, ApJ, 525, L61
Crosby, N. B., Aschwanden, M. J., & Dennis, B. R. 1993, 143, 275
Hudson, H. S. 1991, Sol. Phys., 133, 357
Kane, S. R., Hurley, K., McTiernan, J. M., Sommer, M., Boer, M., & Niel, M. 1995, ApJ, 446, L47
Klimchuk, J. A., Canfield, R. C., & Rhoads, J. E. 1992, ApJ, 385, 327
Lee, J., White, S. M., Gopalswamy, N., & Kundu, M. R. 1997, Sol. Phys., 174, 175
Leka, K. D., Canfield, R. C., McClymont, R. N., de La Beaujardière, J.-F., Fan, Y., & Tang, F. 1993, ApJ, 411, 370
Low, B. C. 1982, Sol. Phys., 77, 43
Melrose, D. B. 1991, ApJ, 381, 306
Melrose, D. B. 1995, ApJ, 451, 391
Melrose, D. B. 1997, ApJ, 486, 521
Metcalf, T. R. 1995, Sol. Phys., 155, 235
Metcalf, T. R., Jiao, L., McClymont, A. N., Canfield, R. C., & Uitenbroek, H. 1995, ApJ, 439, 474
Moreton, G. E., & Severny, A. B. 1968, Sol. Phys., 3, 282
Parker, E. N. 1996, ApJ, 471, 485
Pevstov, A. A., Canfield, R. C., & McClymont, A. N. 1997, ApJ, 481, 973
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C, the Art of Scientific Computing, 2nd edition (Cambridge: Cambridge University Press), 636
Sakurai, T., Shibata, K., Kiyoshi, I., Tsuneta, S., & Acton, L. W. 1992, PASJ, 44, L57
Sammis, I., Tang, F., & Zirin, H. 2000, ApJ, 540, 583
Semel, M., & Skumanich, A. 1998, A&A, 331, 383
Švestka, Z. 1976, Solar Flares (Dordrecht: D. Reidel), 28
Wang, H., Ewell Jr., M. W., Zirin, H., & Ai, G. 1994, ApJ, 424, 436
Wheatland, M. S. 2000a, ApJ, 532, 616
Wheatland, M. S. 2000b, ApJ, 536, L109

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