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Abstract

Highly stressed and nonpotential magnetic fields in solar active region are believed to be the site and source of energy of M or X class flares which release as much as 10^{32} ergs in a periods of 10s to 1000s with intense emission detected over most of the electromagnetic spectrum. Such M or X class flares are the most likely γ-ray emission candidates since sheared magnetic field is the means of energy storage for flare events. We have studied the correlation between 'nonpotentiality' parameters such as 'shear angle' and maximum magnetic field strength with the occurrences gamma-ray events . Also the angle of deviation of the magnetic field from the line of sight has been studied since the bremsstrahlung γ-ray beam produced by relativistic ions and electron is highly directional in the forward direction and required non vertical field-lines for the detection of the disk-center events.

1.Introduction

The Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory is a sensitive all-sky detector system. BATSE consists of eight uncollimated detector modules , arranged on the corners of the Compton Gamma Observatory to provide the maximum unobstructed view of the celestial sphere. Each detector module contains a large-area detector (LAD),each 2025 cm^2, optimized for sensitivity and directional

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response, and a spectroscopy detector (SD),each 127 cm^2, optimized for broad energy coverage and energy resolution. Although optimized for the detector of gamma-ray bursts, these detectors are far more sensitive than any previous spacecraft-borne hard x-ray flare instrumentation both for the detection of flares and the resolution of fine temporal structures. From each of the eight detectors, data is accumulated in four energy channels, (25-50, 50-100,100-300 and >300 keV) with time a resolution of 1.024s. In addition, 64 ms data are also available for most of the 'big' flares. For further detail information, readers are referred to The Compton Observatory Science Workshop, 1991 edition.

2.Solar activity

Since the beginning of BATSE scientific operations on 19 April 1991 through 30 Oct 1992, GOES had reported 474 M or X class flares which occurred in a known active region. During the same period, BATSE reported 3490 flare events. Since BATSE does not produce hard x-ray images of the sun, we matched the flare onset time with the Hα flare onset time reported by the GOES satellite to determine the location of events that are associated with the x-ray emission. We further set the requirement that only those events with peak count rates in the energy channel 25-100 keV greater than 1000 be considered. 227 out of the 474 flares recorded had emission at least of this magnitude in 25-100 keV energy channel. Of those 226, only 30 were seen in energy channel 100-300 keV and 10 were seen in energy channel 1-10 MeV. Figure 1a shows the location of all the events that we have selected from GOES and BATSE database and figure 1b shows a plot of number of events vs days after Jan 1 1991. On figure 1b ,every event count as one single unit (they were not weighted as the their classification). All of the events seen on energy channel

1-10 MeV were produced in 1991. Five of the 10 events seen in energy channel 1-10 MeV occurred in active region 6659 on Jun 1,4,6,9 and 11 respectively. GOES classes were X12.0, X12.0, X12.0, X12.0, and X10.0 respectively. An M5.0 γ-ray flare was produced in active region 6693 on Jun 30th. July 2nd produced an M4.6 in active region 6703 which was also a γ-ray event. The other three were on active region 6891 on Oct 24 (X2.1) and 27 (X6.1) and on active region 6919 on Nov 15 (X1.5). Complete information is available in Table 1.

3.Investigation Approach

The high-energy phenomena of solar γ-ray flares is strongly related to the magnetic field configuration in the active region since the free energy stored in the nonpotential magnetic fields is believed to be the ultimate energy source for the entire flare process. Our objective was to identify characteristics of the magnetic field configuration that are specific to the production of γ-ray flares. Special or extreme features in the magnetic field from which the energy is released are responsible for the acceleration of ions and electrons to relativistic velocities. This ions interact with the plasma in the photosphere to produce the γ-rays that are detectable by BATSE. In our study, we define the parameter 'angular shear' $\Delta\phi$ as the difference between the azimuths ϕ of the transverse(to the line of sight) component of the potential and the reference potential field computed using the line of sight field on the photosphere (see Hagyard et al, 1984). Couple with the strength of the field, this measure of the 'nonpotentiality' has a physical interpretation in terms of electric currents. The angular shear $\Delta\phi$ measured in the transverse component is a measure of the twist in the transverse plane. And the stronger the field, the larger the current produced for the same twisted (Hagyard). We selected those pixels that have field strengths B fitting in the criteria $B \geq 300$ G and $B \geq B^*/2$, where B^* is the maximum field strength along the selected neutral line. Then we designate the field to be moderately stressed if

$$70^0 \leq \Delta\phi \leq 80^0$$

and highly stressed if

$$80^0 \leq \Delta\phi \leq 90^0$$

Maps of these points are shown in the contour shear plot by using two different symbols for the two different ranges of $\Delta\phi$: + and * for the moderately and highly stressed points, respectively.

Most of the γ-ray emission is produced in the region between the photosphere and chromosphere, a region of about a few hundred kilometers thickness and density $10^{12}/cm^3$. Dermer and Ramaty (1986) have calculated detailed angular and energy spectra of bremsstrahlung from anisotropic electron distributions in solar flares. In their model, magnetic field lines are perpendicular to the surface of the photosphere. Taking into accord the pitch angle of the electrons to the magnetic field, they came to the conclusion that since most of the precipitating energetic particle have relativistic velocities and hence that the bremsstrahlung γ-ray are beamed in the forward direction there will be limb brightening for x-ray emission from the solar flares. With the BATSE highly sensitive detector, we have however seen disk-center brightening flares. This may be due to the inclination of the field line from the line of sight. We have studied a model which the magnetic field lines are inclined from the vertical with a range of angle approximated to a force free field. Using a uniform twist force-free magnetic field configuration (e.g Priest 1986) and an analytic fit to the relationship between the angle of emitted photon and the magnetic field derived by Dermer and Ramaty, we find that

$$dI(\delta) = Aexp(Bcos(\alpha))rdr \quad (1)$$

where

$$cos(\alpha) = cos(\delta)cos(\beta) + sin(\delta)sin(\beta)cos(\phi)$$

here dI is the intensity, δ is the angular distance of the source from the line of sight (equal to the central meridian distance) , α is the angle between the emitted photon and the magnetic field line , β is the angle of the magnetic field line from the line of sight, ϕ is the azimuth angle between the emitted photon and magnetic field and A,B are constants of the fit. For a uniform twist force-free field, r and β are related by

$$rdr = tan(\beta)sec^2(\beta)d\beta$$

We have integrated equation (1) numerically from $\beta = \beta_0$ to β_1, and find in general, a smaller amount of limb brightening than Dermer and Ramaty. For some extreme case, we can in fact have limb darkening. Figure 2 show some of the cases we have studied. We will use these three observed 'nonpotentiality' parameters, maximum magnetic field strength, 'shear angle' and β_1 to distinguish the γ and non- γ flares.

4.Data analysis

Four active regions were chosen for further study. These four active regions are AR 6659 Jun 1991, AR 6703 July 1991, AR 6891 Oct 1991 and AR 6919 Nov 1991. On average over a period of 11 day, all four active regions have produced γ and non-γ events. AR

6659 produced the most M or X class flares with total of 34 following by AR 6891 with 28 flares. AR 6703 and AR 6919 have produced 9 and 7 flares respectively. Searching through the MSFC Vector Magnetograph Center database, we come up with 17 days that magnetogram data were available. Out of this 17 days, 8 of the events have Hα images from here , also from Hawaii and Big Bear Observatory. Table 1 list all the cases which we have analyzed. The analysis for nonpotential fields of the events that are too 'close' to the limb have been corrected for projection effects by transforming the measured field into heliographic coordinates. (Gary and Hagyard,1990; Hagyard 1987; Venkatarishnan et al., 1988). The ambiguity of 180^0 in the azimuth is resolved by a method which includes comparison with the direction of the potential field, comparisons with Hα structure, and connectivity between positive and negative fields in the heliographic coordinates. Figure 3-8 shown the observed field , potential field and shear map of all the cases we have studied.

5.Conclusion

Given the small sample of cases we have studied, we conclude that, as five of the most energetic flares recorded by BATSE location at least 50^0 or more toward the limbs with an equal number of the same type of flares were seen in location less than 20^0 from the disk-center, there is no clear different between limbs flares and disk-center flares in the production of γ-ray emission (1- 10 MeV) . As indicated in table 1, on average, all of the γ-ray flares have β greater than 60^0 which agrees quite well with our simple numerical calculation. In general, this trend carries down to soft x-ray produced events. The distribution of the x-ray flares is quite uniform in the latitude band $\pm 35^0$ N-S. The strength of the magnetic field along the neutral line and the corresponding 'shear angle' also do not differ significantly between the flares that produced γ-ray and those do not. However, there is a trend that the stronger the field strength and the greater the 'shear angle', the higher the probability the flare produces γ-ray. This is especially true for γ-ray flares: most of the γ-ray events recorded by BATSE have field strength of at least 800 G and a 'shear angle' greater than 60^0. Further study is needed to correlate the characteristics of the nonpotentail fields with those flares that produced γ-ray emission.

We summarize our study as following.

1) X class flares are not necessary γ-ray emission candidates even if they are on the limb. Impulsive flares (short lived flares) are more likely to be observed in the γ-ray range.

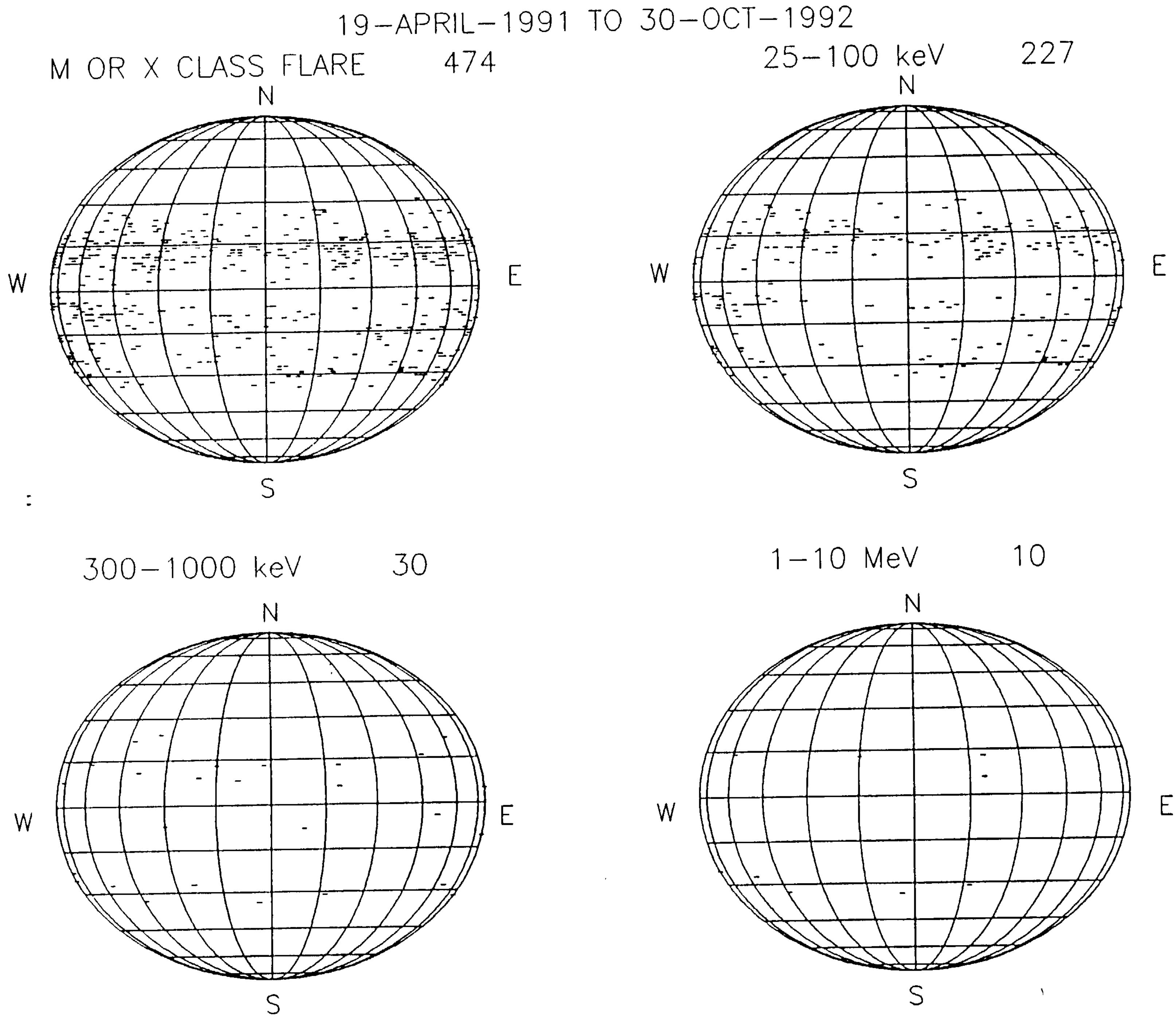
2) Disk-center flares are as likely to produce γ-ray emission as limbs flares.

3) In most of the cases, high magnetic field strength and great 'shear angle' is observed at the site of γ-ray events. And these is a correlation between high β and the γ-ray events.

Date	AR	Start time	End time	Classification	Location	MSFC data	10-50 KeV	300-1000 KeV	1-10 MeV	Max B	No Pixel	ϕ	β
1-Jun-91	6659	1456	1726	1F/X12.0	N25E90	No	Yes	Yes	Yes	??	??	??	??
4-Jun-91	6659	0337	0800	3B/X12.0	N30E65	Yes	Yes	Yes	Yes	??	??	??	??
6-Jun-91	6659	0058	0431	4B/X12.0	N33E44	Yes	Yes	Yes	Yes	1180	10	89	60
6-Jun-91	6659	0058	0431	4B/X12.0	N33E44	Yes	Yes	Yes	Yes	??	??	??	??
7-Jun-91	6659	0025	0300	3B/M4.2	N27E24	Yes	Yes	Yes	No	??	??	??	??
8-Jun-91	6659	1652	01723	SF/C3.6	N32E04	Yes	N/A	N/A	N/A	??	??	??	??
9-Jun-91	6659	0134	0152	3B/X10.0	N34E04	Yes	Yes	Yes	Yes	1922	7	88	55
10-Jun-91	66559	1652	1746	3N/M3.2	N35W11	Yes	Yes	No	No	??	??	??	??
11-Jun-91	6659	0156	0220	3B/X12.0	N08E50	Yes	Yes	Yes	Yes	??	??	??	??
15-Jun-91	6659	1911	1915	SF/M1.6	N08E50	Yes	Yes	Yes	Yes	??	??	??	??
2-Jul-91	6703	1933	1954	1N/M4.6	N27E56	Yes	Yes	Yes	Yes	1071	4	85	60
24-Oct-91	6891	0231	02??6	2N/X2.1	S14E59	Yes	Yes	Yes	Yes	??	??	??	??
26-Oct-91	6891	1846	2243	2N/X1.7	S09E20	Yes	Yes	Yes	No	??	??	??	??
27-Oct-91	6891	0531	0712	3B/X6.1	S13E15	Yes	Yes	Yes	Yes	??	??	??	??
28-Oct-91	6891	2019	2046	1B/M1.3	S11W05	Yes	Yes	No	No	??	??	??	??
11-Nov-91	6919	1941	2014	SF/M1.1	S11E42	Yes	Yes	No	No	1156	0	43	60
15-Nov-91	6919	2233	2254	3B/X1.5	S13W19	Yes	Yes	Yes	Yes	929	12	88	60

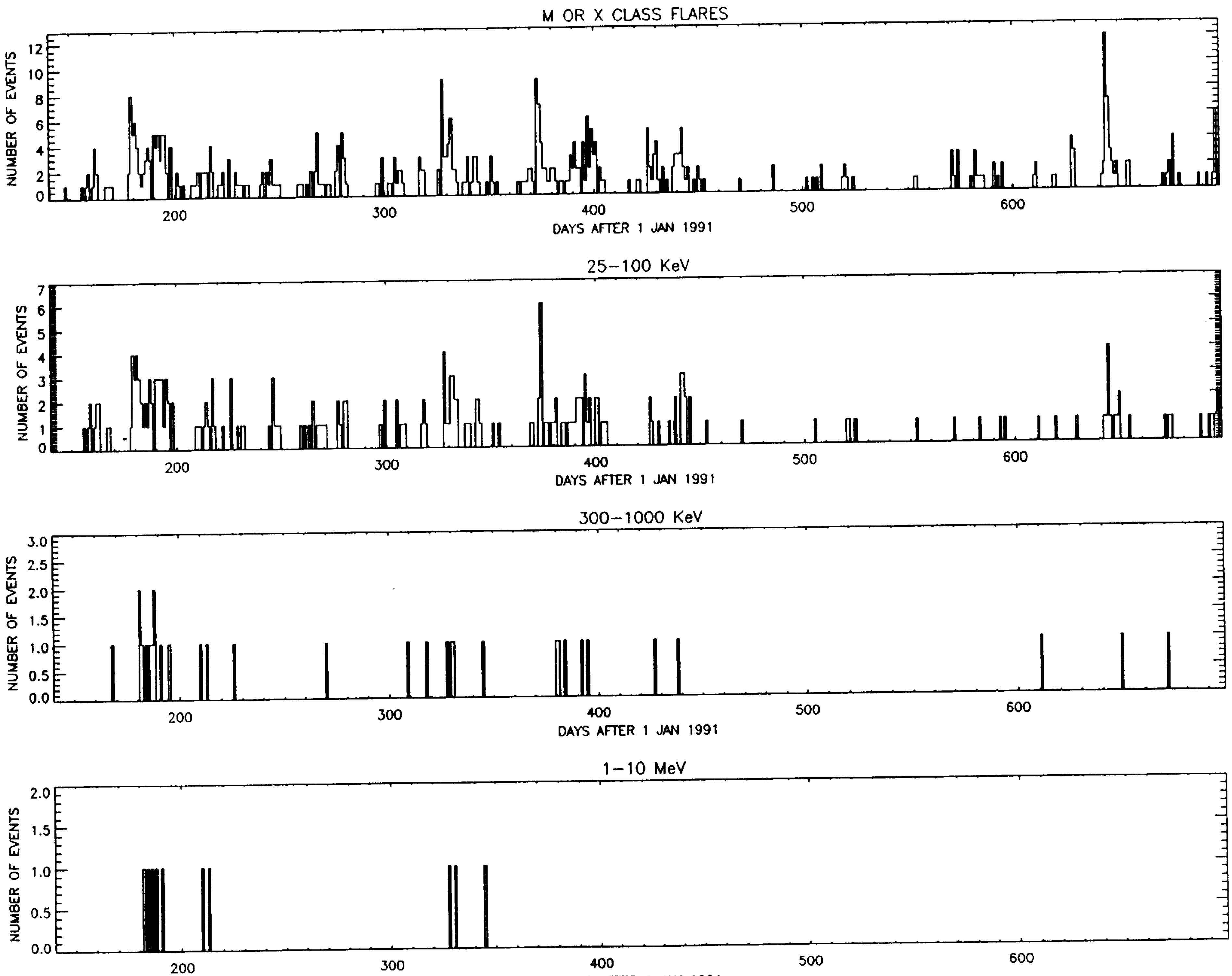
Table 1.

**Note: ?? mean inconclusive. Hα image of the flare is not available or the quality of the image is very poor.



19-APRIL-1991 TO 30-OCT-1992
M OR X CLASS FLARE 474
25-100 keV 227
300-1000 keV 30
1-10 MeV 10
N
S
W
E

FIGURE 1a



M OR X CLASS FLARES
NUMBER OF EVENTS
0
2
4
6
8
10
12
200
300
400
500
600
DAYS AFTER 1 JAN 1991
25–100 KeV
NUMBER OF EVENTS
0
1
2
3
4
5
6
7
200
300
400
500
600
DAYS AFTER 1 JAN 1991
300–1000 KeV
NUMBER OF EVENTS
0.0
0.5
1.0
1.5
2.0
2.5
3.0
200
300
400
500
600
DAYS AFTER 1 JAN 1991
1–10 MeV
NUMBER OF EVENTS
0.0
0.5
1.0
1.5
2.0
200
300
400
500
600
DAYS AFTER 1 JAN 1991

FIGURE 1b

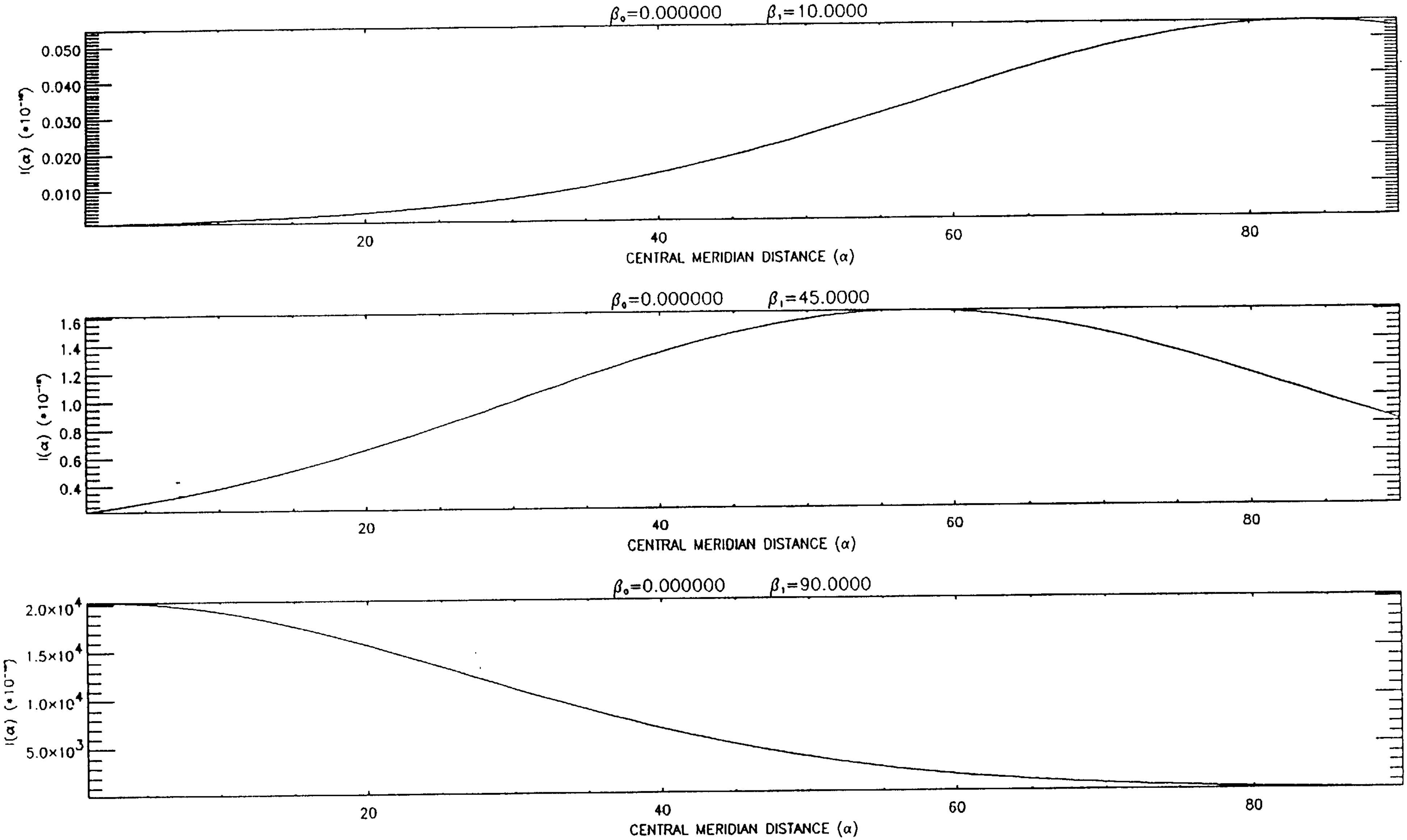
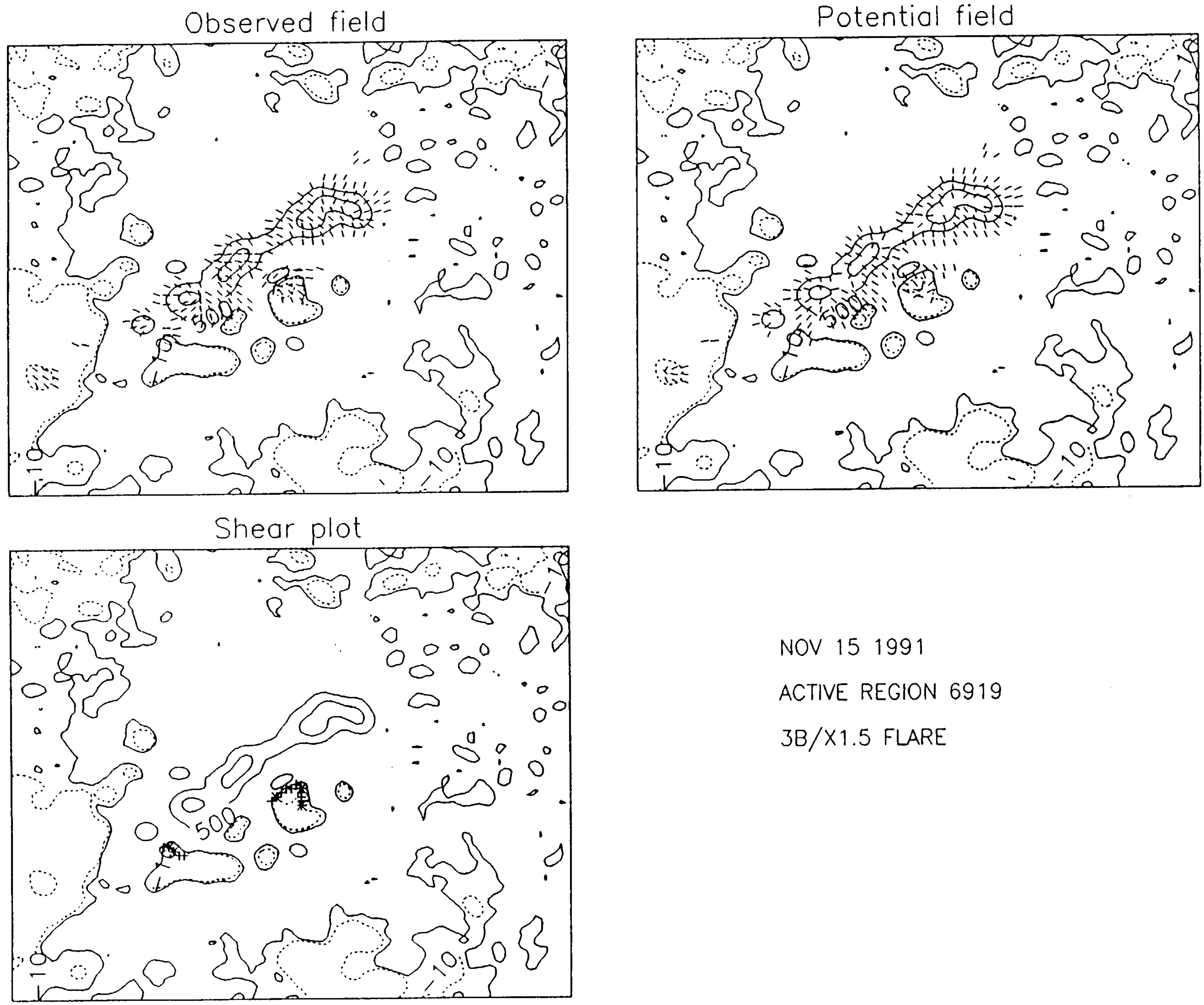


FIGURE 2.

$$dI(\alpha)=A*EXP(B*COS(\alpha)*COS(\beta)+SIN(\alpha)*SIN(\beta)*COS(\phi))*TAN(\alpha)*SEC^2(\alpha)d\beta$$

$A=2.242926e-20$ $B=5.06162$ $\phi=10.0000$

$$I(\alpha)=\int_{\beta 0}^{\beta 1} dI(\alpha)$$

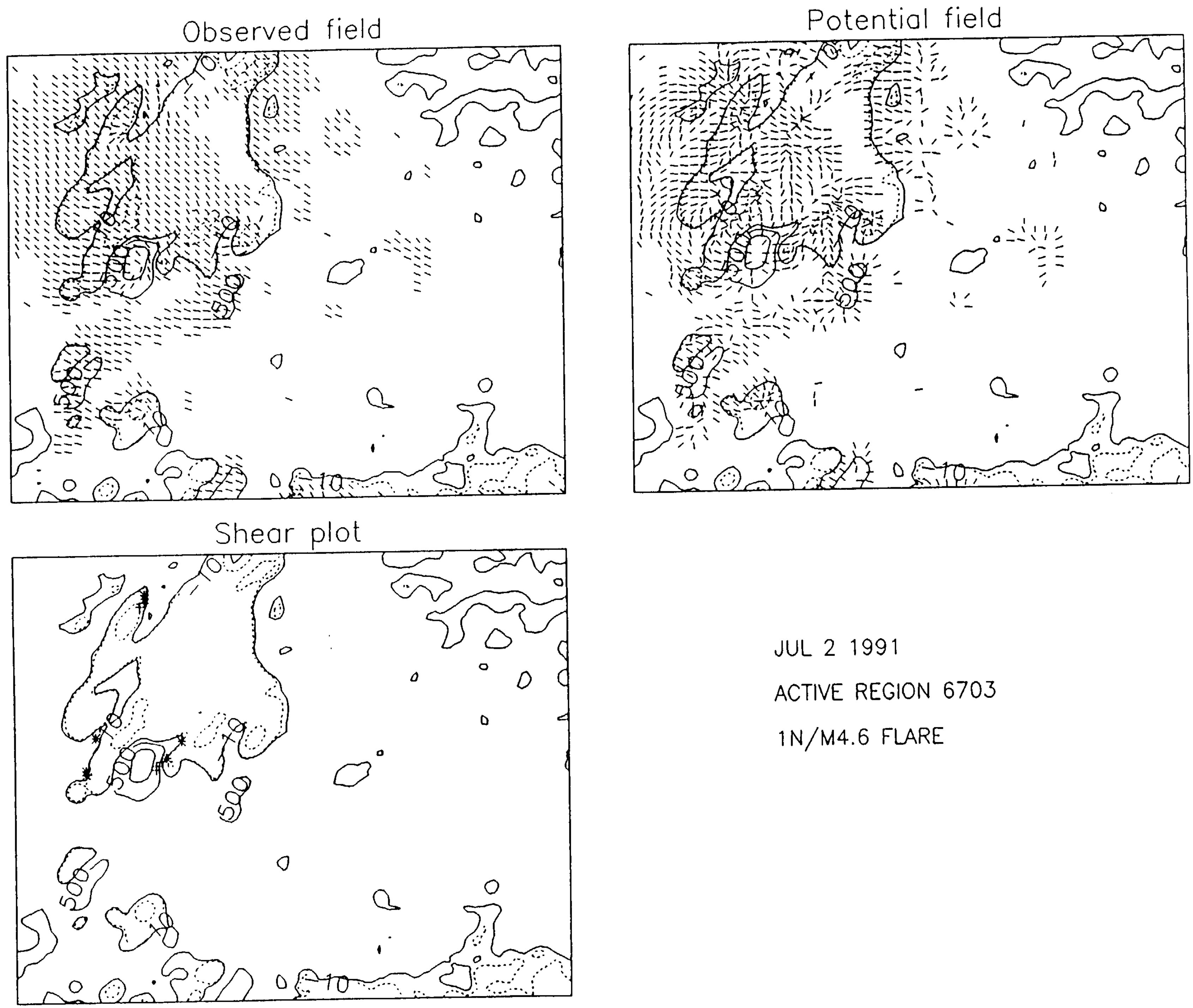


NOV 15 1991

ACTIVE REGION 6919

3B/X1.5 FLARE

FIGURE 3



JUL 2 1991

ACTIVE REGION 6703

1N/M4.6 FLARE

FIGURE 4

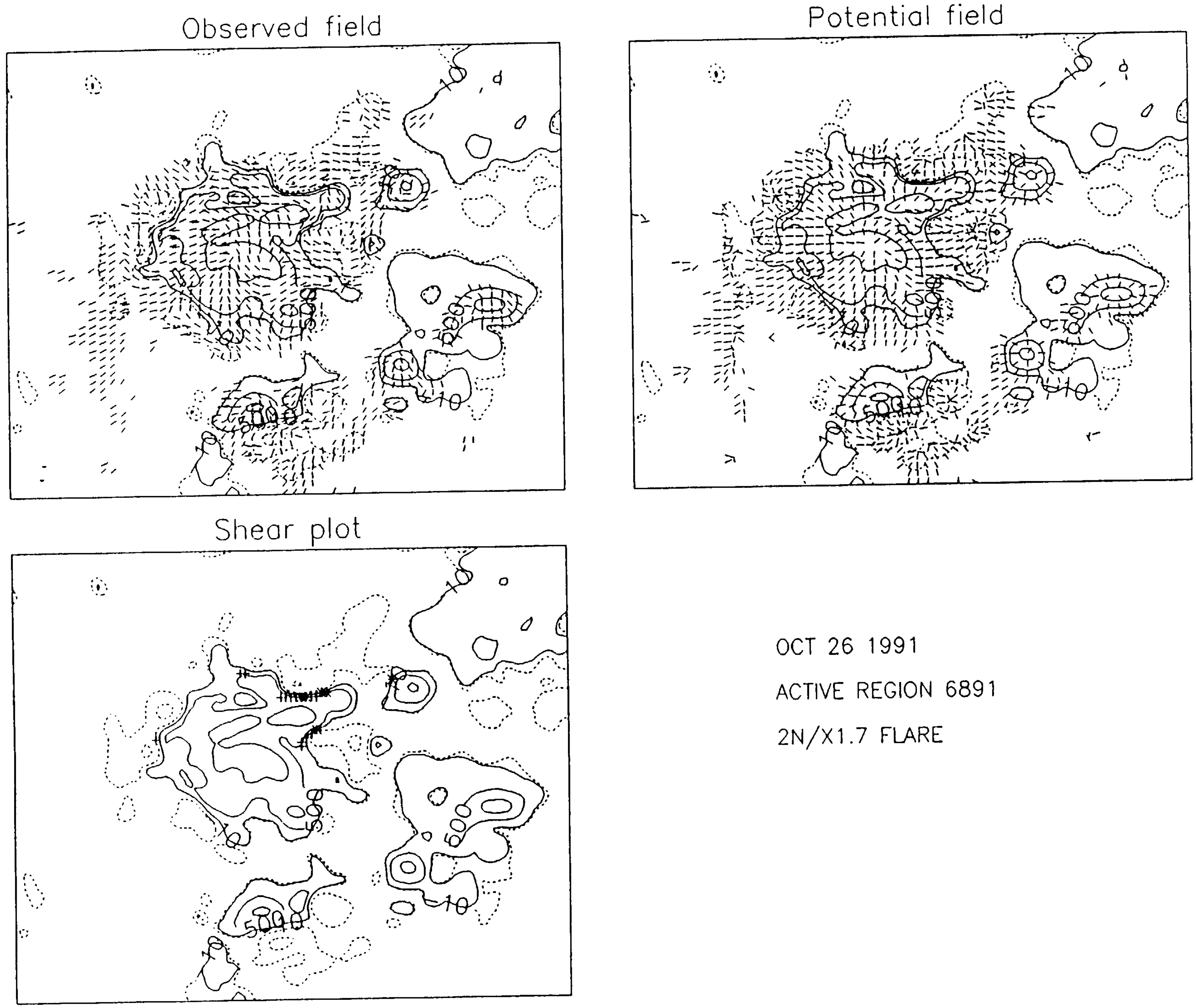

Observed field
Potential field
Shear plot
10
500
OCT 26 1991
ACTIVE REGION 6891
2N/X1.7 FLARE

FIGURE 5

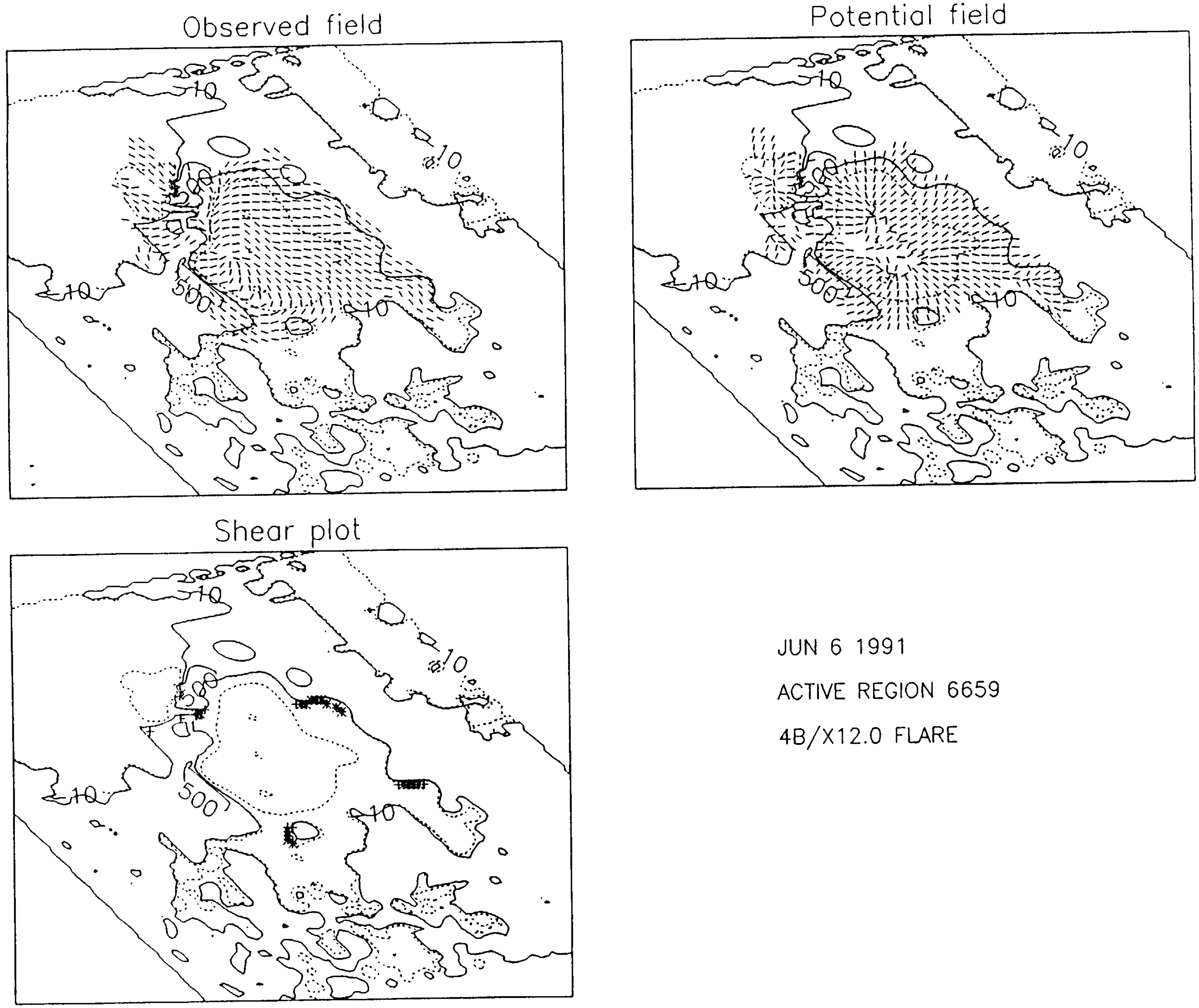
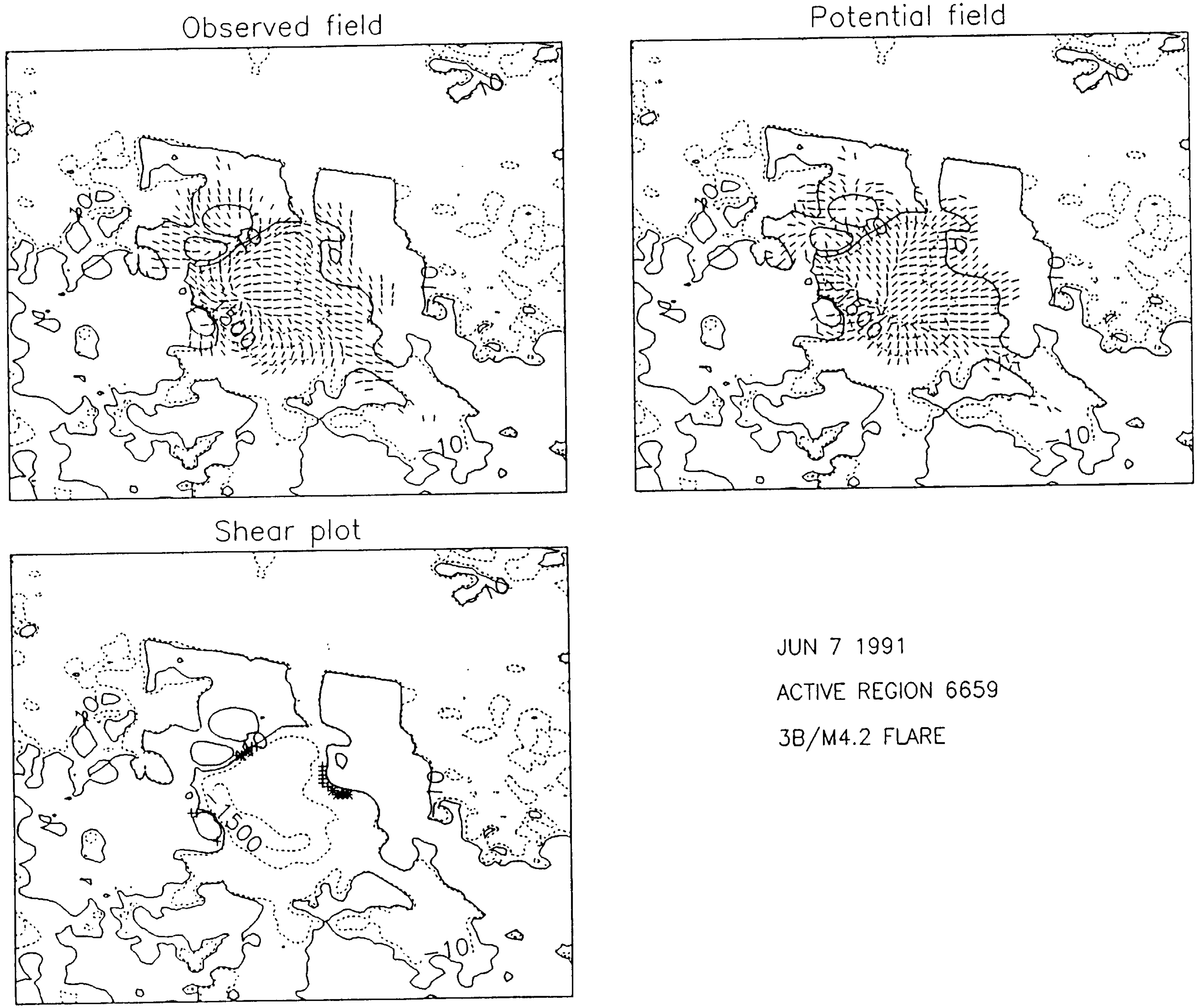

Observed field
Potential field
Shear plot
10
500
JUN 6 1991
ACTIVE REGION 6659
4B/X12.0 FLARE

FIGURE 6



JUN 7 1991

ACTIVE REGION 6659

3B/M4.2 FLARE

FIGURE 7

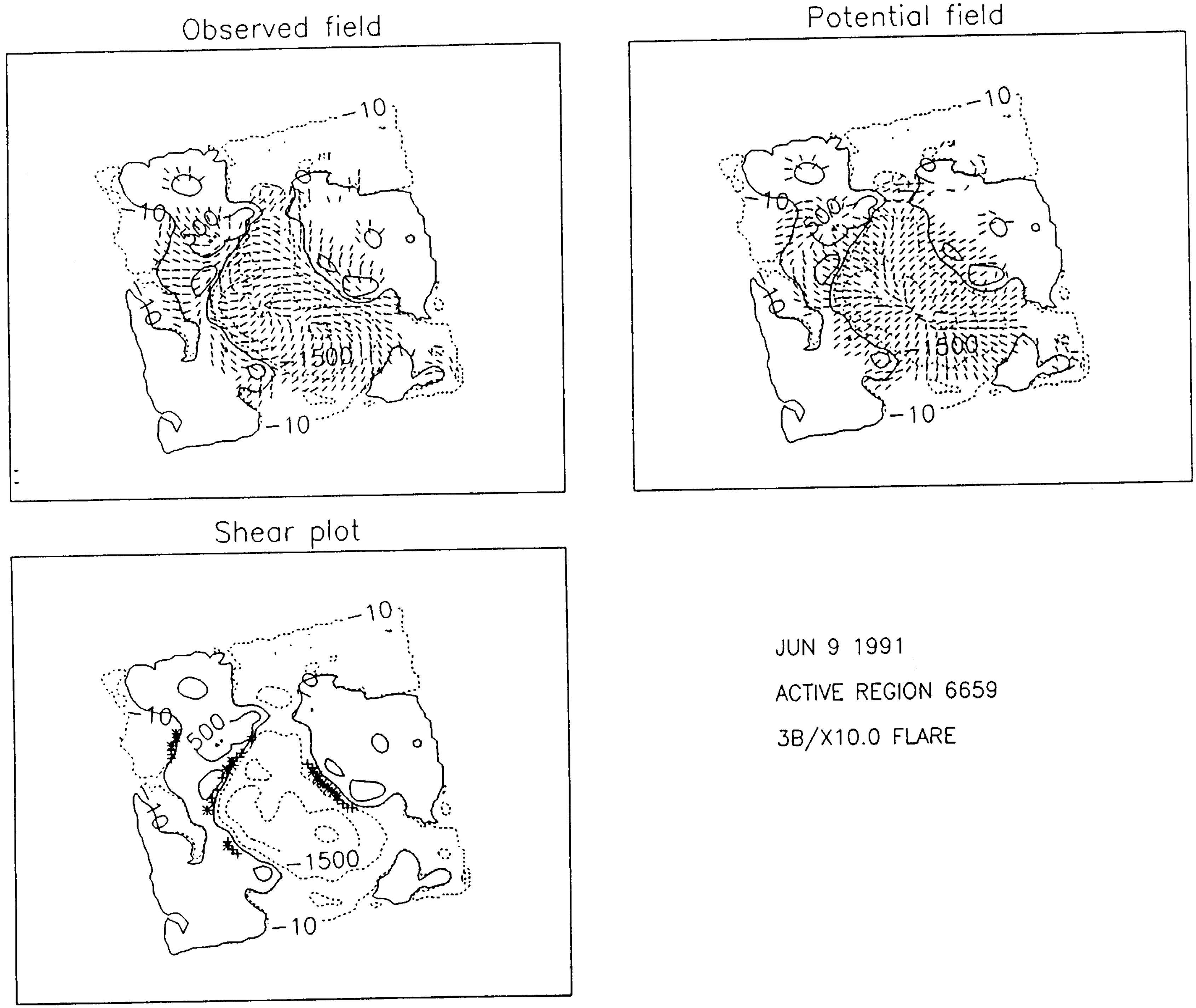

Observed field
-10
500
-1500
-10
Potential field
-10
500
-1500
-10
Shear plot
-10
500
-1500
-10
JUN 9 1991
ACTIVE REGION 6659
3B/X10.0 FLARE

FIGURE 8

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National Aeronautics and Space Administration

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16. Abstract

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