THE CLASSIFICATION OF SUNSPOT GROUPS

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(Received in revised form 21 August, 1989)

Abstract. The 3-component McIntosh classification of sunspots was introduced in 1966, adopted for interchange and publication of data in 1969, and has been used increasingly in recent years. The McIntosh classification uses a modified Zurich evolutionary sequence as its first component, class, where two of the Zurich classes are omitted and more quantitative definitions are used. It then adds descriptions of the largest spot (second component) and the degree of spottedness in the group interior (third component) to define 60 distinct types of sunspot groups. Definitions of the McIntosh classification system and their rationale are presented herein. Correlations with solar flares excel those with the earlier Zurich classification, prompting the use of the McIntosh classification in an expert system (Theo) for predicting X-ray solar flares.

1. Introduction

The earliest statistics of solar flare activity showed a close relationship to sunspots, with larger and more numerous flares near the larger and more complex types of sunspot groups (Waldmeier, 1938; Giovanelli, 1939). The statistics accumulated during the intense activity of Solar Cycle No. 19 (1954–1964) (Smith and Smith, 1963), provided a foundation for solar flare prediction, upon which modern observations and physical models have built the present solar-terrestrial prediction services (McIntosh and Dryer, 1972; Simon, Heckman, and Shea, 1986).

Flare predictions today still rely on sunspot observations. Sunspots are easily observed with small and inexpensive telescopes, which means the data are available every day from observatories at all Earth longitudes. Most important, these data are systematically reduced into a system of classification with an established correlation with solar flares. Use of a simple system of classification allows remote synoptic observatories to report sunspot data quickly and consistently without expensive image processing. Sunspot observations often detect changes in magnetic fields that relate to the location and time of larger flares by virtue of their high-resolution representation of strong magnetic fields. Chromospheric and magnetic-field data so far are only supplemental to sunspot data in operational flare forecasting because these data are not reduced into formats for rapid assimilation by prediction algorithms. The three types of observations together are essential for detecting preflare conditions.

The Zurich sunspot classification (Kiepenheuer, 1953) was developed by Waldmeier (1947) by modifying an earlier scheme of classification introduced by Cortie (1901). The Zurich classification has been correlated with flares, but even within its most active class F, the probability of a large flare is so low as to afford little real value to the forecast (Křivský, 1972). Observers and forecasters have noted structural and dynamical aspects of sunspot groups that are correlated with flares but which are not part of the Zurich classification. Some of these missing parameters were incorporated into a revision of

Solar Physics **125**: 251–267, 1990.

the Zurich classification that was introduced in 1966 to the first meeting of the Solar Physics Division of the American Astronomical Society. This new McIntosh classification was adopted soon thereafter for regular interchange of solar geophysical data (I.U.W.D.S., 1969). Definitions and illustrations of the McIntosh classification have appeared in *Solar-Geophysical Data* (1972), in the *Chinese Solar-Geophysical Data* (1988), in a review paper on sunspots (McIntosh, 1981), and in journals for amateur astronomers (Beck, 1987; Miller, 1988; Hill, 1989). The only detailed discussion of the classification appears in a recent conference proceedings (McIntosh, 1986). This paper provides the definitive description of the McIntosh classification of sunspots, and discusses its interpretation for both predictions and solar physics.

The pattern of evolution is very similar for the majority of sunspot groups. Groups begin as a single spot, or compact cluster of tiny spots, joined some hours later by a second cluster of spots separated from the first by about 3 heliographic degrees (3×10^4 km). This second 'pole' of the group is almost always opposite in magnetic polarity from the first. More than half of the groups will develop a large leader spot (at the western end of the group) through coalescence of two or more of the small spots, and it will become surrounded by penumbra. The larger groups form one or more large spots at the opposite end of the group (trailing, or following, portion), and the more exceptional groups will continue growth until large spots and penumbra appear in the interior of the group. Peak area and complexity are usually reached in less than a week. The decline of the group begins with the fragmentation and dissolution of the trailer spots until there remains only a symmetric leader spot. After a week or two this spot also fragments, loses penumbra, and decays back to a single spot or cluster of spots like it began. The time from birth to death of a sunspot group varies from a few days to six months, with the median at less than two weeks. Few groups pass through all the stages described.

The differences among sunspot groups are greater for the larger groups. Large isolated groups are usually similar in structure to small isolated groups. Most large groups, however, develop through the successive emergence of multiple bipolar groupings of spots (McIntosh, 1969, 1981; Gaizauskas *et al.*, 1983). The expansion and proper motions of the individual bipoles lead to merger among the component bipolar areas, producing complicated geometries seldom repeated in other groups.

2. Definitions of the McIntosh Classification

The Zurich classification was modified and expanded in order to improve the objectivity of the definitions, and to add indicators of size, stability and complexity that appeared to correlate with solar flares. The Zurich system attempts to describe a typical evolutionary sequence to the largest sunspot groups. The Zurich classes are retained in modified form as the first of three components in the new classification. This eases the difficulty in persuading observers to change classification systems. The addition of new parameters takes the form of two simple sequences, thereby expanding the classification to three components. The resulting 60 distinct types of groups, versus the 9 Zurich classes, produce a more accurate description of sunspot groups without demanding much more the solar observer.

The general form of the McIntosh classification is *Zpc*, where Z is the modified Zurich class, *p* is the type of principal spot, primarily describing the penumbra, and *c* is the degree of compactness in the interior of the group. Figure 1 illustrates the sequence within each of the three components of the classification. Table I lists the logical sequence for determining the McIntosh classification.

The definitions are formulated to require only white-light observations in the interest of consistency among all synoptic observatories. The definitions must begin with the distinction between unipolar and bipolar groups, implying a difference in a magnetic

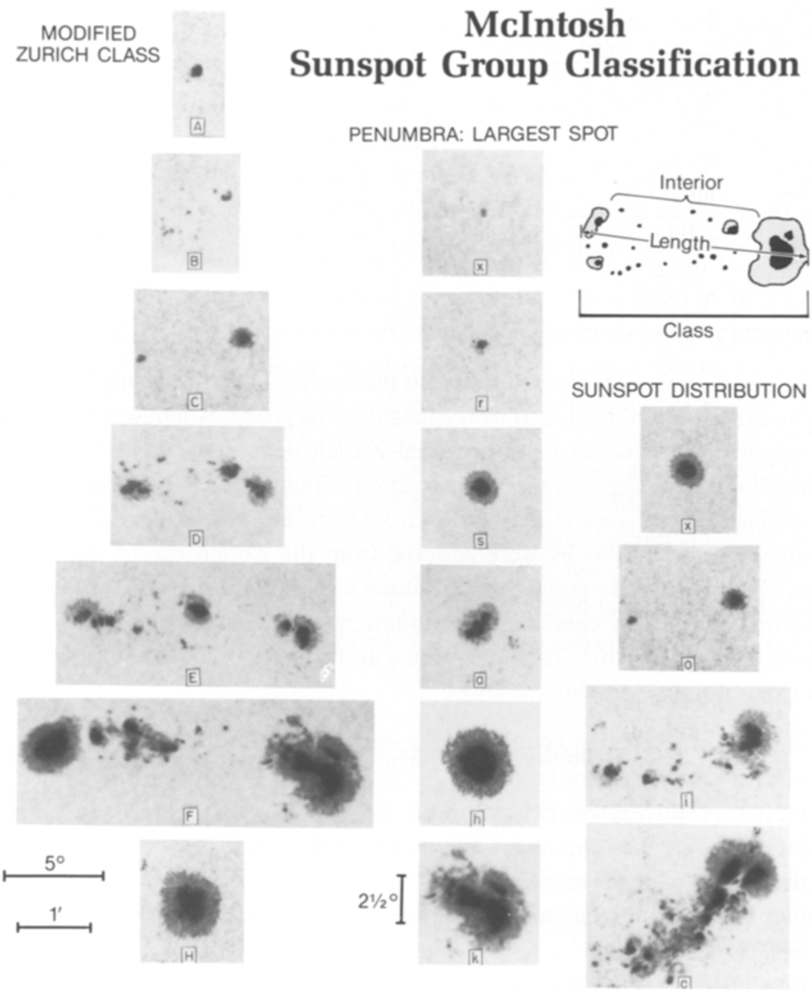

Fig. 1. The 3-component McIntosh classification, with examples of each category.

TABLE I

Logic sequence for determining McIntosh sunspot types

Unipolar or bipolar?
Penumbra or no penumbra?
Penumbra on one end or both ends?
Length of group?
Rudimentary or mature penumbra?
Symmetric or asymmetric largest spot?
N–S diameter of largest spot?
Spots between leader and follower?
Mature penumbra in interior?

topology, but not requiring magnetic-field measurements to make the distinction. Rarely will the measured magnetic class conflict with the following definitions:

Unipolar group: A single spot, or a compact cluster of spots with the greatest separation between spots $\leq 3°$. In the case of a group with penumbra (class H), the greatest separation is measured between the center of the attendant umbra and the nearest border of penumbra surrounding the main spot.

Bipolar groups: Two or more spots forming an elongated cluster of length $> 3°$. Usually there will be a space near the middle of the cluster dividing it into two distinct parts. Groups with a large principal spot must be $> 5°$ in length (i.e., 2.5° plus 3°) to be classified as bipolar.

2.1. Modified Zurich class – Z

The modified Zurich classes are defined on the basis of whether penumbra is present, how penumbra is distributed, and by the length of the group. A judgment of complexity is not required, in contrast to the original Zurich definitions. Length is defined in absolute heliographic degrees, *not* as a projection of that length in heliographic longitude (see inset diagram in Figure 1). This differs from some of the definitions already in print. The definitions of the classes were adopted from the Zurich classification, with the addition of strict limits to group length. Zurich classes G and J were omitted because they can be described by combinations of these modified Zurich classes with the other two McIntosh components. The illustrations in the left-hand column of Figure 1 show typical examples of each class.

A unipolar group with no penumbra, representing either the formative or final stage of evolution in a spot group.

B bipolar group without penumbra on any spots.

C bipolar group with penumbra on one end of the group, in most cases surrounding the largest of the leader umbrae.

D bipolar group with penumbra on spots at both ends of the group, and with length $\leq 10°$.

E bipolar group with penumbra on spots at both ends of the group, and with length defined as: $10° < \text{length} \leq 15°$.

F bipolar group with penumbra on spots at both ends of the group, and length $> 15°$.

H unipolar group with penumbra. The principal spot is usually the leader spot remaining from a pre-existing bipolar group.

2.2. Penumbra: largest spot – *p*

The second parameter of the McIntosh classification is illustrated in the center column of Figure 1. The type of largest spot in a sunspot group can be described by the combination of type of penumbra, size of penumbra, and symmetry of penumbra and umbrae within that penumbra. These descriptors specify size, maturity, stability, and complexity in terms that are simple and, therefore, conducive to consistent classification.

x no penumbra (group is class A or B).

r rudimentary penumbra partially surrounds the largest spot. This penumbra is incomplete, granular rather than filamentary, brighter than mature penumbra, and extends as little as 3 arc sec (2200 km) from the spot umbra. Rudimentary penumbra may be either in a stage of formation or dissolution (McIntosh, 1981, Section 2.3; Bray and Loughhead, 1964, Plate 3.7).

s small, symmetric (like Zurich class J). Largest spot has mature, dark, filamentary penumbra of circular or elliptical shape with little irregularity to the border. There is either a single umbra, or a compact cluster of umbrae, mimicking the symmetry of the penumbra. The north–south diameter across the penumbra is $\leq 2.5°$.

a small, asymmetric. Penumbra of the largest spot is irregular in outline and the multiple umbrae within it are separated. North–south diameter of penumbra $\leq 2.5°$.

h large, symmetric (like Zurich class H). Same structure as type '*s*', but north–south diameter of penumbra $> 2.5°$. Area, therefore, must be ≥ 250 millionths solar hemisphere.

k large, asymmetric. Same structure as type '*a*', but north–south diameter $> 2.5°$, and area ≥ 250 millionths. This type of spot sometimes contains spots of opposite polarity, the Potsdam ∂-configuration (Kunzel, 1960), and may indicate potential for proton flares (Warwick, 1966).

2.3. Sunspot distribution – *c*

A simple ranking of the relative spottedness in the interior of a sunspot group gives additional information about the area of the group and, more important, whether there could be strong spots near the line of polarity inversion lying between the principal leader and follower spots. The illustrations in the right-hand column of Figure 1 show the extreme examples of open and compact groups, and a typical example of an intermediate degree of spottedness in a group's interior.

x undefined for unipolar groups (class A and H).

o open. Few, if any, spots between leader and follower. Interior spots of very small size. Class E and F groups of *open* category are equivalent to Zurich class G.

i intermediate. Numerous spots lie between the leading and following portions of the group, but none of them possesses mature penumbra.

c compact. The area between the leading and following ends of the spot group is populated with many strong spots, with at least one interior spot possessing mature penumbra. The extreme case of compact distribution has the entire spot group enveloped in one continuous penumbral area.

2.4. Statistics of Classification

The number of possible types of sunspot groups in the McIntosh classification is 60, not the full set of combinations of the 17 categories within the three parameters. This is because there is only one type of largest spot for groups lacking penumbra, no sunspot distribution for unipolar groups, and no compact distribution for classes B or C or for groups whose largest spot has rudimentary penumbra. Table II summarizes the allowed combinations of parameters to define McIntosh types.

TABLE II

Allowed types of groups in McIntosh sunspot classification

Class	Penumbra: largest spot	Distribution	Number of types
(A)	(*x*)	(*x*)	1
(B)	(*x*)	(*o i*)	2
(C)	(*r s a h k*)	(*o i*)	10
(D E F)	(*r*)	(*o i*)	6
(D E F)	(*s a h k*)	(*o i c*)	36
(H)	(*r s a h k*)	(*x*)	5
Total allowed types:			60

Table III gives the frequency of occurrence of the 60 types of spot groups during 1969–1976, an interval from sunspot maximum to sunspot minimum (Kildahl, 1980). There were 12411 spot group classifications reported in this period, counting each group as a separate occurrence for each day of its observation. There were less than 3000 different groups, indicating that the average time of group visibility was 4–5 days, dominated by the short-lived class A and class B groups.

These data were compiled from the patrol observations provided in real-time to the Space Environment Services Center, the service portion of the Space Environment Laboratory of the U.S. National Oceanic and Atmospheric Administration. The observations have not been corrected for the errors that are inevitable in quick-look data derived from sunspot drawings. Furthermore, the definitions by which these observers applied the classification differ slightly from those enumerated above. For these reasons the data are not suitable for thorough analysis.

Some combinations of parameters are so rare that even one solar cycle does not provide sufficient statistics for study. The frequency of occurrence for each of the 17 parameters of the classification have been accumulated from Table III and displayed in Figure 2.

TABLE III

The frequency of occurrence of the 60 types of spot groups during 1969–1976

Year	Axx	Bxo	Bxi	Cro	Cri	Dro	Dri	Ero	Eri	Fro	Fri	Hrx
1969	525	318	81	76	38	21	8	4	1	0	1	61
1970	633	403	58	78	30	21	13	1	0	0	0	66
1971	400	293	44	74	31	17	8	0	1	0	0	26
1972	448	421	59	52	23	5	11	0	1	0	1	23
1973	164	143	23	39	9	7	3	1	0	0	0	13
1974	172	170	27	25	10	4	4	0	1	0	0	17
1975	96	99	21	14	3	0	3	0	0	0	0	3
1976	79	59	21	10	6	0	4	0	0	0	0	2
Totals	2517	1906	334	368	150	75	54	6	4	0	2	211
%	20.28	15.36	2.69	2.97	1.21	0.60	0.44	0.05	0.03	0.00	0.02	1.70

No penumbra = 38.3%. Rudimentary penumbra = 7.0%.

Year	Cso	Csi	Dso	Dsi	Dsc	Eso	Esi	Esc	Fso	Fsi	Fsc	Hsx
1969	55	56	110	56	2	8	25	9	3	3	0	340
1970	303	65	227	90	5	32	21	0	8	1	0	490
1971	168	15	101	37	6	12	11	0	0	2	0	393
1972	185	29	56	33	3	22	11	0	2	1	0	306
1973	44	13	15	8	0	1	1	0	0	0	0	100
1974	69	13	28	10	0	6	9	0	0	1	0	172
1975	49	7	12	6	0	1	0	0	0	0	0	73
1976	16	13	4	6	4	0	0	0	0	0	0	89
Totals	889	211	553	246	20	82	78	9	13	8	0	1963
%	7.16	1.70	4.46	1.98	0.16	0.66	0.63	0.07	0.10	0.06	0.00	15.82

Small symmetric penumbra = 32.8%.

Year	Cao	Cai	Dao	Dai	Dac	Eao	Eai	Eac	Fao	Fai	Fac	Hax
1969	55	60	57	82	5	14	27	4	0	3	0	69
1970	38	37	80	72	23	8	18	8	1	4	0	60
1971	28	13	54	36	3	11	7	0	0	0	0	23
1972	59	19	45	58	6	8	20	0	2	3	0	26
1973	19	16	21	41	2	5	7	1	0	2	0	29
1974	20	8	18	19	1	0	2	4	0	0	0	10
1975	8	7	12	7	6	0	0	0	0	0	0	3
1976	5	6	1	9	0	1	1	0	0	0	0	2
Totals	232	166	288	324	46	47	82	17	3	12	0	222
%	1.87	1.34	2.32	2.61	0.37	0.38	0.66	0.14	0.02	0.10	0.00	1.79

Small asymmetric penumbra = 11.6%. All small penumbra = 44.4%.

Table III (continued)

Year	Cho	Chi	Dho	Dhi	Dhc	Eho	Ehi	Ehc	Fho	Fhi	Fhc	Hhx
1969	10	8	4	17	2	1	4	2	4	0	4	23
1970	21	11	15	9	1	14	13	0	4	13	0	29
1971	32	2	12	6	2	12	14	2	0	2	1	38
1972	8	5	9	5	1	7	9	0	2	3	0	13
1973	9	2	2	2	0	2	3	0	0	0	0	6
1974	17	0	1	1	0	3	2	0	0	0	0	32
1975	6	1	0	1	0	0	0	0	0	0	0	7
1976	9	0	0	0	0	0	0	0	0	0	0	2
Totals	112	29	43	41	6	39	45	4	10	18	5	150
%	0.90	0.23	0.35	0.33	0.05	0.31	0.36	0.03	0.08	0.15	0.04	1.21

Large symmetric penumbra = 4.0%.

Year	Cko	Cki	Dko	Dki	Dkc	Eko	Eki	Ekc	Fko	Fki	Fkc	Hkx
1969	13	10	11	23	31	18	5	19	3	1	7	7
1970	10	6	13	17	14	13	23	17	11	9	5	12
1971	5	1	9	12	7	7	24	4	1	18	3	13
1972	11	4	3	9	12	11	16	19	3	11	5	1
1973	10	2	5	12	12	3	7	1	1	1	0	3
1974	3	4	2	9	9	0	2	3	0	1	7	0
1975	0	1	0	5	3	0	4	0	0	6	0	1
1976	0	0	0	1	12	0	0	0	0	0	0	1
Totals	52	28	43	88	100	52	81	63	19	47	27	38
%	0.42	0.23	0.35	0.71	0.81	0.42	0.65	0.51	0.15	0.38	0.22	0.31

Large asymmetric penumbra = 5.1%. All large penumbra = 92%.
Open distribution = 39%. Intermediate distribution = 17%. Compact distribution = 2.4%. Complex groups = *kc* = 1.5%.

Class A = 20.3%. Class D = 15.5%. Class H = 20.8%.
Class B = 18.0%. Class E = 4.9%.
Class C = 18.0%. Class F = 1.3%.

Most sunspot groups are small and of simple structure. Nearly 40% of groups do not have penumbra. A similar number are unipolar. Even within the largest Zurich class E, 30% of the groups have small spots and lack a complex group interior. On the other hand, the class C and D groups, while small on average, contain types with large, complex spots and compact interiors. Just over 10% of class C groups contain large spots, and only 3% have type-*k* spots. Fifteen percent of class D groups have type-*k* spots and/or compact interiors. The McIntosh classification, therefore, distinguishes the small and simple groups from the large and complex groups within each Zurich class, thereby giving an expectation of an improved correlation with solar flares.

More than half of class F groups have large-complex spots, but rudimentary penumbra is almost never present in such groups. The statistics of class H groups are dominated by spots with small, symmetric penumbra, partly due to an inherent frequency of formation, but largely due to the long lifetimes of these stable spots.

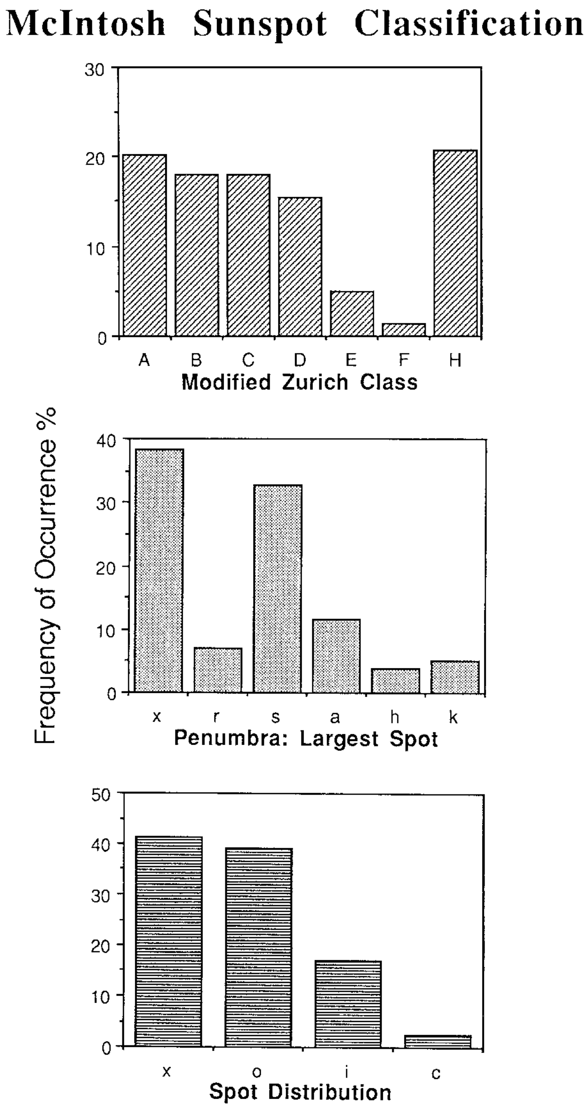

Fig. 2. Frequency of occurrence of the 17 categories within the McIntosh classification. Data from Kildahl (1980).

The most complex groups are those with k-spots and compact interiors. The kc-combination was only 1.5% of this 7-year sample, but included nearly as many class D groups as class E and class F. When group interiors are compact the groups are most likely to also have k-spots (60%). Groups with symmetric principle spots rarely are compact. Large principle spots, with areas in excess of 250 millionths solar hemisphere, represent 9.2% of this sample, which is consistent with 15% of groups having total areas at least this large (Newton, 1958).

3. Difficulties with Sunspot Observations

An awareness of frequent observing difficulties and how to cope with them will improve the consistency and utility of the sunspot observations. Any improvement in the synoptic database for solar active regions also allows better research from that database. Because much of that database now comes from the real-time patrol observatories, rather than from the research facilities, the patrol observatories should be aware of the need for care in making their reports.

3.1. Sunspot areas

The classification gives a proximate measure of the area of the sunspot group by the type of largest spot and whether the group is compact or not. Groups with principle spot '*k*' must have areas of at least 250×10^{-6} solar hemisphere, while single spots with only rudimentary penumbra have areas $20–30 \times 10^{-6}$. If the reported group area is less than 20×10^{-6}, and rudimentary penumbra is reported, perhaps the observer erred in assigning penumbra to groups of class A or B. If the reported area is less than 250×10^{-6}, but the reported class contained a '*k*' spot, there is either an error in the area or the classification. Over-reporting of '*k*' spots has occurred when observers used the east–west extent of the spots instead of the required north–south diameter.

The measurement of sunspot area by real-time patrol observatories is seldom done with high accuracy. Variations of 50% or more are common when comparing one observatory with another. Even when the sunspots are large and symmetric, differences among observatories are seldom less than 10% of the area. This is not surprizing in view of the continued reliance on sunspot drawings made with an image diameter of only 18 cm, and the low level of experience for observers in the patrol observatories. The McIntosh sunspot classification, through its quantitative and simple descriptions, provides improved consistency in estimating the size of groups.

3.2. Rudimentary penumbra

Rudimentary penumbra is difficult to discern consistently by visual means when the solar image diameter is as small as 18 cm, especially when observing conditions are *poor*. Yet, it is important to distinguish penumbra that is small and undeveloped from mature penumbra, as these differences indicate differences in the strength and orientation of the magnetic fields in sunspot groups. An observer who is experienced in viewing high-resolution images of sunspots is aware how easily scattered light can introduce grey areas among closely-spaced, small sunspots, giving an impression of the presence of penumbra when the image is small, or the observing conditions poor. With experience watching the evolution of sunspot groups, an observer can infer the presence of rudimentary penumbra by noting the appropriate stage of development of a group. Use of larger image size improves the distinction of rudimentary from mature penumbra by measurement of differences in the width of penumbra; the rudimentary penumbra does not exdeed 3 arc sec from the edge of the umbra.

3.3. Large asymmetric (k) spots

An examination of sunspot drawings during 1969 and 1978 showed that observers have been over-reporting type-k spots, partly due to systematically drawing spots too large, and partly through misunderstanding that the diameter of the penumbra is to be measured north–south. It is common for leader sunspots to elongate as they age, sometimes increasing the east–west dimension well beyond the 2.5° lower limit for type-k spots. Such elongation is usually correlated with a reduction in spot-group area and a decline in flare activity. By defining large spots by north–south diameter, the observer can measure these spots reliably even near the solar limb. Also, this will reduce the possibility of identifying a smaller spot as type-k.

A spot with north–south extent > 2.5° occurs in only 9% of the groups, yet 77% of class F groups have such spots. The appearance of a type-h or type-k spot at the east limb of the Sun, therefore, could indicate the presence of a truly important sunspot group. It is important, as Section 4 attests, to be accurate in the reporting of the type of principle spot that has the highest correlation with flares.

4. Correlations with Solar Flares

Data from the first year of regular use of the McIntosh classification (October 1966–September 1967) showed that flares of optical importance 2 or greater occurred with Zurich class F groups 40% of the days they were observed, while the more specific *Fkc*-type of group had a correlation at 60% (*Solar-Geophysical Data*, 1972). This was sufficient improvement for adoption of the new classification (I.U.W.D.S., 1969) in operational solar-terrestrial predictions. By that time the preferred measure of flare magnitude at N.O.A.A. was the peak intensity in the 1–8 Å band of X-rays (C, M, and X classification) (Baker, 1970; Simon and McIntosh, 1972). Kildahl (1980) tabulated X-flares detected with the SOLRAD and GOES spacecraft for each of the McIntosh sunspot types, using the real-time sunspot data reported by N.O.A.A. and U.S. Air Force observers in 1969–1976. His report simply listed the number of flares per sunspot type without distinguishing days when there were multiple flares. The flare 'probabilities' in this tables, therefore, are the ratio of the number of events to the frequency of sunspot type, not true 24-hour probabilities of flare occurrence.

These data are sufficient to illustrate the degree to which the McIntosh classification distinguishes active from inactive types of sunspot groups. The Kildahl data have been accumulated to produce the distribution of X-ray flares among the 17 parameters of the McIntosh classification, illustrated in Figure 3. We see what was has been noted before, that flares prefer the larger and more complex spot groups; but, we also see how the activity is very much lower in groups of small, widely-distributed spots. There is evidence here of a dependence on spot symmetry, in that the large but symmetric type-h spots were only one-fourth as active as asymmetric spots of equal size.

Tables IV, V, and VI present a sample of the most flare-active McIntosh types, again showing the correlation with large Zurich classes, and the prevalence of the 'k' and 'c' categories in flare-rich regions. Many flares were associated with the first three sunspot

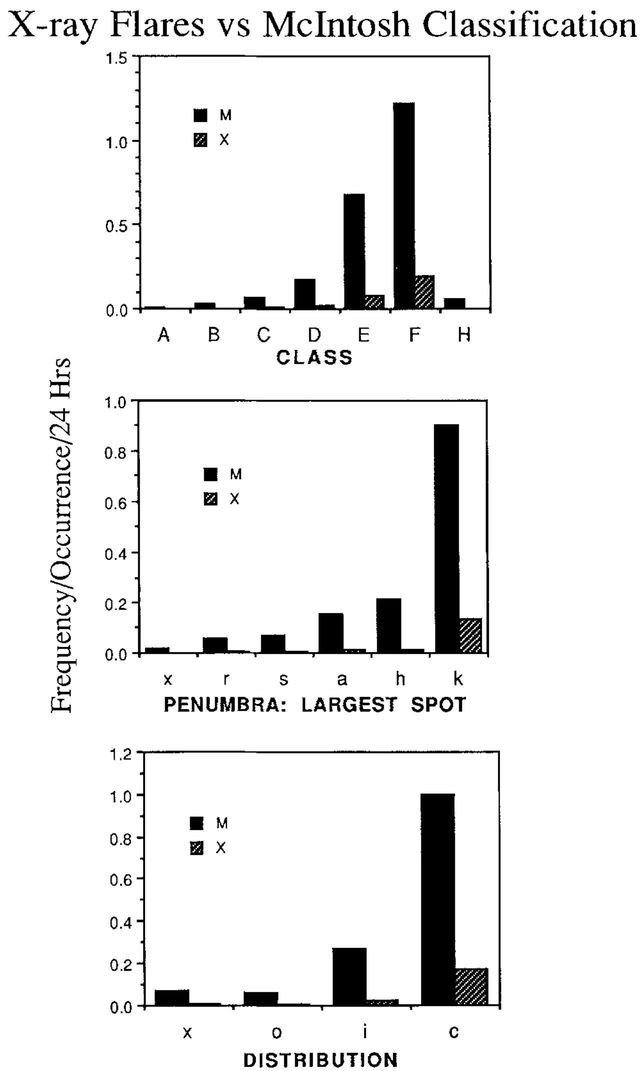

Fig. 3. Frequency of occurrence of X-ray solar flares among the 17 categories of the McIntosh classification. Data from Kildahl (1980).

types in Table IV only because these types are numerous, and slightly active. Table V shows the preponderance of sunspot types '*kc*' in those regions having the most extreme flare activity. The regions in Table V were ranked by their productivity of X-ray flares using an index which is the sum of the numerical multipliers of class M and X flares, divided by 10 (Gaizauskas and McIntosh, 1986). The most flare-productive regions since 1972, listed in Table VI, include F*kc* groups almost exclusively, and some of these were among the largest groups that appeared in the past three solar cycles. Note, however, that the fourth region in Table VI was class D with an area of 500 millionths, suggesting that spot characteristics other than size are also important in the relationship

TABLE IV

Most flare-productive sunspot types 1969–1976 (from Kildahl, 1980)

McIntosh type	Number of occurrences	Number of class M flares	Number of class X flares	Flares/occurrence per 24 hours	
				M	X
H*sx*	1963	99	6	0.05	0.003
D*so*	553	51	6	0.09	0.01
D*ai*	324	58	7	0.18	0.02
D*kc*	100	72	10	0.72	0.10
E*ki*	81	103	11	1.27	0.14
E*kc*	63	149	21	2.36	0.33
F*ki*	47	106	17	2.26	0.36
F*kc*	27	39	13	1.44	0.48

TABLE V

Outstanding X-ray flaring sunspot groups from solar cycle No. 21: top 5 active regions each year

Year	Date	NOAA/SESC region No.	Sunspot region at maximum		X-ray flare index
			Type	Area	
1977	14 Apr.	807	D*ai*	370	1.2
	11 Sep.	889	E*kc*	920	6.9
	6 Oct.	899	E*ao*	270	1.2
	6 Oct.	908	D*ac*	450	1.3
	9 Dec.	950	F*ki*	550	1.6
1978	29 Apr.	1092	E*kc*	1280	12.6
	29 Apr.	1095	E*ai*	450	4.6
	11 July	1203	E*kc*	1370	29.7
	12 Dec.	1447	D*kc*	1100	8.3
	16 Dec.	1444	E*kc*	1050	4.3
1979	20 Feb.	1574	E*kc*	1100	9.2
	25 Mar.	1638	E*ai*	480	5.9
	22 Aug.	1943	F*kc*	1340	13.5
	17 Sep.	1994	F*kc*	1180	16.6
	7 Nov.	2099	E*kc*	1720	9.2

with solar flares. This smaller region appeared 6 months after, and at the same heliographic coordinates as the region ranked No. 2. This 'coincidence' would suggest adding large-scale structures (McIntosh and Wilson, 1985) and previous histories of 'active longitudes' to the list of flare precursors.

Class D groups appear in both Tables IV and V, and we see from Figure 2 that class D groups are several times more numerous than classes E and F. The database for 1969–1976, therefore, contains sufficient examples of class D groups with flare activity

TABLE VI

Strongest active regions of record[a]

Rank	Carrington rotation	CMP date	Latitude	Heliographic longitude	NOAA/SESC region No.	Sunspot region at maximum: Type	Area	Date	X-ray flare index
1	1813	12 Mar., 1989	N 34	257	5395	F*kc*	3500	15 Mar.	57.0
2	1722	8 June, 1982	S 08	086	3763	F*kc*	1270	4 June	42.4
3	1616	3 July, 1974	S 14	159	0433	F*kc*	1400	4 July	≥41.4
4	1729	15 Dec., 1982	S 06	089	4025	D*ki*	0500	15 Dec.	36.7
5	1724	15 July, 1982	N 14	322	3804	F*kc*	3000	12 July	31.6
6	1670	14 July, 1978	N 18	169	1203	E*kc*	1370	11 July	29.7
7	1818	8 Aug., 1989	S 17	076	5629	E*kc*	1320	9 Aug.	≥26.8
8	1590	4 Aug., 1972	N 12	009	0331	F*kc*	1140	4 Aug.	≥26
9	1701	11 Nov., 1980	S 11	098	2779	F*kc*	2300	11 Nov.	25.9
10	1811	12 Jan., 1989	S 31	306	5312	F*kc*	1800	15 Jan.	22.4
11	1748	28 Apr., 1984	S 13	344	4474	F*kc*	2590	27 Apr.	21.2
12	1723	18 June, 1982	N 13	312	3776	F*kc*	3300	14 June	18.8
13	1749	24 May, 1984	S 10	357	4492	F*ai*	0750	21 May	18.4

[a] From August, 1972 to August 18, 1989.

to examine the distribution of flares among the 14 sunspot types within a single class, shown in Figure 4. These data demonstrate that the McIntosh classification effectively separates inactive from active sunspot groups within a single Zurich class. Probabilities of class M flare range from less than 10% to over 50% within this class, keeping in mind that this database does not distinguish regions which produce multiple flares within a 24-hour period. Note that there are equally-low flare occurrences in the small D*ro* and

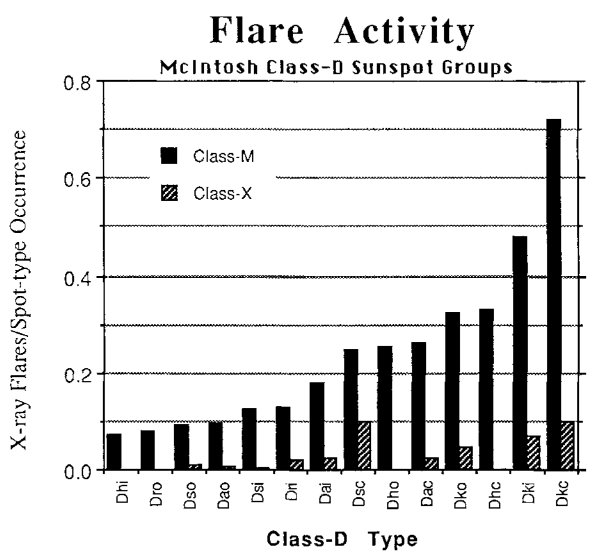

Fig. 4. Distribution of X-ray flare occurrence among the 14 types within McIntosh class D. Data from Kildahl (1980).

large D*hi* types of groups, again suggesting the association of stable, symmetric spots with low flare activity, in spite of their size.

The Kildahl data show a similar distribution of flares among the class E and F groups, but the rarity of some types within these classes makes analysis futile with this limited database. It is sufficient to note that the rate of occurrences of large asymmetric spots and compact distributions go up in these classes and, with them, the flare activity.

5. Expert System Theo

Expert systems are computer programs designed to capture the knowledge and expertise of a human expert in solving very specific problems. A project to demonstrate whether expert systems were useful in solar-terrestrial predictions was begun in the summer of 1985 in cooperation between N.O.A.A. Space Environment Laboratory and the University of Colorado departments of Computer Sciences and Psychology. The McIntosh classification of sunspots was selected as the principle knowledge base because it already encoded knowledge of sunspot-flare relationships, and an extensive database of correlations between flares and the classification already existed. Additional prediction rules were derived by a 'knowledge engineer' interviewing the author to formalize more of his knowledge and experience pertaining to flare forecasting. The additional rules included dynamical properties of spot growth, rotation and shear, and magnetic-field topology inferred from sunspot structure. Previous flare activity and simple magnetic-field classes were also considered. The resulting system was named Theo, after Theophrastus, a disciple of Aristotle who is reputed to be the first European to record a sunspot observation.

The statistical work quoted above provided the framework for assigning 24-hour probabilities for X-ray flares, but the actual assignments were based on subjective judgments because forecast decision rules, which had not been evaluated statistically, were added to the McIntosh classification. The 500 + decision rules included both established spot-flare relationships and the experiential 'rules of thumb' provided by the human expert.

The program's user interface was designed to lead a novice forecaster through an evaluation of each individual sunspot group, using both the standard synoptic sunspot reports and sunspot images. Theo produces a flare prediction for each group, and then assesses which of the groups are close enough to each other to influence flare activity, and concludes with a whole-Sun forecast for the next 24 hours for the three categories of X-ray flares.

Sunspot and flare data for 3 months in 1978 were used by the expert and, independently, by a novice forecaster operating Theo to produce flare predictions. Theo equalled the performance of the expert, and exceeded the performance of the Space Environment Services Center for this period (Lewis and Dennett, 1986). An additional testing period with a different novice produced performance at least as good; therefore, Theo was adopted in 1987 as an operational tool in the daily operations of the Space Environment Services Center.

Theo's success can be attributed, in part, to the ability of the McIntosh sunspot classification to distinguish between active and inactive types of sunspots. A large part of that success is simply the consistent and thorough application of rules for decision making, and the ability of the expert system to give users equivalent expertise.

6. Discussion

The McIntosh revised sunspot classification system has been adopted by the existing synoptic patrol observatories, assuring that every sunspot group is evaluated for flare potential on every day, quickly and consistently. This knowledge is represented in a concise code that is rapidly communicated to a forecast center, where forecast decisions are made consistently with the aid of an expert system. This situation has made the McIntosh sunspot classification a fundamental datum for flare forecasting.

There are many solar observations which, according to current theories concerning the flare process, could provide more information on the physics of the flare-buildup and energy release; but, few of these observations are yet available on a synoptic basis, or processed on the schedule required for real-time prediction services. Most observations are required for a period of at least a solar cycle and for all active regions, before useful probabilistic forecasts can be developed from them.

The statistics reported here are not yet adequate to fully evaluate the ability of this classification to aid flare forecasts. The 24-hour frequency of each of the 60 types must be compared with the number of 24-hour periods in which flares occurred, not just with the count of flares. Some of the McIntosh sunspot types are so rare that a much longer period of data, perhaps three complete solar cycles, should be studied in order to obtain significance in the correlations. Perhaps the frequency of sunspot types changes with the solar cycle and from one cycle to another. A definitive study should use photographic data, which can be examined to verify the sunspot classifications.

The search for reliable precursors to flares from data gathered by orbiting and ground-based solar observatories has not yielded results of use to forecasters (Gaizauskas, 1989). Instead, Gaizauskas concludes that there are a variety of preflare conditions, almost always involving a 'global' context between the flare site and other parts of the active region, and/or the large-scale environment surrounding the active region. This interpretation of the observations would discourage sole dependence on the morphology of the sunspot group for making a flare prediction. McIntosh (1979, 1981) has recorded numerous examples associating specific sunspot groups with the morphology and evolution of nearby patterns of large-scale magnetic fields, implying that the convergence, shear, and vorticity in the large-scale solar circulation influence the birth and development of flaring regions. The classification of sunspot groups, therefore, is but a foundation for flare predictions. Those predictions will often fail until the prediction scheme(s) are expanded to include the long-term and large-scale aspects of solar activity.

Acknowledgements

The McIntosh sunspot classification has been in use for over two decades, allowing this paper to benefit from comments by the many observers and forecasters in the N.O.A.A./U.S. Air Force space environment services. Review of this paper has been particularly helpful from Patricia Bornmann, Harold Leinbach, Ron Zwickl, and an unidentified referee.

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