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Sunspot Group Decay

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Abstract We examine daily records of sunspot group areas (measured in millionths of a solar hemisphere or μHem) for the last 130 years to determine the rate of decay of sunspot group areas. We exclude observations of groups when they are more than 60° in longitude from the central meridian and only include data when at least three days of observations are available following the date of maximum area for a group's disk passage. This leaves data for over 18 000 measurements of sunspot group decay. We find that the decay rate increases linearly from 28 μHem day^{-1} to about 140 μHem day^{-1} for groups with areas increasing from 35 μHem to 1000 μHem. The decay rate tends to level off for groups with areas larger than 1000 μHem. This behavior is very similar to the increase in the number of sunspots per group as the area of the group increases. Calculating the decay rate per individual sunspot gives a decay rate of about 3.65 μHem day^{-1} with little dependence upon the area of the group. This suggests that sunspots decay by a Fickian diffusion process with a diffusion coefficient of about 10 km^2 s^{-1}. Although the 18 000 decay rate measurements are lognormally distributed, this can be attributed to the lognormal distribution of sunspot group areas and the linear relationship between area and decay rate for the vast majority of groups. We find weak evidence for variations in decay rates from one solar cycle to another and for different phases of each sunspot cycle. However, the strongest evidence for variations is with latitude and the variations with cycle and phase of each cycle can be attributed to this variation. High latitude spots tend to decay faster than low latitude spots.

Keywords Sun: sunspots · Sun: active regions

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1. Introduction

Sunspot groups are a key photometric component of active regions. These are the centers of solar activity ranging from compact flares to many of the large-scale coronal mass ejections. They are believed to be the locations where magnetic flux bundles erupt from below the photosphere due to magnetic buoyancy. Sunspot groups within active regions emerge on a time scale of hours to days and survive for days to weeks. Since the size and complexity of sunspot groups play significant roles in determining how active the regions are (Zirin, 1988), it is useful to investigate how the sunspot groups themselves decay. Furthermore, the processes that lead to the formation and decay of active regions are fundamental to flux transport models for the surface magnetic field (DeVore, Sheeley, and Boris, 1984; Schrijver, 2001; Wang, Lean, and Sheeley, 2002) and the growth and decay of sunspot groups play key roles in irradiance variations (Willson *et al.*, 1981).

Sunspots would have lifetimes of about 300 years (considering their size and the photospheric conductivity) if their decay were purely by ohmic dissipation (Cowling, 1946). On the other hand, their dynamical time scale, which is the time taken for Alfvén or magneto-acoustic waves to cross the region, is only about an hour. Further, Parker (1975) suggested that sunspots are intrinsically unstable due to an interchange or fluting instability (caused by magnetic tension in the field which fans out with height as the surrounding pressure decreases) and should decay on that instability timescale. However, for sufficiently large magnetic flux concentrations the added buoyancy can counteract this instability (Meyer, Schmidt, and Weiss, 1977). Consequently, several alternative mechanisms have been suggested to play significant roles in sunspot decay. These mechanisms include turbulent diffusion (Krause and Rüdiger, 1975), turbulent erosion (Petrovay and van Driel-Gesztelyi, 1997), and submergence (Howard, 1992a; Kálmán, 2001).

A sunspot group typically consists of one or more compact spots of one magnetic polarity leading (in the direction of solar rotation) a more scattered group of smaller spots with the opposite polarity. This configuration is believed to be a direct consequence of the effect of the Coriolis force on the rising magnetic flux bundle (Fan, Fisher, and DeLuca, 1993; Fan, Fisher, and McClymont, 1994). The decay of these two types of spots (leading and following) is seen to be different (Bumba, 1963; Martínez Pillet, 2002). The numerous, small following spots tend to decay quickly while the single isolated leader spot decays more slowly. The decay of a sunspot group itself is some combination of these two. Bumba (1963) also noted distinct differences between the decay of recurrent spot groups (long-lived regions that are seen on successive solar rotations) and non-recurrent spot groups. The long-lived regions exhibited significantly smaller decay rates.

One of the important questions regarding the decay of sunspot groups concerns the relationship between decay rate and area. Bumba suggested that there are two different decay rates – a slow one for large stable spots and a fast one for small spots – both independent of area. A decay rate independent of area would indicate a diffusion process (Krause and Rüdiger, 1975; Stix, 2002) in which the diffusion would work to remove flux over the entire spot area. In more recent studies the decay rates were found to depend on the size but with different functional forms. Moreno-Insertis and Vázquez (1988) and Petrovay and van Driel-Gesztelyi (1997) find decay rates that vary like the square-root of the area which suggests erosion from the edges of the spots. On the other hand Howard (1992b) and Chapman *et al.* (2003) find rates that are directly proportional to the area. In this paper, we revisit this problem of sunspot decay by analyzing two large databases of daily sunspot group observations.

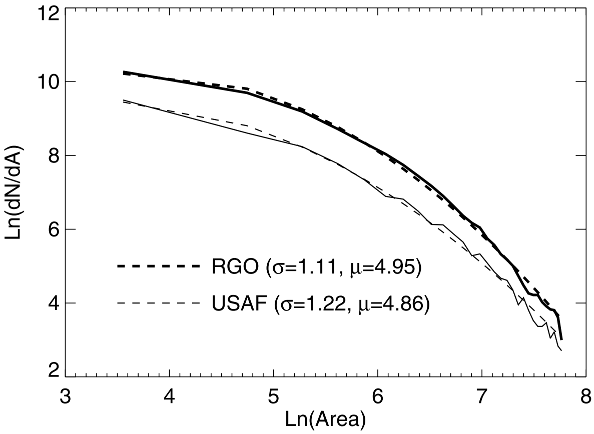


Figure 1 Sunspot group area size distributions for data from the Royal Greenwich Observatory (RGO – thick lines) and the U.S. Air Force (USAF – thin lines). The distributions are well fit with similar lognormal distributions (dashed lines – parabolic in log-log plots) but with a slightly wider distribution for the USAF data.

2. Data and Sunspot Group Selection

The Royal Greenwich Observatory (RGO) compiled observations of sunspot group positions and areas daily from 1874 to 1976. Measurements of area, position, and region type were made from photoheliographic plates taken at Greenwich and sister observatories in: Cape Town, South Africa; Kodaikanal, India; and Mauritius. The electronic version of the data contains entries for each active region observed on each day. The United States Air Force (USAF) has compiled similar data from 1977 to the present. The USAF makes measurements off of sunspot drawings from a network of observatories that has included telescopes in: Boulder, Colorado; Holloman, New Mexico; Kandilli, Turkey; Learmonth, Australia; Manila, The Philippines; Palehua, Hawaii; Ramey, Puerto Rico; and San Vito, Italy. Unfortunately, the method used to measure sunspot areas differs between these two sources. While the methods should be equivalent, intercomparisons with other datasets (*e.g.*, International Sunspot Number, Mount Wilson white light plates) indicate that the USAF areas are some 30% smaller than equivalent RGO areas (Fligge and Solanki, 1997; Hathaway, Wilson, and Reichmann, 2002). Increasing the USAF areas by a multiplicative factor of 1.4 helps to bring the two datasets into agreement but still leaves some differences. Figure 1 shows the distributions of sunspot group areas for these two datasets (with the 1.4× correction applied to the USAF data). This shows that the distributions of sunspot group areas are well fit by lognormal distributions (Bogdan *et al.*, 1988) for both data sets with

$$\frac{\mathrm{d}N}{\mathrm{d}A} = N_0 \frac{1}{A\sigma\sqrt{2\pi}} \mathrm{e}^{-(\ln A-\mu)^2/2\sigma^2}, \tag{1}$$

where $\mathrm{d}N$ is the number of groups in a range of areas $\mathrm{d}A$ about an area A. N_0 is the total number of groups, σ is the width of the distribution, and μ is the natural logarithm of the median area for the distribution. (Lognormal distributions are also obtained for the maximum area measured for each active region and for the initial area measured for regions born on the visible disk.) The offsets between the two curves simply reflects the different number of observations and is of no particular significance. However, the widths of the distributions are slightly, but significantly, different with the USAF distribution being wider with relatively more large area regions.

We have sorted these data to extract sunspot group histories – the daily total sunspot area (corrected for projection effects) for the disk passage of each sunspot group. Since the

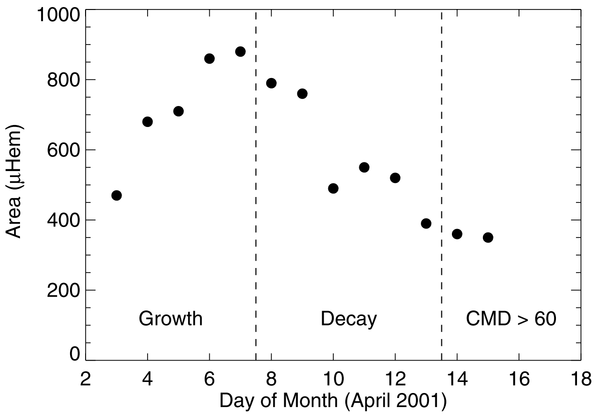


Figure 2 Sunspot group area measurements for NOAA AR 9415. The filled circles represent the daily measurements of the sunspot group area corrected for projection effects. The vertical dashed lines set off the different segments (growth, decay, and CMD $> 60°$) of the active region history. Our selection criteria yield two measurements of the decay rate for this sunspot group at two different values of its area.

sunspot area corrections are large for observation near the limb, we only include observations for spot groups with a central meridian distance (CMD) within 60° of longitude from the central meridian. We also exclude groups with corrected areas less than 35 millionths of a solar hemisphere (μHem). The projected sizes of these smaller spots place them near the limit of spatial resolution thus making the area measurements more uncertain. (These same restrictions were used in compiling the distributions of areas shown in Figure 1.)

Our primary interest is in the decay rate of sunspot groups. For each sunspot group history we determine when the group reaches its maximum size. We then include only those observations that follow the time of maximum and further limit the data to those with at least three consecutive days of monotonically declining area following the maximum. The decay rate, Γ, for day n when the group has area A is then determined by finding the difference in the area between the day before and the day after such that

$$\Gamma\big(A(n)\big) = \big[A(n-1) - A(n+1)\big]/2\ \mu\text{Hem}\,\text{day}^{-1}. \tag{2}$$

These selection criteria eliminate many groups that are either too small or reach maximum size too late in their disk passage. On the other hand, the criteria often include multiple decay rate measurements for a single group.

An example of the measurement of a decaying sunspot group (NOAA AR9415) is shown in Figure 2 to illustrate the process. For this particular group we obtain two measurements of the decay rate: 150 μHem day^{-1} at an area of 760 μHem on 9th April and 80 μHem day^{-1} at an area of 520 μHem on 12th April. The measurements centered on 10th April and 11th April are not included because the areas are not monotonically declining on those dates. Data prior to 8th April are excluded because they come before the decay phase starts. Data after 13th April are excluded because they are obtained at central meridian distances greater than 60°.

3. Decay Rate Behavior

We obtain over 14 000 measurements of sunspot group decay rates using the RGO data from 1874 to 1976 and nearly 4000 measurements using the USAF data. We bin the measurements according to area with 31 bins 80 μHem wide from 35 to 2435 μHem. The distributions of measurements for the full set of data and for the first four area bins are shown in Figure 3.

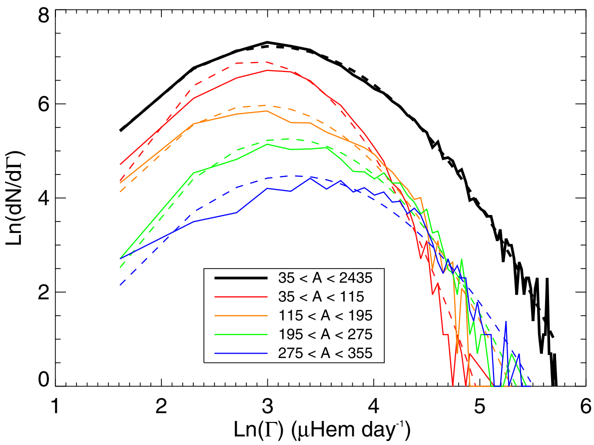


Figure 3 Distribution of decay rates for sunspot groups with areas between 35 and 2435 μHem (solid black line). The distribution is very well fit by a lognormal distribution (dashed black line). The distributions of decay rates for groups binned by group area (solid colored lines) are not as well fit with lognormal distributions (dashed colored lines).

The full distribution is very well fit with a lognormal distribution. This fact was noted earlier by Martínez Pillet, Moreno-Insertis, and Vázquez (1990) and by Martínez Pillet, Moreno-Insertis, and Vázquez (1993). However, the measurements for the individual area bins are not as well fit with lognormal distributions. These individual distributions tend to be flatter at small decay rates and steeper at large decay rates. The mean decay rates are well defined regardless of the shape of the distribution. This is born out by the fact that the mean calculated from the lognormal fits are virtually identical to the those calculated by simply averaging the decay rate measurements in an area bin. However, the error in the mean is more problematic. The individual decay rate distributions are neither normally nor lognormally distributed (a sampling linear in area gives a distribution skewed toward large decay rates while a sampling logarithmic in area gives a distribution skewed toward small decay rates). We choose to present the errors in the means as two standard deviations divided by the square root of the number of measurements.

The average decay rates and their errors for each of the 31 sunspot area bins are shown in Figure 4. The decay rates increase linearly with region area up to about 1000 μHem with

$$\Gamma(A) = 24 + 0.116A \ \mu\text{Hem}\,\text{day}^{-1}. \tag{3}$$

Howard (1992b) found a similar relation for the decay of umbral areas as seen in the digitized Mount Wilson white light plate collection – the decay rate was a percentage of the group area and that percentage was nearly independent of area. Here we find in addition that the largest regions have decay rates that tend to fall below this linear relationship.

The source of this drop-off for the largest groups may be related to the drop-off in the linear relationship between the number of individual spots in a group and the group area. The USAF Region Summaries include entries for the number of individual spots in each group (this information is not contained in the RGO data). The average number of individual sunspots per group as a function of the area of the group is also plotted in Figure 4. The striking resemblance between the two suggests that the decay rate per sunspot in each group is independent of the total area of the group.

In Figure 5 we plot the ratio of the mean decay rate to the mean number of sunspots for our measurements in each of the group area bins. This ratio is a nearly constant 3.65 μHem day^{-1} with little evidence for any variation with the total group area except for the smallest groups. The smallest groups, those with areas between 35 and 115 μHem, have significantly higher decay rates per sunspot than groups with larger total area. Note that

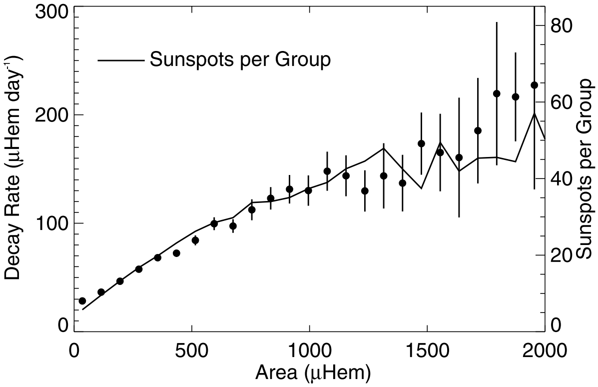
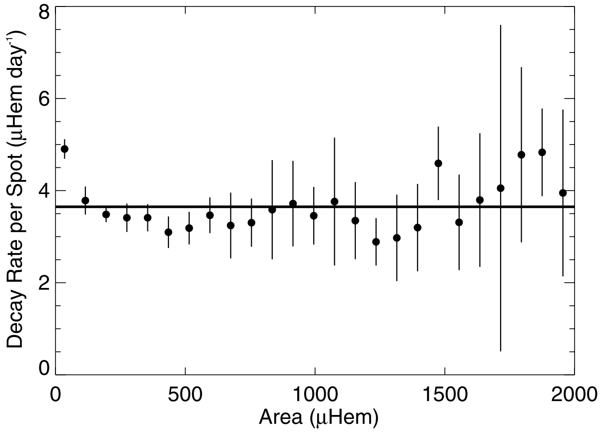


Figure 4 The decay rate of sunspot group area (dots with error bars) as a function of area itself. The decay rates increase linearly with area up to areas of about 1000 µHem. The largest groups (> 1000 µHem) have decay rates that fall somewhat below this linear relationship. The solid line shows the average number of sunspots per group as a function of area on the scale given on the right. The similarity in behavior for these two quantities suggests a constant decay rate for each individual sunspot with the number of sunspots in each group adding to the decay rate for the group itself.

Figure 5 The ratio of the mean decay rate to the mean number of sunspots (dots with error bars) as a function of the total group area. The decay rates per sunspot are a nearly constant 3.65 µHem day^{-1} for groups of all sizes except the very smallest.



this average decay rate per sunspot is very similar to the 4.2 µHem day^{-1} found by Bumba (1963) for recurring groups (which often consist of a single spot).

We have examined the decay rate per sunspot for each of the sunspot cycles covered by the data – cycles 12 through 23. Without exception we find similar behavior – a constant decay rate per spot but with significantly higher decay rates per spot for the smallest groups. Figure 6 shows the average decay rate per sunspot for each cycle. While a constant value of 3.65 µHem day^{-1} passes through nearly all of the error bars, we do find some interesting variations. There are significant differences between the RGO data and the USAF data with significantly larger decay rates in the USAF data. Through the RGO data there also appears to be a variation with the size of the cycle. The smaller cycles (cycles 12 through 16 and 20) have lower decay rates than the larger cycles (cycles 17 through 19). Moreno-Insertis and Vázquez (1988) found little evidence for significant variations in the decay rate for cycles 12

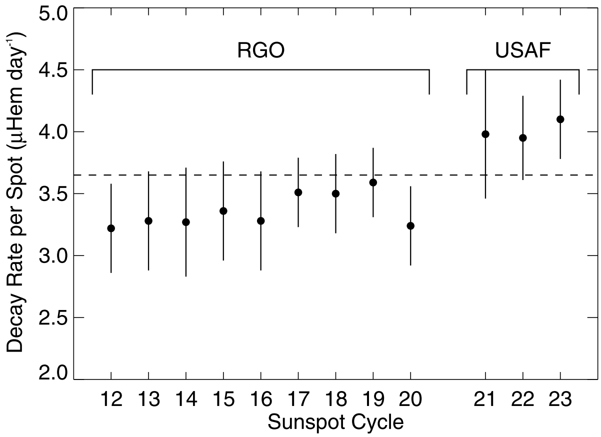


Figure 6 The mean decay rate per sunspot (dots with error bars) as a function of sunspot cycle number. The full data set mean of 3.65 μHem day^{-1} (dashed line) passes through nearly all error bars but reveals some indication of systematic variations. The decay rates for the USAF data appear to be higher than those for the RGO data. Within the RGO data the smaller cycles (12 – 16 and 20) have smaller decay rates than the larger cycles (17 – 19).

through 16 (the only cycles they examined). Martínez Pillet, Moreno-Insertis, and Vázquez (1993) drew a similar conclusion from their analysis of the full RGO dataset.

We have also separated the data by sunspot cycle phase and sunspot group latitude. In one pairing we examine the minimum and maximum phases in which the data are separated at the midpoint in time between adjacent minima and maxima. This pairing gives a large sample from the maximum phase and a much smaller sample from the minimum phase. In another pairing we examine the rising and falling phases. The rising phases begin with the appearance of the first new cycle spots at high latitudes prior to the time of sunspot cycle minimum and end at smoothed sunspot cycle maximum. Likewise, the falling phases begin at the time of smoothed sunspot cycle maximum and ends with the last appearance of old cycle spots near the equator after the next cycle minimum. This second pairing gives two sample of nearly equal size. The final pairing is for “high” latitude groups (latitudes greater than 15°) and “low” latitude groups (latitudes less than or equal to 15°).

Figure 7 shows the decay rate per sunspot for these different phases of the solar activity cycle and different latitudes. The maximum phase has a slightly higher decay rate than the minimum phase. The rising phase has a higher decay rate than the falling phase with a somewhat larger difference than between maximum and minimum phases. The biggest difference in decay rate is between high and low latitudes. High latitude spots decay more rapidly than low latitude spots. (This latitude dependence was noted earlier by both Howard (1992b) and Lustig and Wöhl (1995).) This suggests that the latitude dependence is the source of the cycle phase variations – there are more high latitude spots during the rising and maximum phases of each cycle. The latitude dependence may also be the source of the cycle-to-cycle variations seen in Figure 6 – large cycles tend to have more high latitude spots than small cycles.

4. Discussion

We find that the decay rate for the area of sunspot groups increases linearly with area for groups with areas from 35 to about 1000 μHem. Similar behavior was also noted in several previous studies (Bumba, 1963; Moreno-Insertis and Vázquez, 1988; Howard, 1992b; Chapman *et al.*, 2003). The decay rates for groups with areas larger than about 1000 μHem fall below this linear relationship in much the same manner as the fall off in the linear relationship between the number of sunspots in a group with the group area. We find that

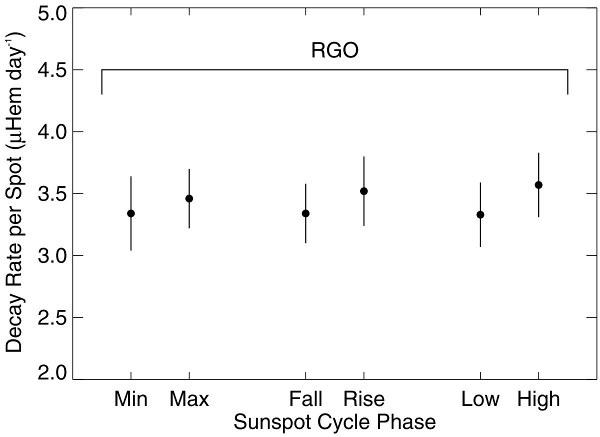


Figure 7 The mean decay rate per sunspot (dots with error bars) for different phases of the sunspot cycle and for high and low latitude groups. The higher decay rates for high latitude groups may be the source of the cycle phase and cycle-to-cycle variations in decay rate.

the ratio of the average decay rate to the average number of spots in a group is nearly independent of the group area. This suggests that each individual sunspot decays at a rate that is, on average, independent of the area of the spot. This average decay rate per spot of 3.65 μHem day^{-1} is similar to the 4.2 μHem day^{-1} found by Bumba (1963) for the late phase in the decay of recurrent sunspot groups when the group usually consists of a single regular spot.

The constant decay rate per spot suggests a purely diffusive process (Krause and Rüdiger, 1975; Stix, 2002) for the decay. The decay rate for normal "Fickian" diffusion of a passive scalar quantity is independent of area. Consider the diffusion in two dimensions of a point source. The concentration, $C(r,t)$, is governed by the diffusion equation

$$\frac{\partial C}{\partial t} = \eta \nabla_{\mathrm{H}}^2 C = \frac{\eta}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right), \tag{4}$$

where η is the diffusivity and r is the radial distance from the origin of the point source. Starting with a delta function source of intensity F, the concentration is given by

$$C(r,t) = \frac{F}{4\pi\eta t}\exp\left(-\frac{r^2}{4\eta t}\right). \tag{5}$$

If we chose a concentration level, C_0, the circle containing higher concentration levels grows and then decays. The area contained within its boundary is given by

$$A(t) = -4\pi\eta t \ln\left(4\pi t\eta\frac{C_0}{F}\right). \tag{6}$$

During the decay phase the decay rate becomes

$$\Gamma = -4\pi\eta \tag{7}$$

a rate that is independent of area. The decay rate of 3.65 μHem day^{-1} indicates a diffusivity of about 10 km^2 s^{-1} for sunspots. Not surprisingly, Krause and Rüdiger (1975) arrived at a similar value using the Bumba (1963) results. This diffusivity is much smaller than the 200–600 km^2 s^{-1} used in flux transport models (DeVore, Sheeley, and Boris, 1984; Schrijver, 2001; Wang, Lean, and Sheeley, 2002). The larger diffusivity is appropriate for the transport of magnetic elements by evolving supergranules. The small diffusivity for sunspots themselves indicates that significantly weaker motions govern the decay of sunspots.

Moreno-Insertis and Vázquez (1988) studied active region decay using the RGO data from 1874 to 1939. They tested different functional forms for the decay phase by fitting an exponential, a quadratic, and a linear decrease in area with time for the disk passage of decaying active regions. They also limited the data to observations within 60° of the central meridian and to spots with areas > 35 μHem. In addition they limited their analysis to those regions with five or more daily observations within these limits. They found an average decay rate for all groups of about 27.8 μHem day^{-1} which agrees with the results for our smallest area bin (which contains nearly half of the measurements).

Martínez Pillet, Moreno-Insertis, and Vázquez (1993) measured active region decay rates using the full RGO dataset from 1874 to 1976 and concluded that the decay rates are distributed lognormally. We find that this is true for the full set of sunspot group decay rates but can be attributed to the lognormal distribution of group areas (Figure 1) and the linear relationship between decay rate and area (Figure 4). When the decay rate measurements are binned according to the instantaneous area of the group the decay rate distributions are not well fit by either lognormal or normal distributions. These skewed distributions do not alter calculations of the mean decay rates that are used in this study.

We do find some evidence for variations in the decay rate per sunspot with the latitude of the sunspot groups and suggest that this variation is responsible for the variations seen over the phase of each cycle and from cycle-to-cycle.

Finally, we note that there remain significant differences between the RGO and USAF data sets that are not diminished by simply multiplying the USAF areas by a factor of 1.4. The distributions of group areas are different (Figure 1) and the measurements of decay rate per sunspot are different (Figure 6). Removing this correction factor completely still leaves the USAF data with a broader lognormal distribution of group areas and significantly higher decay rates per sunspot.

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