A NEW DETERMINATION OF THE SOLAR ROTATION RATE

N. R. SHEELEY, JR., Y.-M. WANG, AND A. G. NASH1,2

Code 4172, E. O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000

Received 1992 April 29; accepted 1992 June 6

ABSTRACT

We use "stackplot" displays to compare observations of the photospheric magnetic field during sunspot cycle 21 with simulations based on the flux-transport model. Adopting nominal rates of diffusion, differential rotation, and meridional flow, we obtain slanted patterns similar to those of the observed field, even when the sources of flux are assigned random longitudes in the model. At low latitudes, the slopes of the nearly vertical patterns of simulated field are sensitive to the rotation rate used in the calculation, and insensitive to the rates of diffusion and flow during much of the sunspot cycle. Good agreement between the observed and simulated patterns requires a synodic equatorial rotation period of $26.75 \pm 0.05$ days, which is within the limits obtained by Komm et al., but significantly less than the traditional 26.90 day value of Snodgrass and Newton & Nunn. Below 55° latitude, we obtain the synodic rotation rate $\omega(\theta) = 13.46 - 2.7 \cos^2 \theta + 1.2 \cos^4 \theta - 3.2 \cos^6 \theta$ deg day$^{-1}$, where $\theta$ is colatitude.

Subject headings: Sun: magnetic fields — Sun: rotation

1. INTRODUCTION

Synoptic observations of the Sun's photospheric magnetic field have been obtained over the past 40 yr, and now span more than three sunspot cycles. As these measurements have accumulated, a variety of methods have been devised to display them. The displays include "Carrington maps" of the field plotted as a function of latitude and longitude (or time) during a ~27.3 day Carrington rotation, "butterfly diagrams" of the longitudinal averaged field (Howard & LaBonte 1981; Wang, Nash, & Sheeley 1989a) or of the unaveraged field in highly compressed format (Ulrich 1990) plotted as a function of latitude and time, and "stackplots" of the field at a given latitude plotted as a function of Carrington longitude and time during the sunspot cycle (Bumba & Howard 1969; Stepanyan 1982; Gaizauskas et al. 1983; McIntosh, Willock, & Thompson 1991). In this paper, we shall use stackplots to analyze the fields during sunspot cycle 21.

At a given latitude, a stackplot shows the longitudinal structure of the field as a function of time. Also, when the evolving patterns are not dominated by the field's axisymmetric component, they provide a graphical measure of its phase velocity. Thus, the striking array of slanted patterns in McIntosh et al.'s (1991) Atlas of Stackplots ought to indicate phase velocities consistent with those previously obtained by the cross-correlation and autocorrelation of synoptic maps (cf. Wilcox & Howard 1970; Wilcox et al. 1970; Schatten et al. 1972; Stefano 1974, 1977). Furthermore, based on the agreement between the phase velocities obtained for the observed field and the field simulated with the flux-transport model (Sheeley, Nash, & Wang 1987; Wang, Nash, & Sheeley 1989b), we would expect to obtain such slanted patterns in stackplots of the simulated field. Thus an objective of this study was to construct such stackplots and see if they agreed with those of the observed field.

As described in detail elsewhere (Leighton 1964; Sheeley, DeVore, & Boris 1985; Wang et al. 1989b), the model is based on the assumption that flux originates in bipolar magnetic regions and is subsequently redistributed over the Sun's surface by a combination of supergranular diffusion, differential rotation, and poleward meridional flow. The best fit to date (Wang et al. 1989b) uses a source term based on estimates of flux in observed bipolar magnetic regions, an effective diffusion term of 600 km$^2$ s$^{-1}$, a latitude-dependent poleward meridional flow term of 10 m s$^{-1}$ maximum speed, and the Snodgrass (1983) synodic differential rotation rate

$$\omega(\theta) = 13.38 - 2.30 \cos^2 \theta - 1.62 \cos^4 \theta \text{ deg day}^{-1},$$

where $\theta$ is colatitude. As we shall see below, at low latitudes the slopes of the simulated stackplot patterns are sensitive to the intrinsic rotation rate used in the calculations, and agreement with the patterns of observed field requires a faster rate than measured by Snodgrass (1983).

2. RESULTS

2.1. Stackplot Characteristics

In previous studies, stackplots have been constructed by slicing Carrington maps into latitude strips and reassembling these strips into vertical columns. This gave pictures of magnetic field at each latitude as a function of Carrington longitude and Carrington number (or time in years) over a sunspot cycle (cf. Bumba & Howard 1969; Stepanyan 1982; McIntosh et al. 1991).

For aesthetic reasons, we select strips whose length approximates the Sun's synodic rotation period at the equator (26.90 days according to Snodgrass 1983), rather than the 27.3 day Carrington period. Also, we reverse the northern hemisphere strips so that longitude runs from right to left instead of left to right as it does in conventional Carrington maps. In this way, the stackplot patterns slant symmetrically away from the equator in each hemisphere, as shown in Figure 1. By comparison, in McIntosh et al.'s (1991) display, the patterns are asymmetric, converging toward 16°N and diverging away from 16°S where the rotation period is approximately 27.3 days, whereas in Stepanyan's (1982) display they converge symmetrically toward 16° in both hemispheres.

378

© American Astronomical Society • Provided by the NASA Astrophysics Data System
Figure 1 shows stackplots of the photospheric field measured at the Wilcox Solar Observatory (WSO) (top) and simulated using the flux-transport model with the Snodgrass formula (1) (bottom). The field strengths in the original WSO Carrington maps have been corrected for line profile saturation by multiplying by 1.8 and for line-of-sight projection by dividing by the cosine of latitude, a procedure which has been justified in detail by Wang & Sheeley (1992). The lower spatial resolution WSO measurements were selected over the higher resolution measurements at the Mount Wilson Observatory (MWO) and the National Solar Observatory (NSO) because they had less noise. As discussed in § 2.2, autocorrelations performed using the higher resolution observations give smaller pattern sizes, but essentially the same rotation rates.

The simulated field was calculated by depositing 2700 doublet sources over the interval 1976 August–1986 April onto a 256 x 128 numerical grid representing the photosphere and allowing the flux to evolve according to the transport rates derived by Wang et al. (1989b). In this case, the stackplots were constructed from instantaneous maps of the entire photosphere made at 27.275 day intervals, rather than from daily central-meridian weighted strips as was the case for the stackplots of the observed field; the month-long gap between successive maps produced the jagged “seams” visible in the high-latitude panels of the simulated field.

As one can see in Figure 1, our stackplots have an overall symmetry with nearly vertical patterns at the equator and increasingly slanted patterns progressing smoothly toward the poles in each hemisphere. This poleward slant reflects the increase of recurrence period with latitude, not the poleward migration of flux. The poleward migration applies to the axisymmetric component of field and is revealed only indirectly by the gradual reversal of the dominant polarity at high latitudes. Other properties of the axisymmetric field, such as large poleward surges (Howard & LaBonte 1981; Wang et al. 1989a) and the equatorward migration of leading polarity, are relatively subtle features partially masked by the non-axisymmetric component of field.

The stackplots of WSO field and simulated field share a number of characteristics. At each latitude, they are composed of individual features which have a variety of sizes and slopes, sometimes corresponding to temporarily diverging or converging patterns. These features are small and closely packed near sunspot maximum, but become larger and more widely spaced later in the cycle when they appear as multiple images in adjacent columns and have more vertical slopes. This transition corresponds to the increase in the structural sizes and phase velocities obtained from cross-correlations of the field during the sunspot cycle (Bumba & Howard 1965; Wilcox & Howard 1970; Wilcox et al. 1970; Schatten et al. 1972; Stenflo 1974, ...
2.2. The Rotation Rate

Although the stackplots of observed and simulated field in Figure 1 agree in their overall properties, closer scrutiny reveals some significant differences. At 0° the WSO patterns seem to be slanted very slightly from upper left to lower right, indicating an average recurrence period shorter than 26.90 days, while the simulated patterns are slanted from upper right to lower left, indicating a longer period. In the model, diffusion can make the period longer by transporting flux equatorward from the more slowly rotating sunspot latitudes during the rising phase of the cycle, or by blunting the nose of the non-axisymmetric component’s neutral line at sunspot minimum (Sheeley et al. 1987; DeVore 1987). However, diffusion cannot make the observed field recur with a period that is less than the minimum intrinsic rotation period of the Sun. Assuming that this minimum period occurs at the equator, the Sun’s equatorial rotation period must be less than 26.90 days.

The trend for the observed field to have a smaller recurrence period than the simulated field is also visible in Figure 1 at ±10° where the nearly vertical WSO patterns indicate a 26.9 day period and the slanted patterns of the simulated field indicate a period close to the 27.05 day Snodgrass value at that latitude.

This discrepancy is shown more quantitatively by the autocorrelation measurements of Figure 2 for the intervals 1979–1981 (Carrington rotations 1677–1716) around sunspot maximum (top) and 1983–1985 (rotations 1730–1769) toward minimum (bottom). At the equator, the WSO period (thin line) is about 0.2 day shorter than the period of the simulated field (thick line) during both intervals. Also, as expected, the latter period closely agrees with the 26.90 day Snodgrass period at the equator. At higher latitudes, the WSO and simulated rates are both faster than the Snodgrass rate, especially toward sunspot minimum. Above 55° latitude, the relatively weak non-axisymmetric component of the WSO field is dominated by noise and gives unreliable rotation rates which are not shown here.

These results suggest that the intrinsic rotation rate used with the simulations should be modified to give a faster speed near the equator without deviating appreciably from the Snodgrass (1983) rate at high latitudes. This “two-zone” constraint is equivalent to sharpening the profile near the equator and can be satisfied by adding a cos^6 θ term to the analytical expression for the synodic rotation rate, as follows

\[ \omega(\theta) = 13.46 - 2.7 \cos^2 \theta + 1.2 \cos^4 \theta - 3.2 \cos^6 \theta \text{ deg day}^{-1}. \]  

The coefficients in this expansion were adjusted to obtain the best overall agreement between the simulated and observed profile, as shown by the autocorrelation measurements in Figure 3. The first term corresponds to an equatorial rotation period of 26.75 days, which minimizes the equatorial offset between the simulated, observed, and intrinsic rotation curves. We assign to this value an uncertainty of ±0.05 days, which allows for fluctuations in the observed equatorial rate over the sunspot cycle. The sum of the first two terms in the new formula gives a period of 26.9 days at latitudes of ±10°, consistent with the vertical orientation of the observed patterns in the 10° panels of Figure 1. The remaining terms were chosen to optimize the agreement between the simulated and observed phase velocities at higher latitudes, especially near sunspot maximum when frequent source eruptions keep those phase velocities close to the intrinsic rate.

Figure 4 compares stackplots of the WSO field (top) and the field simulated using the new rotation rate (middle). To show the weak-field patterns near sunspot minimum more clearly, we saturate the display at 0.01 G, which effectively gives polarity rather than field strength. The stackplot cadence was the 26.75 day equatorial period corresponding to the first term in equation (2). For comparison, we include a stackplot of the simulated field when diffusion and flow are excluded from the model (bottom). In this case, there is no transport across lati-
SOLAR ROTATION RATE

The recurrence patterns show the small spatial scale of the sources and the intrinsic rotation rates at their latitudes of eruption. Clearly, in this example, the poleward slants have nothing to do with a poleward migration of flux, but simply represent the rotation rates given by equation (2). The latitudinal limits of the source eruptions are indicated by the empty columns at high latitude and the nearly empty column at the equator.

As one can see, at 0°, the source stackplot consists of vertical streaks signifying the 26.75 day recurrence period of the undiffused sources. The corresponding WSO and simulated patterns are nearly vertical, except toward sunspot minimum when they become dominated by larger features slanting from upper right to lower left. This longer period is a property of the large-scale asymptotic field obtained during an extended absence of flux eruptions: A balance occurs between differential rotation, which sharpens the nose of the backward-C shaped neutral line of the nonaxisymmetric field component, and diffusion, which blunts it, causing the neutral line to drift eastward in the 26.75 day equatorial system (Sheeley et al. 1987; DeVore 1987).

At ±10°, the WSO patterns are not vertical as they were in Figure 1, but have slants comparable to those of the simulated field. Also, in the −10° to +10° latitude range, the polarity stackplots show very large features during 1977–1978. These features are caused by the equatorward diffusion of flux from the high-latitude sunspot groups of the new cycle, and give rise to an “equatorial bulge” in the autocorrelation widths during that time (Sheeley et al. 1987).

It is instructive to compare the new rotation rate given by equation (2) with the rotation rates that Snodgrass (1983) and Komm et al. (1992a, b) obtained by cross-correlating daily magnetograms obtained at MWO and NSO, respectively. For the −60° to +60° latitude range, Figure 5a compares our intrinsic rotation rate (solid curve) with the measurements provided to us by R. Komm using 1 day lags (plusses) and with the measurements of Snodgrass (1983) using 2 day lags (triangles). Both sets of measurements include contributions from active regions as well as from weaker background fields.

Although the profile is in reasonable overall agreement with both data sets, it shows some differences when examined in detail. First, most of the data points lie inside the curve, indicating that our new rate is systematically faster than those of Komm et al. (1992a, b) and Snodgrass (1983). Second, below 40°, the fit is slightly better in the northern hemisphere than in the southern hemisphere, indicating an asymmetry in the observed rates. Komm et al. obtained slightly faster rates and greater asymmetry when they excluded active regions from their cross-correlations. Thus both of these discrepancies with the Komm et al. measurements would be removed if equation (2) referred to the background field.

The enlargement in Figure 5b shows some of the discrepancies at low latitude. There is a progressive increase in period as one goes from our intrinsic profile (thick solid curve), to a four-parameter least-squares fit to Komm et al.’s data (thin solid curve), to a three-parameter fit to the same data (long dashes), and finally to the three-parameter Snodgrass profile (dotted curve). Our intrinsic rate lies within the scatter of Komm et al.’s measurements, except near −10° where the measurements show an asymmetry with respect to the northern hemisphere values. As mentioned above, this asymmetry may be produced by active regions. However, our rate is substantially faster than the low-latitude rates measured by Snodgrass (1983), which, as he pointed out, show a “dimple” at the equator.

As we have seen in Figure 3, autocorrelations of the simulated field give lags (rotation rates) that are in good agreement with those obtained for the WSO field. However, those same autocorrelations gave widths (pattern sizes) that were systematically smaller for the simulated field than for the WSO field. In particular, low-latitude patterns at sunspot maximum had simulated widths of 8°–10° and WSO widths of 14°–16°. The 8°–10° widths must represent the true sizes of the simulated patterns because they are larger than the 1/4 pixels of the 256 × 128 computational grid and the 5° pixels of the 72 × 36 interpolation grid used to display the computations. This suggests that the 14°–16° WSO widths may be overestimates, perhaps degraded from their true values by using the relatively large 10/4 (helio-centric) pixels in the daily images and by overlapping these images to make the Carrington maps.
A natural question is whether the spatial mismatch between the simulated field and the WSO field might affect the determination of the rotation rate. Stackplots that we made using the higher resolution NSO field showed slopes similar to those of the WSO field, suggesting that the rotation rates do not depend sensitively on the spatial resolution. Nevertheless, to test this possibility, we smoothed the simulated field prior to performing the autocorrelations and making the stackplots. We used running means of 18° in longitude by 9° in latitude, corresponding to 13 × 7 pixels of the 256 × 128 computation grid. While the correlation widths increased to ~14° at low latitude near sunspot maximum, the rotation profiles did not change appreciably. Similarly, the stackplot of the smoothed field had larger features at low latitude, comparable in size and strength to those of the WSO field, but slopes that were not visibly different from those of the unsmoothed field.

Another question concerns the possible influence of the non-axisymmetric component of field. This component has virtually no effect on the autocorrelation measurements, which depend only on the longitudinal distribution of field strength. However, it has a drastic effect on the stackplot polarity stripes, whose boundaries converge and disappear at high latitudes as trailing polarity becomes dominant. Thus, to see what the autocorrelations are measuring, we must remove the axisymmetric field from our stackplots.

The result is shown in Figure 6 for the WSO field (top) and for the simulated field (bottom). At low latitudes, these stackplots do not differ appreciably from their total field counterparts; the only noticeable change is the removal of the slight excess of leading polarity. However, at high latitudes, the removal of excess trailing polarity now reveals stripes of simulated field from 1977 until sunspot minimum in 1986. The
SOLAR ROTATION RATE

magnetic doublets assumed to erupt at the central meridian at the following dates and latitudes: 1977 January 1 at $35^\circ$S; 1979 July 1 at $15^\circ$S; 1980 July 1 at $5^\circ$N; 1984 January 1 at $5^\circ$S. Each source contained $200 \times 10^{21}$ Mx of flux of each polarity, taken an order of magnitude larger than is typically encountered for individual active regions on the Sun in order to enhance the visibility and duration of the evolving patterns. The pole separation of each doublet was $0^\circ$ in latitude (to remove the axisymmetric component), and $12^\circ$ in longitude with the leading polarity positive in the northern hemisphere according to Hale's law for sunspot cycle 21.

In 1977, the single source at $35^\circ$S latitude produced a successsion of stackplot images extending over a wide range of latitudes from $60^\circ$S to $10^\circ$S. They are faintly visible across the equator to about $30^\circ$N as reflected patterns. At first glance, the images seem to form simultaneously at all of these latitudes; closer scrutiny reveals that they form first in the panels closest to the source latitude and some weeks to months later in the more distant panels.

The slopes of these images vary with latitude, but less strongly than the slopes of the "source patterns" obtained in the absence of diffusion and flow (cf. Fig. 4, bottom). Autocorrelation measurements indicate that the rotation is slower than the intrinsic rate at latitudes below the source and faster above it, as if these stackplot features are attempting to move with the source (see also Fig. 10 of Sheeley et al. 1987). The faint northern hemisphere images are more vertical because they attempt to move with the equator which is the "entry point" for flux diffusing there from the southern hemisphere.

In 1984, the single source at $5^\circ$S latitude produces stackplot images that are stronger and more vertical than the 1977 images throughout the entire $60^\circ$S to $60^\circ$N latitude range. After 2 or 3 yr, the high-latitude features curve downward and the low-latitude features curve upward, showing their eventual approach to the asymptotic rate (Sheeley et al. 1987; DeVore 1987). As mentioned in a previous section of this paper, this asymptotic behavior requires an extended interval without sunspot activity, and therefore tends to occur near sunspot minimum. By contrast, at times of continual flux eruption, the phase velocity reflects the latitudes of those eruptions.

In 1979 and 1980, the sources at $15^\circ$S and $5^\circ$N produce images over a wide range of latitudes in both hemispheres. Individually, these images show properties consistent with those of the 1977 and 1984 sources. However, as the 1979 and 1980 images run together, they form transient features with sudden changes in slope. Such interacting patterns may be responsible for some of the observed fluctuations of phase velocity during the sunspot cycle (see Sheeley et al. 1987).

Taken together, these idealized source stackplots illustrate that a given latitude panel may have a variety of slopes different from the intrinsic rate at that latitude. This variety reflects the corresponding variety in the latitudes and longitudes of flux eruption. In particular, the rapid spreading of flux to neighboring latitudes gives slopes that lie between the intrinsic slopes at the "source latitudes" and at the "local latitudes." Also, longitudinal fluctuations produce apparent shifts in the slopes of the interacting patterns. These effects explain the converging and diverging patterns recently emphasized by McIntosh et al. (1991).

Finally, Figure 8 shows the stackplots obtained for the simulated field when the 2700 empirically determined sources are assigned random longitudes at their times of eruption. To show the asymptotic behavior, we extend the simulation.

Fig. 5.—Intrinsic rotation rate given by eq. (2) compared with the measured values of Komm et al. (plusses) and Snodgrass (triangles). (a) Overall comparison in the latitude range ($-60^\circ$, $+60^\circ$); here the solid line represents the rotation curve of eq. (2). (b) Detailed comparison in the latitude range ($-20^\circ$, $+20^\circ$), here, in addition to the rotation curve of eq. (2) (thick solid line), we have plotted a 4-parameter (thin solid line) and a 3-parameter (long dashes) least-squares fit to the data points of Komm et al., as well as the Snodgrass profile given by eq. (1) (dotted line).

Next, we consider the origin of the individual features which contribute to a stackplot. Such features are most easily resolved near sunspot minimum, when they appear as nearly vertical bipolar structures in adjacent low-latitude panels. They are multiple-latitude images of evolving bipolar magnetic regions, as one can see by constructing stackplots of idealized sources.

Figure 7 shows stackplots of the field generated by idealized stripes of WSO field are less visible due to the increased noise at high latitude, consistent with the autocorrelation measurements.

2.3. Origin of the Stackplot Features

Next, we consider the origin of the individual features which contribute to a stackplot. Such features are most easily resolved near sunspot minimum, when they appear as nearly vertical bipolar structures in adjacent low-latitude panels. They are multiple-latitude images of evolving bipolar magnetic regions, as one can see by constructing stackplots of idealized sources.

Figure 7 shows stackplots of the field generated by idealized
through the end of 1987 without adding sources after 1986 April and we saturate the display at 0.01 G to show polarity rather than field strength. Although the individual stackplot features are arranged differently in longitude, they give the same overall patterns that we have already seen for the unrandomized sources in Figure 4: large low-latitude features during 1977–1978, pattern widths that tend to increase with latitude and time during the sunspot cycle, and slopes that become more vertical with time. Also, during 1986–1987, the polarity patterns slant from upper right to lower left in the equatorial panel, indicating an asymptotic rotation period greater than 26.75 days.

Thus the overall stackplot characteristics do not seem to reflect a deep-seated longitudinal organization of the fields. Perhaps the only discernible effect of the randomization is to fragment some of the multiple-latitude images that were

Fig. 6.—Stackplots of the nonaxisymmetric components of the WSO field (top) and the simulated field (bottom) plotted in 26.75 day rows as in Fig. 4, but with saturation levels at ±1 G as in Fig. 1.

Fig. 7.—Stackplots showing polarity patterns created by four large idealized sources deposited at latitudes 35°S (1977 Jan 1), 15°S (1979 Jul 1), 5°N (1980 Jul 1), and 5°S (1984 Jan 1). Saturation occurs at ±0.01 G.
present near sunspot minimum, thereby confirming Bumba &
Howard's (1965) conclusion that these large-scale fields or-
ginate with several sources or complexes of activity.

3. SUMMARY AND DISCUSSION

We have used stackplots to compare the field observed at
the WSO with the field simulated according to the flux-
transport model. The comparison revealed immediately that
the rotation rate used as input to the simulations was too slow
near the equator. In our corrected formula given by equation
(2), the synodic rotation period at the equator is 26.75 days,
significantly less than the 26.90 day value of Snodgrass (1983).
This result is not affected by the relatively low spatial
resolution of the WSO measurements, which give essentially
the same stackplot slopes as the higher resolution measure-
ments from the NSO and the MWO.

The stackplots of the WSO field were similar to those of the
field simulated with the flux-transport model when the new
rotation rate was accompanied by an effective diffusion rate of
600 km s$^{-1}$, a latitude-dependent poleward meridional flow
rate of 10 km s$^{-1}$, peak speed, and sources of flux estimated from
NSO daily magnetograms (Wang et al. 1989b). The same
overall characteristics were obtained even when the sources of
flux were assigned random longitudes at their times of
ereption. Thus, stackplots of the observed field can be understood
in terms of the flux-transport model without the need for ad
hoc postulates about the in situ emergence of weak large-scale
fields or a special deep-rooted longitudinal organization
(McIntosh et al. 1991). Indeed, they simply provide another
method of demonstrating the validity of the model.

Near sunspot maximum, the individual stackplot features are
blended together in slanted patterns whose average slopes are
approximate measures of the intrinsic rotation rates in the
sunspot belts. However, toward minimum, individual features
are sometimes visible as separate, quasi-vertical images in
adjacent latitude columns. Their slopes more closely match the
intrinsic rotation rates at the latitudes of flux eruption, which
are near the equator at that phase of the cycle. At these times,
the quasi-rigid rotation reflects the near-equatorial latitude of
the erupting bipolar magnetic regions. However, during a pro-
longed absence of sources, the evolving field approaches its
asymptotic configuration and the recurrence rate is determined
by the “balance” between the shearing effect of differential
rotation and the transport of flux across latitudes. Thus, obser-
vations near sunspot maximum ought to be most effective for
determining the intrinsic rotation rate, whereas observations
during an extended minimum ought to be most effective for
measuring the rates of diffusion and flow.

We are grateful to R. W. Komm, R. F. Howard, and J. W.
Harvey (National Solar Observatory/Kitt Peak) for providing
unpublished rotation measurements from NSO daily magneto-
grams and for helpful discussions. We are also grateful to J. T.
Hoeksema and P. H. Scherrer (Wilcox Solar Observatory/
Stanford) for providing Carrington maps of the observed field
and for clarifying their reduction procedure. Financial support
was provided by the Solar Physics Branch of the NASA Space
Physics Division (DPR W-14429) and by the Office of Naval
Research.

REFERENCES

1056
Conf. Ser., Vol. 27, ed. K. L. Harvey, p. 325
McIntosh, P. S., Willock, E. C., & Thompson, R. J. 1991, World Data Center A
for Solar Terrestrial Physics (Boulder), Rep. UAG-101
26, 283

© American Astronomical Society • Provided by the NASA Astrophysics Data System