SOLAR MERIDIONAL MOTIONS DERIVED FROM SUNSPOT OBSERVATIONS

M. A. KAMBRY*, J. NISHIKAWA†, T. SAKURAI, K. ICHIMOTO, and E. HIEI

National Astronomical Observatory, Mitaka, Tokyo 181, Japan

(Received 15 June, 1990; in revised form 12 October, 1990)

Abstract. Sunspot drawings obtained at the National Astronomical Observatory of Japan during the years 1954–1986 were used to determine meridional motions of the Sun. A meridional flow of a few $\mathrm{m\,s^{-1}}$ was found, which is equatorward in the latitude range from $-20°$ to $+15°$ and is poleward at higher latitudes in both hemispheres. A northward flow of $0.01°\ \mathrm{day^{-1}}$ or $1.4\ \mathrm{m\,s^{-1}}$ at mid-latitudes (between $10°$ and $20°$) was also detected. From our limited data-set of three solar cycles, an indication of solar-cycle dependence of meridional motions was found.

1. Introduction

For an understanding of the differential rotation in the photospheric layer of the Sun, one has to know the mechanisms of angular momentum transport because they generate and sustain the solar differential rotation. Gilman (1980) suggested that meridional circulation toward the equator in the photospheric layer and toward the pole in a deeper layer may produce a net equatorial acceleration. Fluid moving toward the equator on the outer branch would contain more angular momentum than fluid moving toward the pole underneath because of the viscous coupling between the two layers and the difference in the lengths of moment arms. Such meridional circulation can be maintained either by anisotropic viscosity or by a latitude dependent convective energy transport (Schröter, 1985). Meridional motions toward the equator of the order of a few $\mathrm{m\,s^{-1}}$ are needed in these theories to maintain the observed differential rotation.

The solar meridional flow in the photospheric layer can be determined by two different ways: the spectroscopic method and from the tracing of solar features (mostly sunspots). Meridional motions measured by sunspot proper motion techniques are not in complete agreement with meridional motions obtained by spectroscopic methods. The spectroscopic results were discussed by Duvall (1979), Howard (1979), LaBonte and Howard (1982), Snodgrass (1984), Andersen (1984), and Cavallini, Ceppatelli, and Righini (1985a, b, 1986). They found that meridional motions in the photospheric layer are generally directed toward the pole. These spectroscopic results apparently do not support the theory of differential rotation. Cavallini, Ceppatelli, and Righini (1986) suggested that the problem is complicated by a possible dependence of convection

* Permanent address: Indonesian National Institute of Aeronautics and Space, Ionospheric Research and Development Center (LAPAN) Jl. Dr Junjunan 135 P.O. Box 26, Bandung 40173, Indonesia.
† Present address: Hiraiso Solar Terrestrial Research Center, Communications Research Laboratory, Ministry of Post and Telecommunication, Isozaki, Nakaminato, Ibaraki 311–12, Japan.

efficiency on the activity cycle. Spectroscopic measurements may also be affected by the center-to-limb variations of turbulent broadening and asymmetry of spectral lines.

The situation is somewhat better when sunspots are used as tracers. However, the tracing of sunspots can only determine meridional motions within the sunspot belt (latitude up to 40°). Equatorward flow near the solar equator was found in the present result. This result was also found by Richardson and Schwarzschild (1953), Becker (1954), Ward (1965, 1973), Arevalo *et al.* (1982), Tuominen (1941, 1945, 1952, 1955a, b, 1961, 1976), Tuominen and Kyröläinen (1982), Tuominen, Tuominen, and Kyröläinen (1983), Balthasar and Wöhl (1980), Balthasar, Vázquez, and Wöhl (1986), Howard and Gilman (1986), Lüstig and Hanslmeier (1987), Hanslmeier and Lüstig (1986). The discrepancy between these and the spectroscopic methods is not so great because the spectroscopic results are unreliable at low latitudes, where the tracer results show equatorward flow.

2. Observations and Data Reduction

The sunspot telescope of the National Astronomical Observatory at Mitaka, which has been used to obtain the present data, has a focal length of 3600 mm and an aperture of 200 mm. The observations consisted of drawings of the Sun with a diameter of 240 mm. The daily sunspot positions can be determined by overlaying a Stonyhurst disk on the drawings, with an expected accuracy of 0.5 deg in heliographic coordinates. In the case of large groups or bipolar sunspot groups the definition of the spot position has some ambiguity. Balthasar, Vásquez, and Wöhl (1986) used sunspot groups from the Greenwich data set for measuring differential rotation and meridional motions of the Sun. They determined the positions of sunspot groups by eye estimates. Howard and Gilman (1986) defined the position of a sunspot group by the area-weighted mean of the positions of constituent sunspots. In the present work, the position of a sunspot group in the data from 1954 to 1980 was defined by following the same particular spot in the group. In the data from 1981 to 1986, the center of gravity by eye estimates similar to Balthasar, Vázquez, and Wöhl (1986) was used for defining the position of a sunspot group. The data cover three activity cycles, namely cycle 19 (1954–1964), cycle 20 (1965–1975), and cycle 21 (1976–1986).

Meridional motions can be calculated by the difference of daily positions and the time interval between the two observations. For this purpose only sunspots with absolute values of longitude and latitude smaller than 70° and 40°, respectively, were selected. We eliminated the single A-type spots from the data that were not observed on two consecutive days. For other types of sunspots, two observations separated by more than a day were included in the data if the shapes of the sunspots on the two days were similar. In the present study we use the same sunspot position data that were used for the differential rotation analysis by Kambry and Nishikawa (1990).

3. Results

3.1. Profile of Meridional Motions

The meridional motions we obtained are shown in Figure 1 for every 5° latitude zone, together with the results of Howard and Gilman (1986) and of Balthasar, Vázquez, and Wöhl (1986). A flow of a few ms^{-1} was found, which is equatorward in the latitude range from $-20°$ to $+15°$ and is poleward at higher (but less than 35°) latitudes in both hemispheres. This is in good agreement with Howard and Gilman (1986).

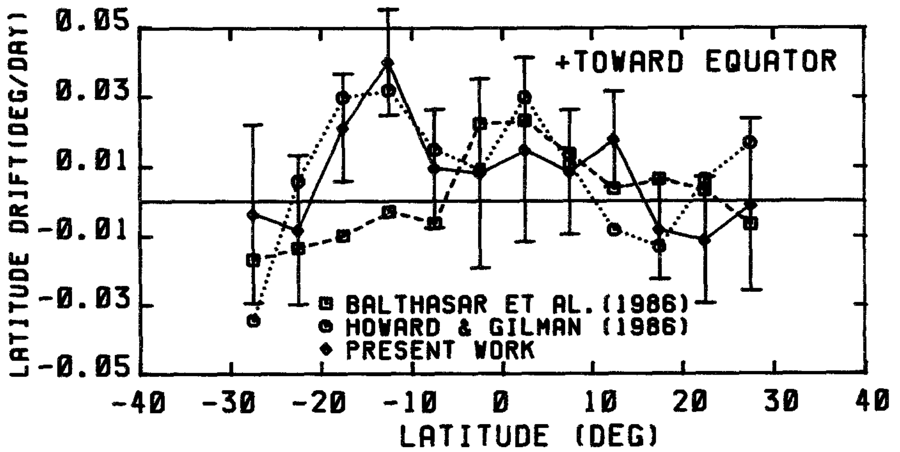

Fig. 1. Meridional motions derived from the data obtained at the National Astronomical Observatory of Japan in the interval 1954–1986, together with the results of Balthasar, Vázquez, and Wöhl (1986) and Howard and Gilman (1986).

We divided the meridional motions into two components, which are symmetric (a positive value means toward the equator) and antisymmetric (a positive value means toward the north pole) with respect to the equator, respectively. In the symmetric component shown in Figure 2, an equatorward flow was found up to 20° of solar latitude. Our trend of symmetric meridional motion is similar to Balthasar, Vázquez, and Wöhl (1986) and Howard and Gilman (1986). In the antisymmetric component shown in Figure 3, a northward flow of 0.01 deg day^{-1} or 1.4 ms^{-1} at intermediate latitudes (from 10° to 20°) was found, in accordance with Howard and Gilman (1986). The existence of this antisymmetric component makes the meridional flow velocity in the northern hemisphere smaller than in the southern hemisphere, as is seen in Figure 1. These results are different from Balthasar, Vázquez, and Wöhl (1986), Hanslmeier and Lüstig (1986), and Lüstig and Hanslmeier (1987). They found a general southward flow in both hemispheres.

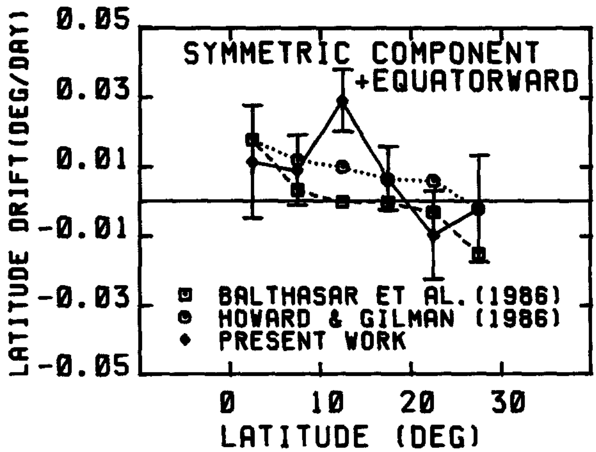

Fig. 2. Symmetric component of meridional flow. Positive velocity means toward the equator.

3.2. Meridional motions in three solar cycles

We also derived meridional flows in three solar cycles separately. The result is shown in Figures 4(a) and 4(b), with the error bars for cycle 21 data points. The antisymmetric flows (Figure 4(b)) are nearly the same for three cycles, showing a northward flow at latitudes 10°–20°. The symmetric component (Figure 4(a)) shows different behavior for three cycles. The data point closest to the equator (i.e., 0°–5°) comes from a small number of measurements and should not be taken literally. An equatorward flow is found for cycles 19 and 21 at mid latitudes, whereas a poleward flow is found for cycle 20 at higher latitudes. This difference in meridional flows in odd/even cycles may be related to the 22-year solar magnetic cycle. Some earlier investigations seem to indicate that the

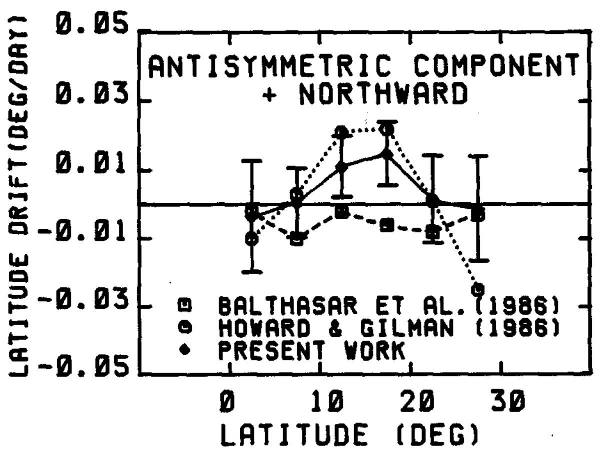

Fig. 3. Antisymmetric component of meridional flow. Positive velocity is toward the north pole.

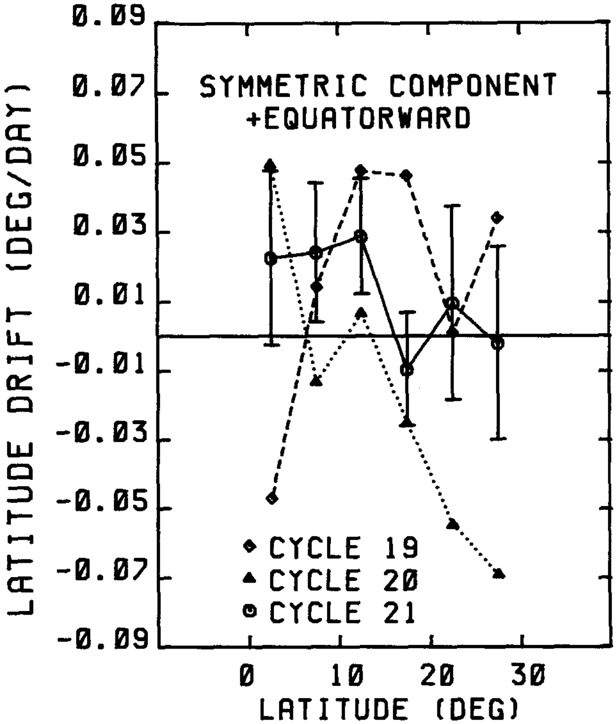

Fig. 4a. Symmetric component of meridional flow in three solar cycles.

latitudinal profile of meridional motions changes with the solar cycle (Tuominen, 1952, 1955, 1976; Richardson and Schwarzschild, 1953; Becker, 1954; Tuominen and Kyröläinen, 1982; Ribes, Mein, and Mangeney, 1985). Tuominen (1952) found that the

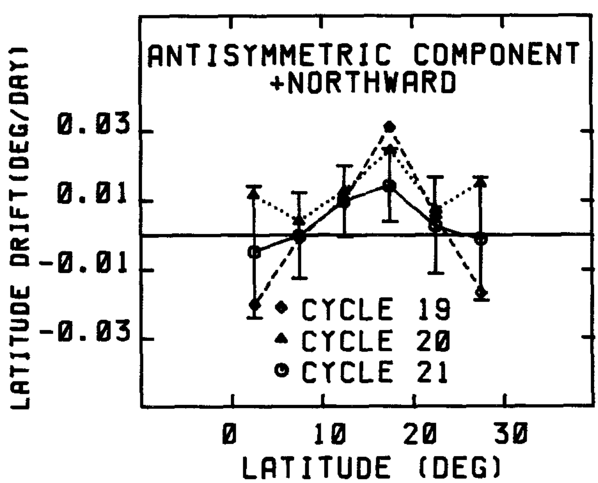

Fig. 4b. Antisymmetric component of meridional flow in three solar cycles.

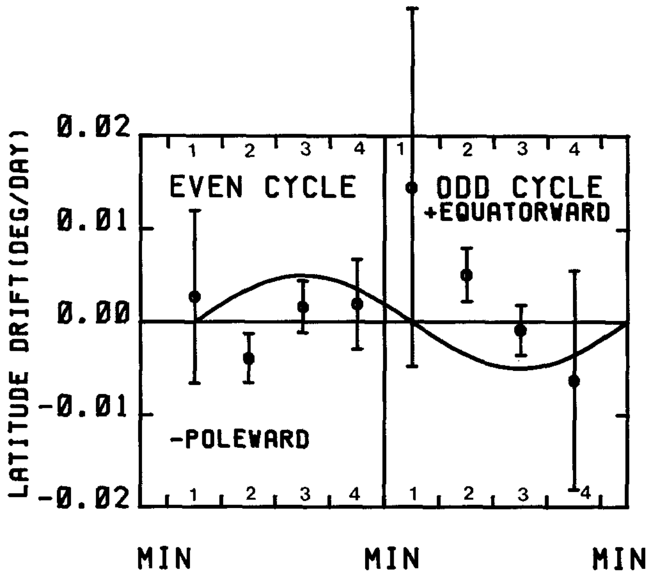

Fig. 4c. Symmetric component of the average drift of sunspots in solar latitude for odd and even cycles together with the sinusoidal variation proposed by Richardson and Schwarzschild (1953).

meridional motions between 7° and 20° of solar latitude seem to vary with a period of 22 years. Ribes, Mein, and Mangeney (1985) also found that the profile of meridional motions sometimes changes sign. Richardson and Schwarzschild (1953) found evidence for a 22-year oscillation between poleward and equatorward motions with an amplitude of 0.005° day^{-1} or 60 cm s^{-1}. We also derived the average drift in latitude, the average being made over all sunspot groups in every quarter of a cycle. The result is shown in Figure 4(c) together with the sinusoid of Richardson and Schwarzschild (1953). They studied 8 solar cycles, from cycle 11 to cycle 18. The odd cycles of our data are cycles 19 and 21, and cycle 20 is our even cycle. Figure 4(c) shows that the latitude drift seems to vary, possibly with a period of 22 years, but apparently our data do not reproduce the result of Richardson and Schwarzschild (1953).

3.3. Dependence of Meridional Motions on Cycle Phase

Kambry and Nishikawa (1990) found that the solar rotation velocity at the equator (A) shows a systematic variation within each cycle. The value of A is higher at the beginning of the cycle and decreases subsequently. We looked for this variation in meridional motions. Meridional motions in the latitude ranges of 10°–15°, 15°–20°, and 20°–25° were derived separately for 3 solar cycles and were then averaged.

The symmetric component (Figure 5(a)) is found to decrease from positive to negative values. However, the behavior of the symmetric component is different in three cycles as was described above, and the significance of this cycle-phase dependence in the cycle-averaged data is rather questionable. The antisymmetric component stays con-

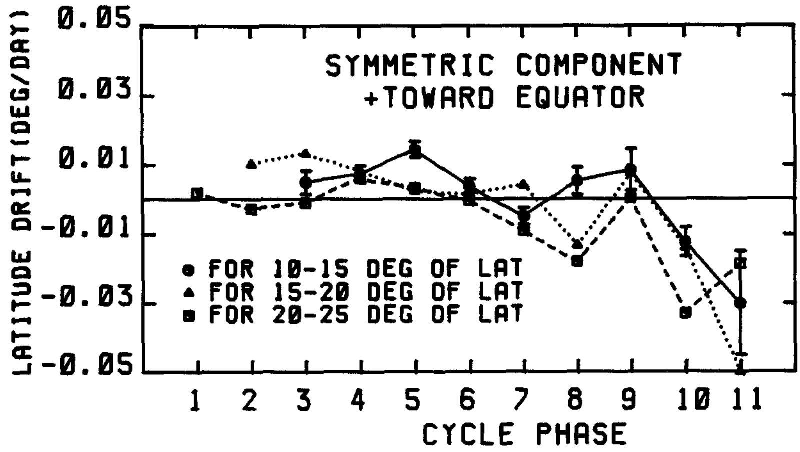

Fig. 5a. The dependence of the symmetric component of the meridional flow, in the latitude ranges of 10°–15°, 15°–20°, and 20°–25° on cycle phase.

stant, except at the beginning and at the end of the cycle where the accuracy is low, because of a limited amount of data.

4. Conclusions

The sunspot drawing data from the National Astronomical Observatory during the years 1954–1986 were used to determine the meridional motions of the Sun. An equatorward flow up to 15° of solar latitude in the symmetric component was found, in agreement with Howard and Gilman (1986), Lüstig and Hanslmeier (1987),

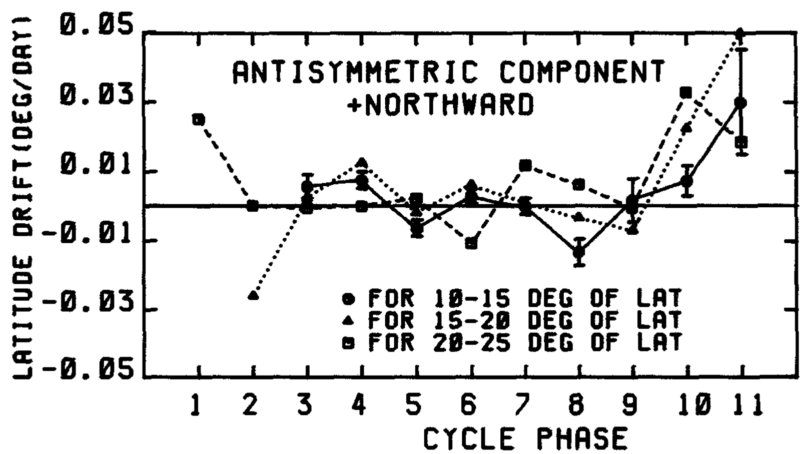

Fig. 5b. The dependence of the antisymmetric component of the meridional flow, in the latitude ranges of 10°–15°, 15°–20°, and 20°–25° on cycle phase.

Hanslmeier and Lüstig (1986), and Balthasar, Vázquez, and Wöhl (1986). We also found a northward flow at latitude 10°–20°, which, however, contradicts the results of Balthasar, Vázquez, and Wöhl (1986), Hanslmeier and Lüstig (1986), and Lüstig and Hanslmeier (1987). We obtained an indication of a solar-cycle dependence of meridional motions, but this is not definitive, considering the accuracy in the data.

The meridional flow obtained from sunspot positions is somewhat more reliable than spectroscopic results, but it should be kept in mind that the proper motion of sunspots may not exactly represent the motions of the photosphere, and that the tracing of sunspots can only determine meridional motions up to 40° of solar latitude.

References

Andersen, B. N.: 1984, *Solar Phys.* **94**, 49.
Arevalo, M. J., Gomez, R., Vázquez, M., Balthasar, H., and Wohl, H.: 1982, *Astron. Astrophys.* **111**, 266.
Balthasar, H. and Wöhl, H.: 1980, *Astron. Astrophys.* **92**, 111.
Balthasar, H., Vázquez, and M. Wöhl, H.: 1986, *Astron. Astrophys.* **155**, 87.
Becker, U.: 1954, *Z. Astrophys.* **34**, 129.
Cavallini, F., Ceppatelli, G., and Righini, A.: 1985a, *Astron. Astrophys.* **143**, 116.
Cavallini, F., Ceppatelli, G., and Righini, A.: 1985b, *Astron. Astrophys.* **150**, 256.
Cavallini, F., Ceppatelli, G., and Righini, A.: 1986, *Astron. Astrophys.* **163**, 219.
Duvall, T. L., Jr.: 1979, *Solar Phys.* **63**, 3.
Gilman, P. A.: 1980, *Highlights Astron.* **5**, 91.
Hanslmeier, A. and Lüstig, G.: 1986, *Astron. Astrophys.* **154**, 227.
Howard, R.: 1979, *Astrophys. J.* **228**, L45.
Howard, R. and Gilman, P. A.: 1986, *Astrophys. J.* **307**, 389.
Kambry, M. A. and Nishikawa, J.: 1990, *Solar Phys.* **126**, 89.
LaBonte, B. J. and Howard, R.: 1982, *Solar Phys.* **80**, 361.
Lüstig, G. and Hanslmeier, A.: 1987, *Astron. Astrophys.* **172**, 332.
Ribes, E., Mein, P., and Mangeney, A.: 1985, *Nature* **318**, 170.
Richardson, R. S. and Schwarzschild, M.: 1953, *Accad. Naz. Linc., Fond. Ales. Volta, Atti Conv.* **11**, 228.
Schröter, E. H.: 1985, *Solar Phys.* **100**, 141.
Snodgrass, H. B.: 1984, *Solar Phys.* **94**, 13.
Tuominen, J.: 1941, *Z. Astrophys.* **21**, 96.
Tuominen, J.: 1945, *Observatory* **60**, 160.
Tuominen, J.: 1952, *Z. Astrophys.* **30**, 261.
Tuominen, J.: 1955a, *Vistas Astron.* **1**, 691.
Tuominen, J.: 1955b, *Z. Astrophys.* **37**, 145.
Tuominen, J.: 1961, *Z. Astrophys.* **51**, 91.
Tuominen, J.: 1976, *Solar Phys.* **47**, 541.
Tuominen, J. and Kyröläinen, J.: 1982, *Solar Phys.* **79**, 161.
Tuominen, J., Tuominen, I., and Kyröläinen, J.: 1983, *Monthly Notices Roy. Astron. Soc.* **205**, 691.
Ward, F.: 1965, *Astrophys. J.* **141**, 534.
Ward, F.: 1973, *Solar Phys.* **30**, 527.