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Observation of the Angular Momentum Flux Carried by the Solar Wind

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ABSTRACT

Using data from the Mariner 5 spacecraft, we have measured the angular momentum flux carried by the solar wind and find it in agreement with earlier estimates based on observations of the deflection of comet tails.

In this note we report measurements of the non-radial velocity components of the solar wind flow determined by the plasma experiment on Mariner 5 during the period from June to November, 1967. We use those results to estimate the angular momentum flux transported by the solar wind from the equatorial region of the sun and find that the magnitude of the flux is similar to that estimated by Weber and Davis (1967, 1970) and agrees with the most recent estimates from comet tail observations (Brandt and Heise, 1970). Using his early results, Brandt (1966) pointed out that the solar wind must be considered as an important mechanism for slowing the rotation of the sun, and the recent results imply a slowing down time of $\sim 7 \times 10^9$ years.

It is hard to make an unbiased measurement of the average solar wind flow direction. At 1 AU the average departure from radial flow is on the order of 2°, and the variation about that average is $\sim \pm 5°$ in the course of a solar rotation (e.g. see Hundhausen *et al.*, 1970a). Vela 2 data taken from July 1964 to July 1965 indicated an average flow coming from $1\frac{1}{2}°$ east of the sun (see Coon, 1968 for the data, a discussion of their significance, and a caution by Parker). Vela 3A and 3B data (July 1965-Nov. 1967) give average flow directions of 2.52° and .93° from east of the sun indicating, as the authors point out, a source of systematic error (Hundhausen *et al.*, 1970a). Moreover, IMP 1 data (late 1963 to early 1964) give an average flow from 1.5° *west* of the sun (Egidi *et al.*, 1969).

A partial explanation for the observation of an average flow from the west may come from the fact that during the interaction of high and low speed streams of solar wind, the higher speed wind is deflected so that it appears to come from the west while the lower speed wind appears to come from the east (Siscoe *et al.*, 1970). There was a chance coincidence between the passages of such interaction regions and the location of IMP 1, such that the spacecraft was inside the magnetosphere during a portion of the time of lower speed wind and may have missed some of the wind from the east. There is, however, no clear indication that the average speed measured by IMP 1 is unusually high.

The Mariner 5 spacecraft trajectory took it inwards to ∿ 0.6 AU which increased the magnitude of the expected tangential velocity component and hopefully reduced the importance of small systematic errors.

The experiment used a modulated grid Faraday cup similar to that flown on Mariner 4 (Lazarus *et al.*, 1966). The spacecraft was 3-axis stabilized, and the detector directly faced the sun. The bulk speed, number density, and thermal speed of the proton component of the plasma were determined by comparing the measured energy distribution with that expected from a convected, isotropic Maxwellian distribution. The flow direction for an individual measurement was determined to within $\pm\frac{1}{2}^{\circ}$ (∿ ±4 km/sec transverse velocity) by comparing the particle fluxes incident on three 120°-sectors of a circular collector plate with the fluxes expected from a convected Maxwellian distribution having the parameters determined above and a particular flow direction.

The systematic error of the direction determination could be checked after launch when the spacecraft was in the solar wind and it rolled about the sun-spacecraft axis for approximately $2\frac{1}{2}$ hours. The resulting angles were consistent with the solar wind flow direction being nearly constant during the three roll periods but with an effective detector alignment error of $\frac{1}{2}^\circ$. Such an error is consistent with mounting and construction uncertainties, and that error was used to correct the measured angles. Unfortunately, no such check was available near the end of the flight.

The coordinate system used in this paper is spacecraft centered solar equatorial: The radial coordinate, r, is positive outward along the Sun-spacecraft line; the transverse coordinate, t, is parallel to the solar equatorial plane and is positive in the direction corresponding to the orbital motion of the planets; and the normal coordinate, n, is the third member of the right-handed coordinate system. The spacecraft's orbital plane is inclined 2.7° to the ecliptic, and during the period of these data the heliographic latitude of the spacecraft varies from ∿0° to 4.5°N and back to 0°.

Hourly averages of the velocity components and other quantities of interest were used to form averages over complete solar rotations taking into account the changing position of the spacecraft. The velocity of the spacecraft obtained from the JPL trajectory data was used to correct for aberration effects.

The results are given in the first five columns of Table 1. As the Sun-spacecraft distance decreases, the solar wind comes more from east of the sun. There is also a consistent southward flow.

We can estimate the angular momentum flux by using our measurements of angular momentum flux density near the sun's equatorial plane: The angular momentum flux density carried by the protons is given by $m_p N V_r V_t R$, where N is the number of protons per cc, m_p is the mass of a proton, V_r and V_t are the radial and transverse components of the proton bulk velocity, and R is the Sun-spacecraft distance. The magnetic field also exerts a torque which is given by the appropriate Maxwell stress tensor component; and the equivalent angular momentum flux density is $-B_r B_t R/4\pi$, where $B_r B_t$ are the radial and transverse components of the magnetic field.

Another contribution to the angular momentum flux could come from the anisotropic thermal pressure of the solar wind (Hundhausen, 1970b). This contribution is small, on the average, compared to the magnetic stress contribution quoted above (Eviatar and Schulz, 1970), and therefore we shall neglect the particle pressure anisotropy in our estimate.

The sixth through eighth columns of Table 1 show the two contributions to the angular momentum flux density and also the estimate of the solar equatorial angular momentum flux per unit solid angle obtained by multiplying the average of the sum of the two flux densities by R^2. For reference, the final column of Table 1 shows the proton flux per sterradian averaged over the same rotation. We estimate that our systematic error in average flow direction early in the flight is equivalent to a transverse velocity of $\sim$ 2 km/sec. We can only assume that no significant directional bias developed as the flight progressed.

We have only indirect measurements of solar wind properties outside the ecliptic plane, and in order to estimate the net angular momentum loss rate due to the solar wind, we follow Brandt and include only the solar wind flow between latitudes of ± 30° and assume that its behavior in that region is the same as we observe near the ecliptic. Assuming an equatorial angular momentum flux of approximately 1.2×10^{30} dyne-cm/dΩ we obtain a net slowing torque of 7×10^{30} dyne-cm which is the same as Brandt's estimate.

Our results differ from the theoretical work of Weber and Davis (1967, 1970) in the observation that the magnetic field contribution to the angular momentum flux is definitely smaller than the particle contribution.

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TABLE I

Solar Wind Properties Observed on Mariner 5

(averaged over solar rotations)

Solar Rotation					Angular Momentum Flux Density		Flux/dΩ=	Proton Flux/dΩ
	$\bar{R}$	$\bar{V}_r$	$\bar{V}_n$	$\bar{V}_t$	$\overline{N m_p V_r V_t R}$	$-\overline{B_r B_t R/4\pi}$	$\overline{\text{Sum}} \times \bar{R}^2$	
	(AU)	(km/sec)			(dyne-cm/cm^2)		(dyne - cm)	
1832	1.0	392	-1.8	.84	3.0×10^3	$.9 \times 10^3$	8.7×10^{29}	6.7×10^{34}
1833	.95	373	-1.3	5.2	5.3	.8	12	5.8
1834	.87	438	-1.3	8.5	6.1	1.4	13	5.1
1835*	.80	441	-4.1	7.7	9.3	1.6	16	5.0
1836	.73	417	-3.1	11.2	7.7	2.5	12	4.5
1837*	.68	415	-5.3	11.0	8.4	2.2	11	4.5

*Data missing from a portion of the solar rotation

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