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Microscale "Alfvén Waves" in the Solar Wind at 1 AU

by

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and

J. M. Turner

Abstract

Analysis of IMP I (Explorer 43) plasma and magnetic field fluctuations on a scale of our hour for the period March 18, 1971 to April 7, 1971 reveals that linearly and circularly polarized Alfvén waves are rarely present in the solar wind at 1 AU. The most prevalent microscale fluctuations appear to be large-amplitude, ($\delta B_x/\bar{B} \approx 0.4$) "Alfvén waves" with small but non-zero fluctuations in the magnetic field intensity, B ($\delta B/\bar{B} \approx 0.06$). These waves are present $\approx 40\%$ of the time and are predominantly propagating away from the sun along $\underset{\sim}{B}$.

I. Introduction

It is widely believed that the fluctuations in the solar wind near 1 AU are predominantly circularly polarized Alfvén waves with $|B|$=constant. Several works are in progress based on this assumption, which derives from the work of Belcher et al. (1969) and Belcher and Davis (1971) (hereafter referred to as BDS and BD, respectively) who showed that frequently there is a high correlation between the magnetic field $\underset{\sim}{B}$ and the solar wind velocity $\underset{\sim}{V}$ consistent with large-amplitude waves moving away from the sun at the Alfvén speed. They suggested that changes in the magnitude, B, are negligibly small, which led to the inference that the waves are circularly polarized. Coleman (1966, 1967) reported essentially the same results concerning the microscale fluctuations, except that he found significant power in the spectrum of B and inferred that the fluctuations are consequently <u>not</u> pure Alfvén waves. This conflicts with the results of BD and BDS and the conflict has never been resolved, but the results of BD and BDS have been accepted most widely, perhaps because of their appealing simplicity. In this note, we examine a subset of fluctuations seen on a scale of one hour in the IMP I (Explorer 43) plasma and magnetic field data of Ogilvie and Ness, respectively, for the period March 18 to April 7, 1971, and we show that they are predominantly finite-amplitude, outward-propagating, Alfvén waves with B $\neq$ constant.

The plasma and magnetic field experiments are briefly described in Burlaga and Ogilvie (1973) and Fairfield (1974), respectively. A plasma measurement is made at a series of different energy per charge ratios every 12 sec and the fluid parameters are computed from a group of such measurements at the rate of approximately one set every four minutes. Thus, the measurements are taken in ~ 1 minute and repeated every four minutes. The relative uncertainties in the radial component of the velocity are $\approx \pm 5\%$ and those in density, n, are $\approx \pm 5\% - \pm 10\%$, depending on n, V, and the proton temperature, T_p. The magnetic field sampling rate is 12.5/sec., the rms sensor noise in each component is only 0.03 - 0.05γ and the digitization error is $\approx \pm 0.06$, so that the uncertainties in the 15 sec averages in $\underset{\sim}{B}$, which were used in this study, are negligibly small for our purposes (e.g. generally $\delta B/B < 0.01\gamma$).

II. Some General Observations of Microscale Fluctuations

A necessary condition for Alfvèn waves is

$$\underset{\sim}{v} = \pm \frac{V_A}{B_o} \underset{\sim}{b}, \qquad (1)$$

where $\underset{\sim}{v}$ and $\underset{\sim}{b}$ are the perturbations in $\underset{\sim}{V}$ and $\underset{\sim}{B}$, B_o is the average magnetic field intensity normal to $\underset{\sim}{b}$, and

$$V_A = B_o / \sqrt{4\pi m n} \qquad (2)$$

is the Alfvèn speed. The GSFC plasma analyzer on Explorer 43 measures the magnitude of $\underset{\sim}{V}$, which is nearly equal to the component of $\underset{\sim}{V}$ in the radial ($\hat{x}$) direction ($V \approx V_x$), so we can test the radial component of (1). This is a necessary condition for an Alfvèn wave. (We cannot detect transverse waves moving radially away from the sun, but it will be shown that such waves are rarely present). We test the radial component of (1) by measuring the correlation coefficient, ρ, between V_x (t) and $B_x(t)$, which should ideally be unity for Alfvèn waves.

Fig. 1 (solid lines) shows the distribution of ρ for the 440 hours of data in the interval under consideration. A rather similar distribution is obtained if hours with directional discontinuities (e.g. see Burlaga, 1969, Turner, 1974) are removed. There is generally a high correlation, but ρ is rarely 1. Very similar results were obtained for 6 hr. intervals in the Mariner data by BD and BDS. A statistical correction must be made to our results because only approximately 15 points were used to compute $|\rho|$ so that $|\rho|$ could be high due to chance. If we assume that all of the points between 0 and 0.1 correspond to a $|\rho|$ which is essentially zero, we can correct the observations using the results in Bevington, 1969. This gives the dashed histogram in Figure 1a as an estimate of the distribution of $|\rho|$'s corresponding to fluctuations with a correlation between V_x and B_x. The correlation between V_x and B_x is now more pronounced, but it is still not unity. However, we must consider that V_x is not measured exactly (the errors in B_x are negligibly small in comparison). In this case, if all of these fluctuations were Alfvén waves, so that $|\rho|$ would equal 1 for each hour in the absence of measurement uncertainties, the measured ρ would be 1 x R where $R = [1 + (\sigma_{vn}/\sigma_B)^2 (V_x/V_A)^2]^{-\frac{1}{2}}$; here σ_{vn} is the rms of the random fluctuations in V_x (δV_x) divided by the average $V_x(\overline{V}_x)$ and σ_B is the rms of the fluctuations in B_x divided by $\overline{B}$. The fluctuations in δV_x are due both to the uncertainties in the measurement of V and to the uncertainties in the direction of $\underset{\sim}{V}$. We estimate that $\delta V_x/V_x \approx 0.05$. This gives for the expected distribution of $|\rho|$ for Alfvén waves the dotted histogram in Figure 1. Since this is close to the corrected distribution of correlated events in Figure 1, which includes approximately 66% of the observations, we infer that the data are consistent with up to two thirds of the fluctuations being Alfvén waves. At this point, however, we cannot exclude the possibility that some or all of these fluctuations are fast modes or mixed modes, for which $|\rho|$ can also be 1.

We cannot discuss all of the Explorer 43 fluctuations in this paper, but a study has shown that those with $|\rho| \geqslant 0.6$ and $\delta B/B < 0.2$ form a nearly (but not entirely) homogeneous class with many of the properties of Alfvén waves. These constitute $\sim 38\%$ of the microscale fluctuations. The remainder of our discussion will concern this subset.

III. Observations of 'Alfvén Waves'.

From the correlation between V and B_x, it is possible to compute V_A from (1) for each hour and compare it with the theoretical $\overline{V}_A$ computed from (2) with the measured average n and B for that hour. The distribution of $D = V_A/\overline{V}_A = (\delta V/(R\sigma_B))/\overline{V}_A$, shown in Figure 2, is skewed with a most probable value between 0.5 and 0.75 and a mean value of 1.1. The skewness and width of the distribution are probably mainly due to uncertainties in δV_x and limitations in our estimate that the fluctuations in V_x due to the waves, δV_x, is approximately $\delta V/R$. In view of these uncertainties, the results in Figure 2 are consistent with those to be expected if all of the fluctuations are Alfvén waves.

The polarity of the waves is also obtained from (1). For outwardly propagating waves, sgn $(\rho B_x) < 0$ and for inwardly propagating waves sgn $(\rho B_x) > 0$. It is found that at least 78% of the waves are moving away from the sun.

The relative amplitude of the transverse fluctuations, $\delta B_x/\overline{B}$ (where δB_x is the rms of B_x and $\overline{B}$ is the average $|\underset{\sim}{B}|$ for each hour) is shown in Figure 3a. The number of hours with small amplitude fluctuations ($\delta B_x/\overline{B} < 0.1$) is very small, $\approx 10\%$ of the total. The most probable value of $\delta B_x/\overline{B}$ is between 0.3 and 0.4, and for 83% of the events, $0.1 \leq \delta B_x/\overline{B} < 0.5$. This indicates moderately large amplitude waves. The actual amplitudes are even somewhat larger because we are looking only at the radial component of the perturbations. All of the observations just discussed are similar to the corresponding results in BD and BDS, except that they were considering 3 hr. and 6 hr. intervals rather than 1 hour intervals. Thus, we are probably discussing essentially the same phenomenon in a slightly different frequency domain. BD and DS did not discuss the variations in $|\underset{\sim}{B}|$ except to say that they were small. This is the result that has led some theorists to erroneously infer that the waves are circularly polarized. Figure 3b shows the distribution of $\delta B/\overline{B}$, for events with $|\rho| \geq 0.6$ and $\delta B/\overline{B} < 0.2$. It is apparent that the fluctuations, although small, are not zero. Since the half-width due to experimental uncertainties in $\delta B/\overline{B}$ is $\leqslant 0.01$, at least 85% of the intervals have measureable fluctuations in $\delta B/\overline{B}$, the most probable value being between 0.05 and 0.075. These fluctuations are not Alfvén waves with $|\underset{\sim}{B}|$ = constant.

If we are to have an Alfvén wave with large perturbations in the direction of $\underset{\sim}{B}$ and small, non-zero, perturbations in the magnitude of $\underset{\sim}{B}$, the polarization cannot be circular. We have computed the minimum variance ellipsoids for each hour using the technique described by Daily

(1973), and others. Let λ_1 be the largest eigenvalue and let λ_3 be the smallest eigenvalue. The distribution of λ_2/λ_1, λ_3/λ_2, and λ_3/λ_1 for the fluctuations with $|\rho| \geqslant 0.6$ and $\delta B/B < 0.2$ are given in Figure 4. Most of the waves are planar with $0.2 \leq \lambda_2/\lambda_1 < 0.7$. If the waves were linearly polarized, λ_2/λ_1 would always be much less than 1. Few waves satisfy this criterion. For example, only 5% have $\lambda_2/\lambda_1 < 0.1$. Thus, most of the waves are not linearly polarized. None of the large amplitude waves ($\delta B_x/\bar{B} \geq 0.4$) is linearly polarized ($\lambda_2/\lambda_1 < 0.2$). If the waves were circularly polarized with the tip of the perturbation $\underset{\sim}{B}$ vector tracing a full circle, we should observe a well-defined direction of minimum variance about which the perturbation vector rotates ($\lambda_3/\lambda_2 \ll 1$) and we should find $\lambda_2/\lambda_1 \approx 1$. Figure 4 shows that while the perturbations are nearly confined to a plane, there are relatively few circularly polarized waves with $\lambda_2/\lambda_1 \approx 1$; only 12% of the waves satisfied $\lambda_2/\lambda_1 > 0.9$. It is possible that the perturbation vector traces only a circular arc, in which case $\lambda_2/\lambda_1 < 1$ (Hollweg, 1974), but this still requires that $|\underset{\sim}{B}|$ = constant. The distribution of $\delta B/\bar{B}$ in Figure 3b is sufficient to show that circularly polarized Alfvèn waves rarely occur in the solar wind at 1 AU.

Figure 4 shows that the perturbations of the wave are primarily confined to a plane. This plane is generally nearly perpendicular to the average magnetic field direction as shown by Figure 5, which gives the distribution of ω, the angle between the eigenvector corresponding to the minimum eigenvalue (i.e., the normal to the plane of polarization) and the average magnetic field. The ordinate shows the number of events in a certain ω interval divided by the number of events expected in that interval for an isotropic distribution. The half-width of this distribution is only $\approx 10^{\circ}$. Thus, the perturbations are essentially normal to the mean field, consistent with an Alfvėn wave propagating nearly along $\underset{\sim}{B}$.

In summary, we have shown that 38% of the fluctuations in a representative 21 day period in the solar wind showed a correlation between V_x and B_x consistent with unity; most of them moved away from the sun at the Alfvėn speed nearly along the average field direction; the polarizations were not linear or circular; the perturbations were approximately transverse to the mean field, and of moderately large amplitude; and $|\underset{\sim}{B}|$ was <u>not</u> constant.

IV. <u>Theory</u>

The theory of <u>small</u> amplitude Alfvėn waves in the solar wind is well-developed (e.g. see the review by Burlaga, 1971); the recent theories of large-amplitude, circularly polarized Alfvėn waves with B = constant and of large amplitude linearly polarized waves with $B \neq$ constant are reviewed by Hollweg (1974 a,b); and a theory of linearly polarized, large-amplitude Alfvėn waves with B = constant was recently presented by Goldstein et al. (1974). None of these theories describes the observations presented above, which indicate large amplitudes $(\delta B_x/\overline{B})$, polarizations which are neither linear nor circular, and $B \neq$ constant. Of course, this does not imply that none of the conclusions of the existing theories is applicable to the solar wind. In the following paragraphs we discuss a wave mode which is suggested by the observations.

We must consider a wave with moderately large perturbations $\underset{\sim}{b}$ transverse to the average field $\underset{\sim}{B}_o = B_o\hat{z}$, with small perturbations in $|\underset{\sim}{B}|$ =

$|\underset{\sim}{B}_o + \underset{\sim}{b}|$. Such a wave is obtained if the tip of the perturbation vector follows an ellipse whose plane is normal to $\underset{\sim}{B}_o$. In this way one can have $|\underset{\sim}{b}|/|\underset{\sim}{B}| \leq 1$ and $0 < ||\underset{\sim}{B}_o + \underset{\sim}{b}_{x\,max}| - |\underset{\sim}{B}_o + \underset{\sim}{b}_{ymax}||/|B_o| \ll 1$. The observations (Figure 3b) indicate that $\delta B/\bar{B} \approx |b_{y\,max}{}^2 - b_{x\,max}{}^2|/(2B_oB) \approx 0.06$, which implies that $b_{x\,max}/b_{y\,max} \approx 0.5$ in a 5γ field. Assuming that the perturbation vector does trace an ellipse, this implies that $\lambda_2/\lambda_1 \approx 0.25$, which is where the peak occurs in Figure 4.

We assume that the waves satisfy $\underset{\sim}{v} = (V_A/B)\,\underset{\sim}{b}$, as suggested by the results of Figure 1, and that the waves propagate along $\underset{\sim}{B}_o$. Then to first order, $\underset{\sim}{b} = b_x\,(z,t)\,\hat{x} + b_y\,(z,t)\hat{y}$, $\underset{\sim}{v} = V_x\,(z,t)\,\hat{x} + V_y\,(z,t)\,\hat{y}$, and from the momentum equation we obtain

$$p + B^2/8\pi = \text{constant} \tag{4}$$

and

$$mn\,\frac{\partial \underset{\sim}{v}}{\partial t} = \frac{B_o \xi}{4\pi}\,\frac{\partial \underset{\sim}{b}}{\partial z} \tag{5}$$

where $\xi = 1 - (p_\parallel - p_\perp)/(B^2/4\pi)$ is a measure of the thermal anisotropy. To the same approximation, Maxwell's equations for a perfectly conducting fluid give

$$\frac{\partial \underset{\sim}{b}}{\partial t} = B_o\,\frac{\partial \underset{\sim}{v}}{\partial z} \tag{6}$$

(e.g. see 3.13 in Burlaga (1971)). Eqs. (5) and (6) are consistent with (1) and give $\frac{\partial^2 v}{\partial t^2} - V_{A_o}{}^2\,\frac{\partial^2 v}{\partial z^2} = 0$, where $V_{A_o}{}^2 = V_A{}^2\,\xi$. In this sense the disturbance is indeed an Alfvén wave. (In general, ξ is observed to be quite close to unity (> 0.9) (e.g., see Table 1 in Burlaga, 1971) and it can be set equal to 1 for the purposes of this paper). Unlike the Alfvén wave of incompressible MHD, the magnetic field intensity does vary for the wave we are considering, but it is subject to the condition that the total pressure given by (4) is constant. This implies that there will be small fluctuations in the thermal pressure p:

$$\frac{\delta p}{p} = -\frac{2}{p}\frac{B^2}{8\pi}\frac{\delta B}{B} = \frac{-2}{\left(1 + \frac{p}{B^2/8\pi}\right)}\frac{\delta B}{B} .$$

Since $p \approx B^2/8\pi$ (e.g. Burlaga and Ogilvie, 1970), $\delta p/p \approx \delta B/B \approx 0.06$, which is too small to be detected by the Explorer 34 plasma analyzer and most other detectors. There will also be fluctuations in $v_z \lesssim V_A\ \delta B/B \approx 3$ km/sec, which are likewise of second order and too small to be detected with the Explorer 34 instrument. Hollweg (1971) discussed a wave similar to that just described, except he assumed linear polarization to be crucial, whereas we do not make that assumption because the waves are not observed to be linearly polarized.

In summary, "Alfvén waves" with finite amplitude magnetic perturbations transverse to the mean field and small, but non-zero fluctuations in $|\underset{\sim}{B}|$ can propagate along the average field, $\underset{\sim}{B}_o$, with the Alfvén speed, V_{A_o}. The thermal pressure changes such that the total pressure is constant and there are second order perturbations in the speed along $\underset{\sim}{B}_o$, but these changes are too small to be detected by most plasma analyzers. Most of the observations in the first part of this paper have characteristics similar to the non-linear "Alfvén wave" just described. However, we cannot exclude other possibilities. A more complete study of interplanetary fluctuations requires more precise measurements of p, and more accurate, three-dimensional measurements of $\underset{\sim}{v}$.

Figure Captions

Fig. 1 Distributions of correlation coefficients between V and B_x for 440 hour-intervals between March 18, 1971 to April 7, 1971. Solid line shows all observations, dotted line shows approximate distribution of events excluding those for which ρ could be ≤ 0.1, and the dashed line shows a predicted distribution for events with ρ actually equal to unity but modified by uncertainties in the measurement of V.

Fig. 2 Distribution of the ratio of the "observed" Alfvén speed to the "theoretical" $V_A = B/(4\pi mn)^{\frac{1}{2}}$. The results are consistent with those to be expected for Alfvén waves.

Fig. 3 a) Distribution of $\delta B_x/\bar{B}$ for events with $\rho > 0.6$ and $\delta B/\bar{B} < 0.2$. b) Distribution of $\delta B/\bar{B}$ for events with $\rho > 0.6$ and $\delta B/\bar{B} < 0.2$.

Fig. 4 Distributions of eigenvalues of the variance ellipsoids of $\underset{\sim}{B}$ for hour intervals, relative to the maximum eigenvalue, λ_1.

Fig. 5 Distribution of ω, the angle between the minimum eigenvalue and the average magnetic field. Most of the fluctuations are nearly transverse to the average field.

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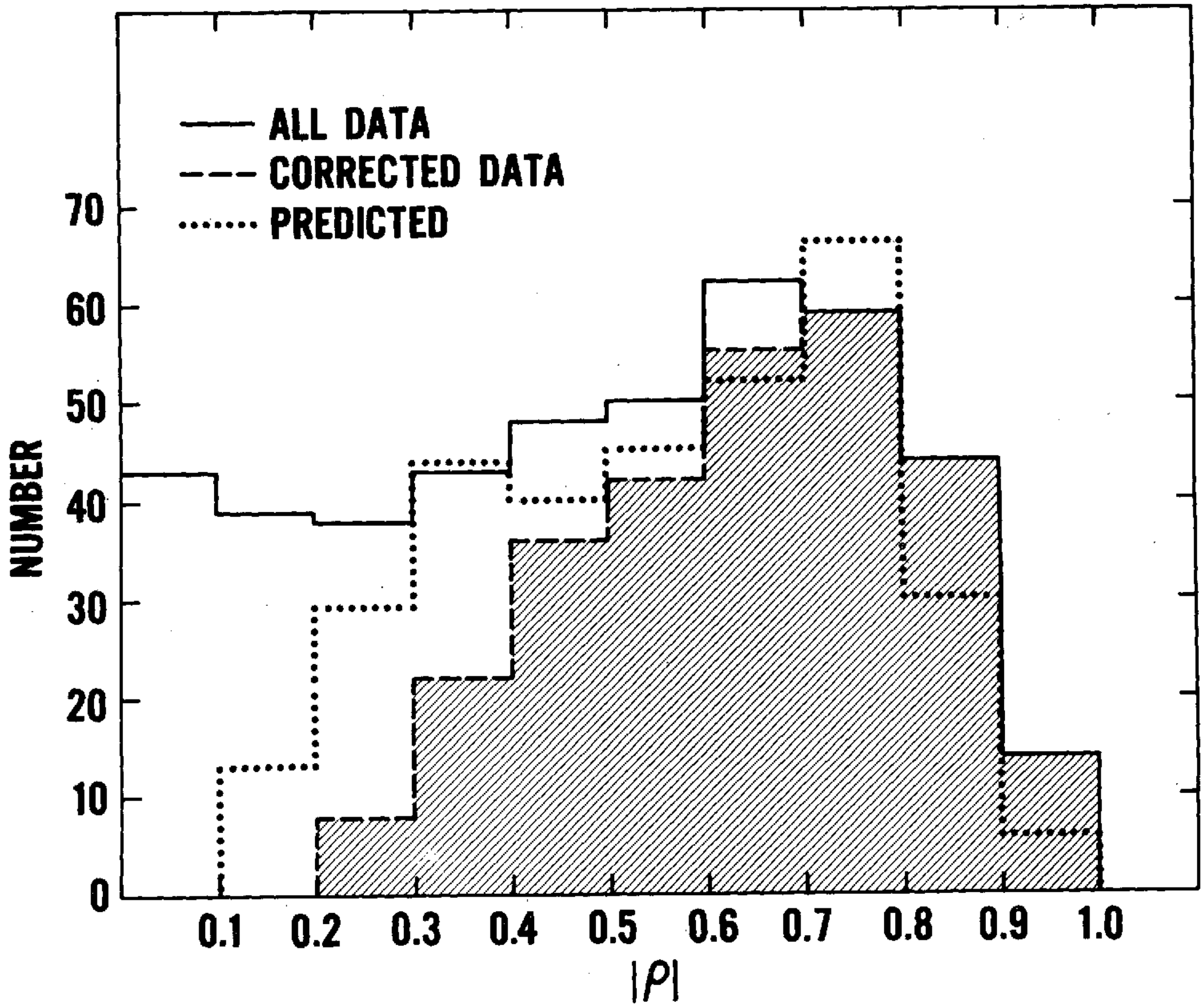
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PREDICTED
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50
40
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20
10
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0.7
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0.9
1.0
|ρ|

Figure 1

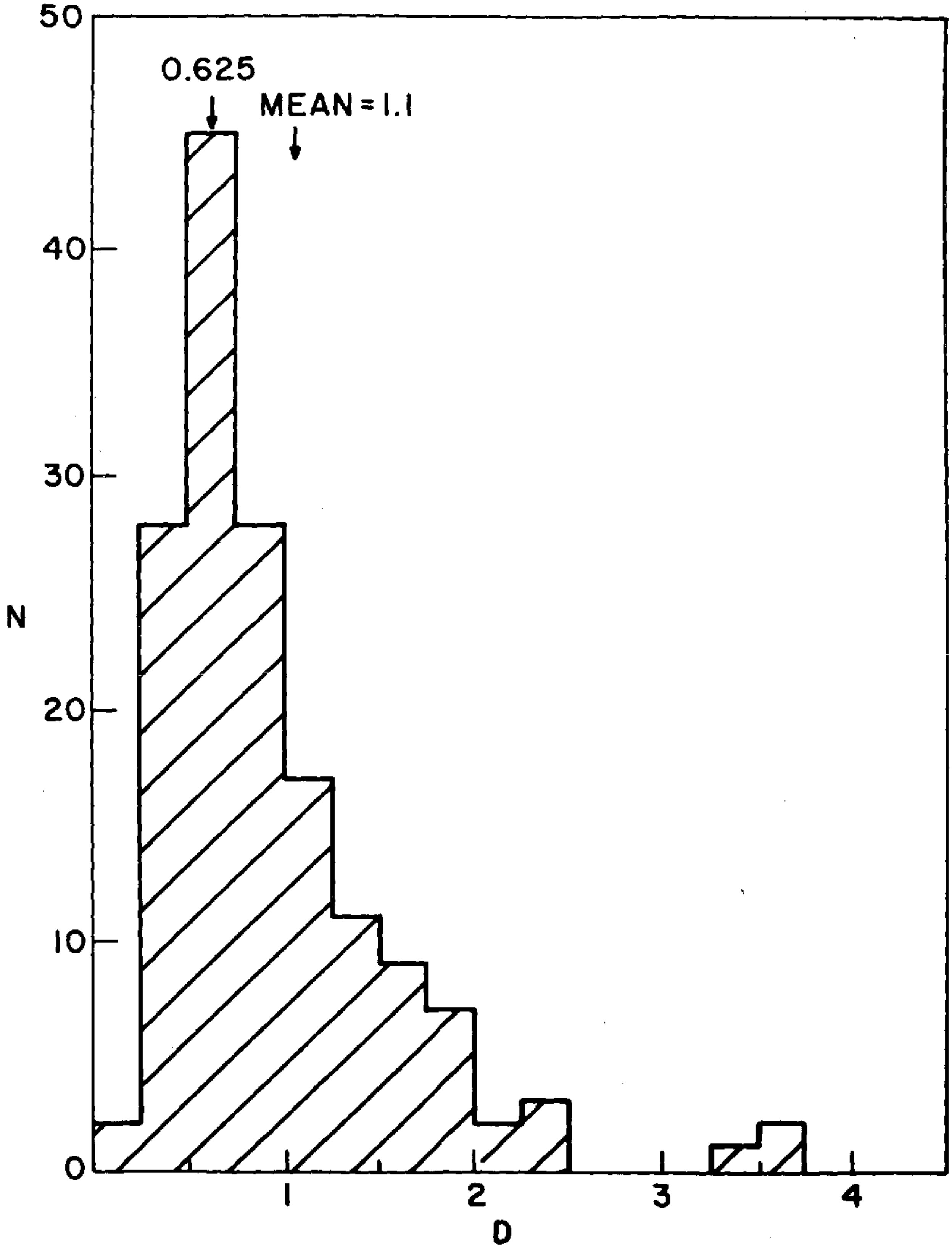


Figure 2

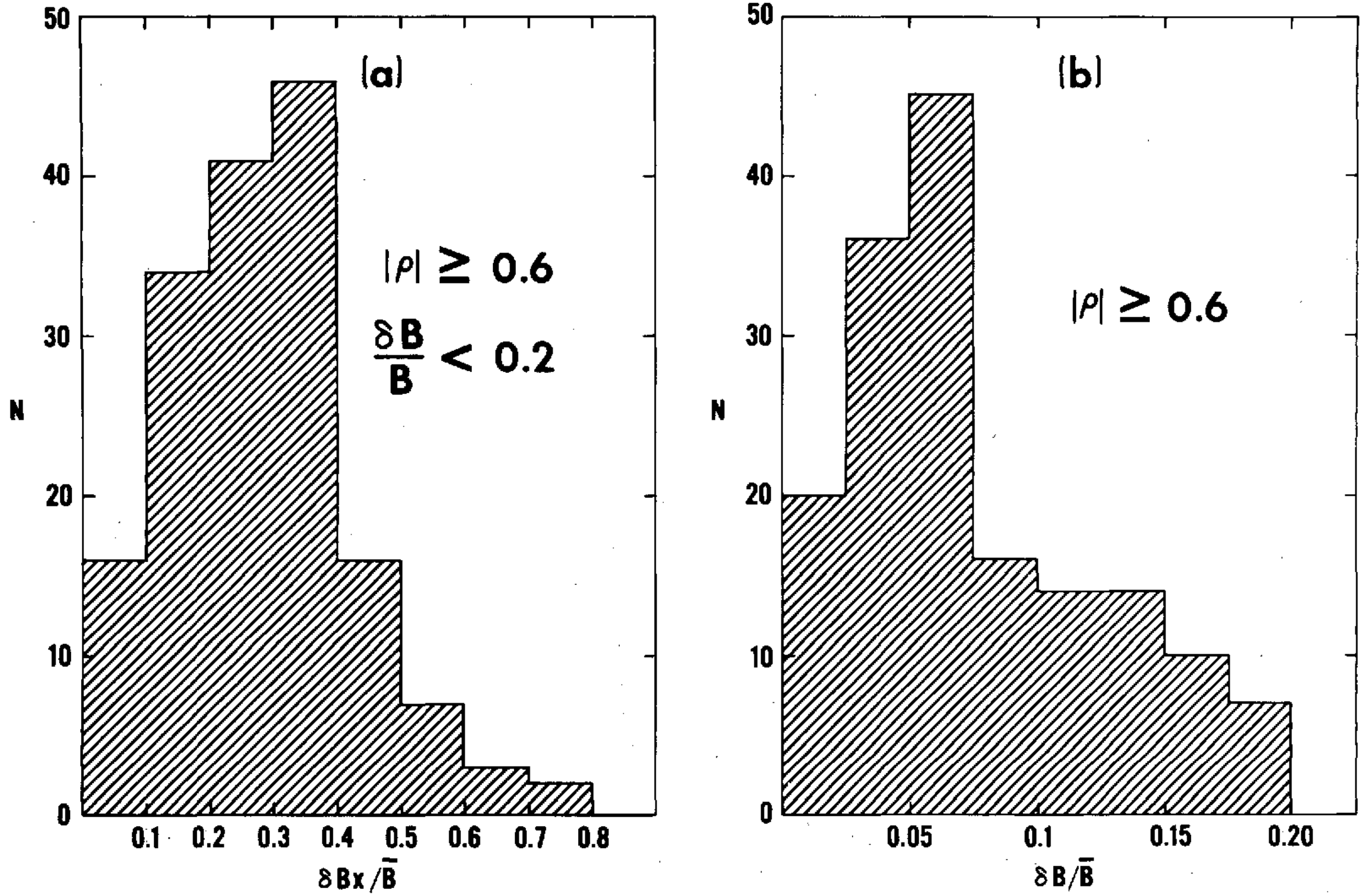
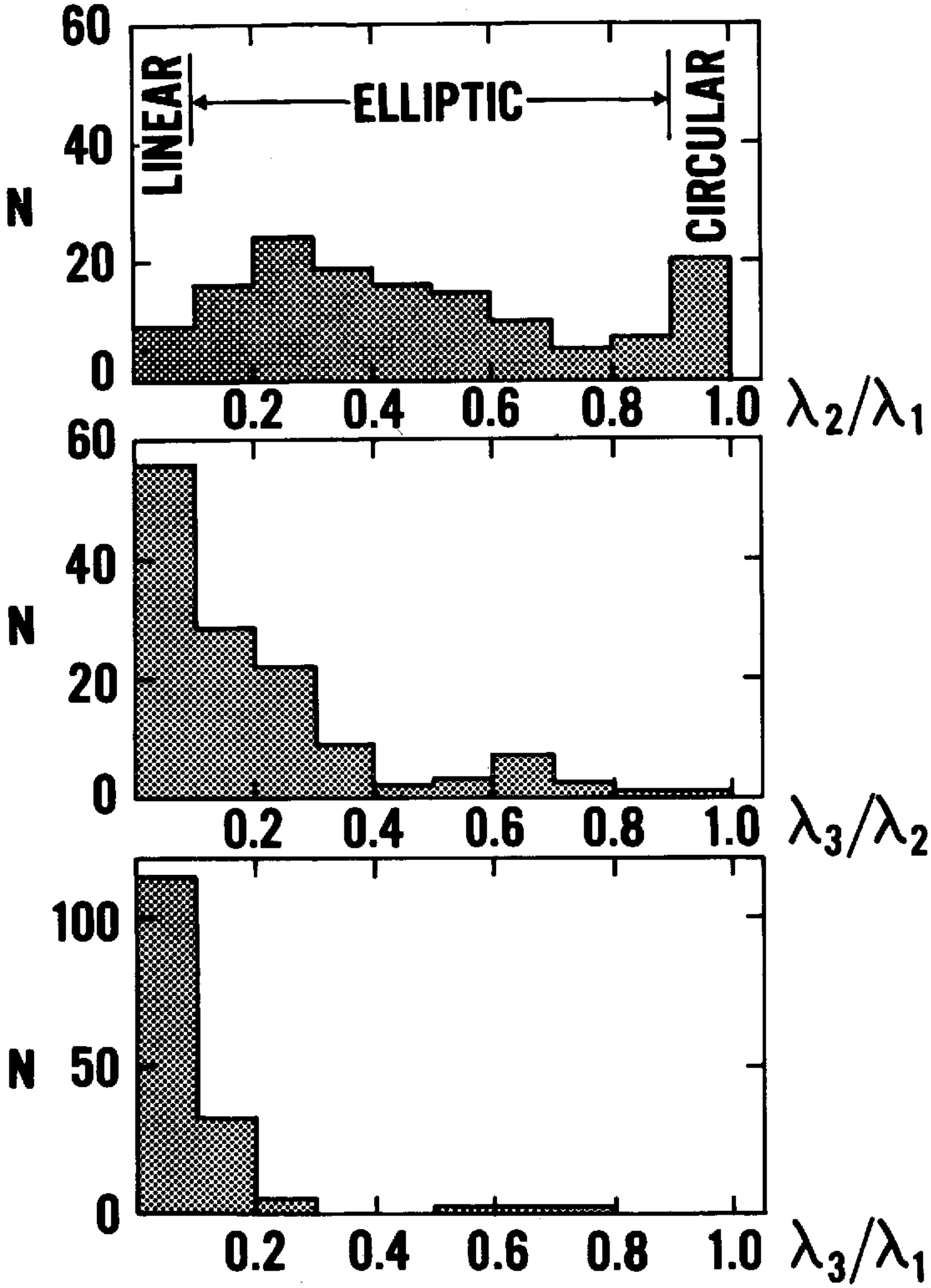

50
40
30
20
10
0
N
(a)
$|\rho| \geq 0.6$
$\frac{\delta B}{B} < 0.2$
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
$\delta Bx/\bar{B}$
(b)
$|\rho| \geq 0.6$
0.05 0.1 0.15 0.20
$\delta B/\bar{B}$

Figure 3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40
N
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0.4
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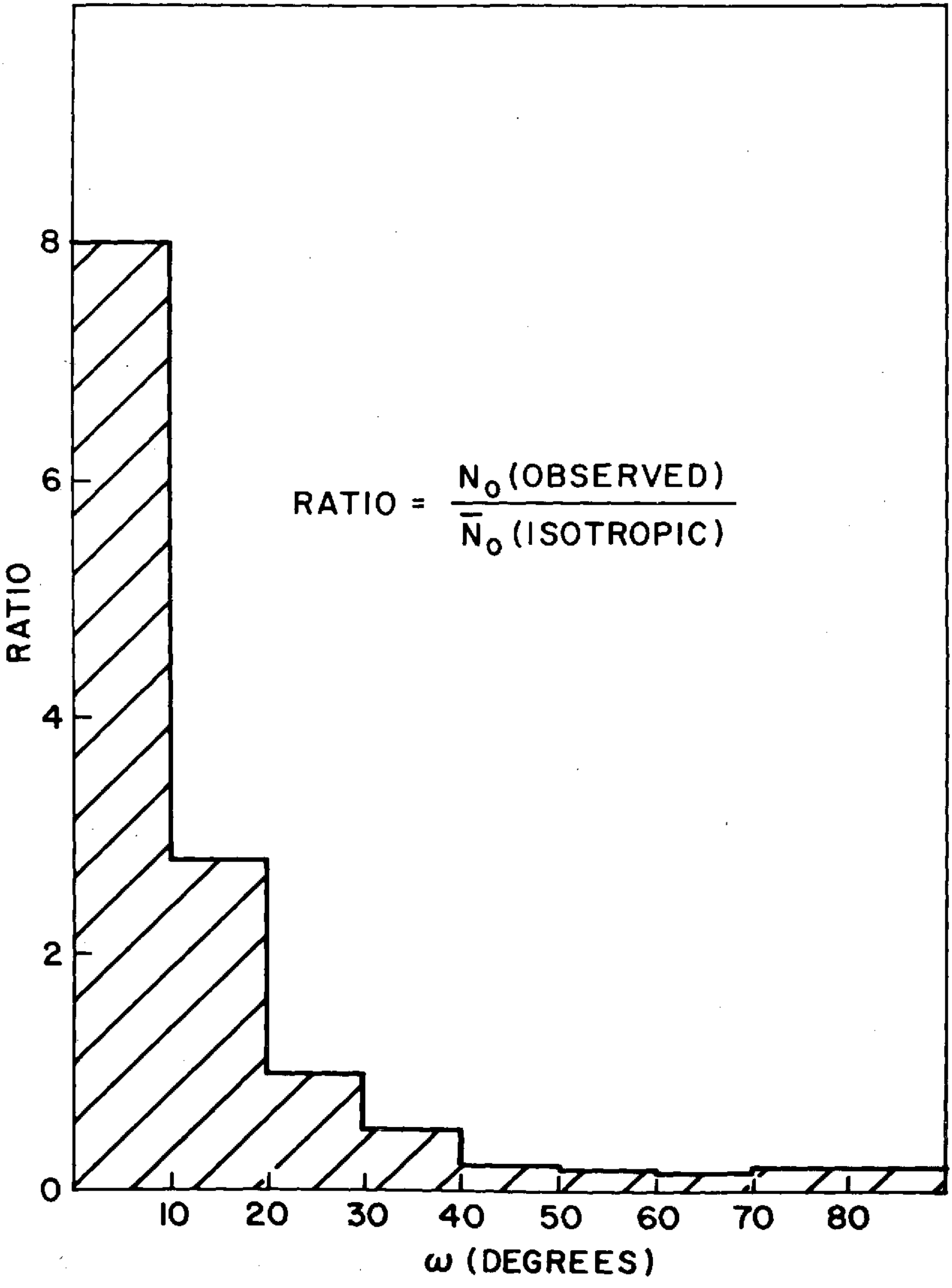
1.0
λ_2/λ_1
60
40
N
20
0
0.2
0.4
0.6
0.8
1.0
λ_3/λ_2
100
N
50
0
0.2
0.4
0.6
0.8
1.0
λ_3/λ_1

Figure 4



8
6
4
2
0
RATIO
RATIO = N₀ (OBSERVED) / N̄₀ (ISOTROPIC)
10
20
30
40
50
60
70
80
ω (DEGREES)

Figure 5