CORONAL MAGNETIC FIELDS

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Abstract. The observational evidence on the strength of the coronal magnetic field above active regions is reviewed. Recent advances in observations and plasma theory are used to determine which data are the more reliable and to revise some earlier estimates of field strength. The results from the different techniques are found to be in general agreement, and the relation $B = 0.5[(R/R_\odot) - 1]^{-1.5}$ G, $1.02 \lesssim R/R_\odot \lesssim 10$ is consistent with all the data to within a factor of about 3.

1. Introduction

Evidence for magnetic fields in the solar corona can be found in several kinds of observations, but there are remarkably few which give values of field strength. In situ measurements have been made no closer than about 0.3 AU. The only 'direct measurements' of field strength at lower heights come from Zeeman splitting of emission lines in the visible part of the spectrum observed when prominences are seen on the limb. And these 'direct measurements' are not of the field in the hot coronal material, but of the field in the denser, cooler material of the prominences. All other evidence on coronal field strength is indirect, involving, in some cases, interpretation in terms of physical ideas of uncertain validity. However, in recent years, both the observational techniques and the theory of the plasma physical processes have advanced considerably, so it is appropriate to re-evaluate the interpretations of old observations and to compile the information coming from new observations which bears on the coronal magnetic field.

Reviews of coronal magnetic fields have been compiled by Newkirk (1967, 1971). In this paper we re-evaluate his sources of data, identify those where the interpretation is suspect, revise others, and then add the new estimates of field strength that have recently become available. Most of the sources of information, especially between a few tenths of a solar radius and a few tenths of an astronomical unit, involve radio observations. We exclude from consideration those radio bursts, mainly moving type IV, where it is likely that strong fields in the outer corona are being carried from low altitudes by transient disturbances.

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We will concentrate our attention on the magnetic field above active regions because there are very few observations which bear directly on the quiet corona. All radio bursts, or at least their exciting agents (particles or shocks), emanate from active regions.

2. Sources of Coronal Magnetic Data

In this section we discuss each of the following sources of data from which information on the coronal magnetic field has been derived: (A) in situ measurements; (B) Zeeman effect in active region prominences; (C) extrapolations from photospheric magnetic data; (D) microwave radio bursts; (E) decimeter radio bursts; and (F) meterwave radio bursts, including types I, II, III, and IV. We consider some of these sources to be unreliable; we state the reasons for our belief and the estimates of the field derived, but exclude them from our presentations in Figures 1 and 2.

As described later, some of the radio data relates not to the magnetic field alone, but also to the particular combination $B/\sqrt{n_e}$ of the field intensity B (gauss) and the plasma electron density n_e (cm^{-3}) found in the Alfvén speed

$$v_A = B/\sqrt{4\pi\mu n_e}, \tag{1a}$$

$$\approx 2.1 \times 10^6\, B/\sqrt{n_e}\ \text{km s}^{-1}, \tag{1b}$$

$$\approx 1.9 \times 10^4\, B/f_p\ \text{km s}^{-1}, \tag{1c}$$

$$\approx 6.6 \times 10^3\, f_B/f_p\ \text{km s}^{-1}, \tag{1d}$$

where $\mu \approx 1.9 \times 10^{-24}$ g is the average mass associated with each electron in the corona, $f_p \approx 9 \times 10^{-3}\sqrt{n_e}$ MHz is the plasma frequency and $f_B \approx 2.8B$ MHz is the electron gyromagnetic frequency. Therefore, to use data of this type to derive the magnetic field strength and height in the atmosphere to which it pertains, we require a model of the density above the active region. Most of the radio data is statistical, covering many active regions, so that an average density model is appropriate. But even the average density above active regions is not well known and the range of densities among active regions is probably quite large. Therefore, the magnetic field strengths discussed in the following sections will be presented for two density models; Figure 1 is for a low-to-moderate density model taken to be twice that given by Newkirk (1967) or Saito (1970) (see also Saito *et al.*, 1977) for the equatorial corona at sunspot minimum, and Figure 2 is for a high density model taken to be eight times the Newkirk-Saito model. It turns out that the derived field strength depends weakly, if at all, on the model, but the pertinent height in the atmosphere is affected significantly.

A. IN SITU DATA

Measurements of the interplanetary magnetic field have been made by several different spacecraft. Behannon (1976) has compiled the data between 0.5 AU and

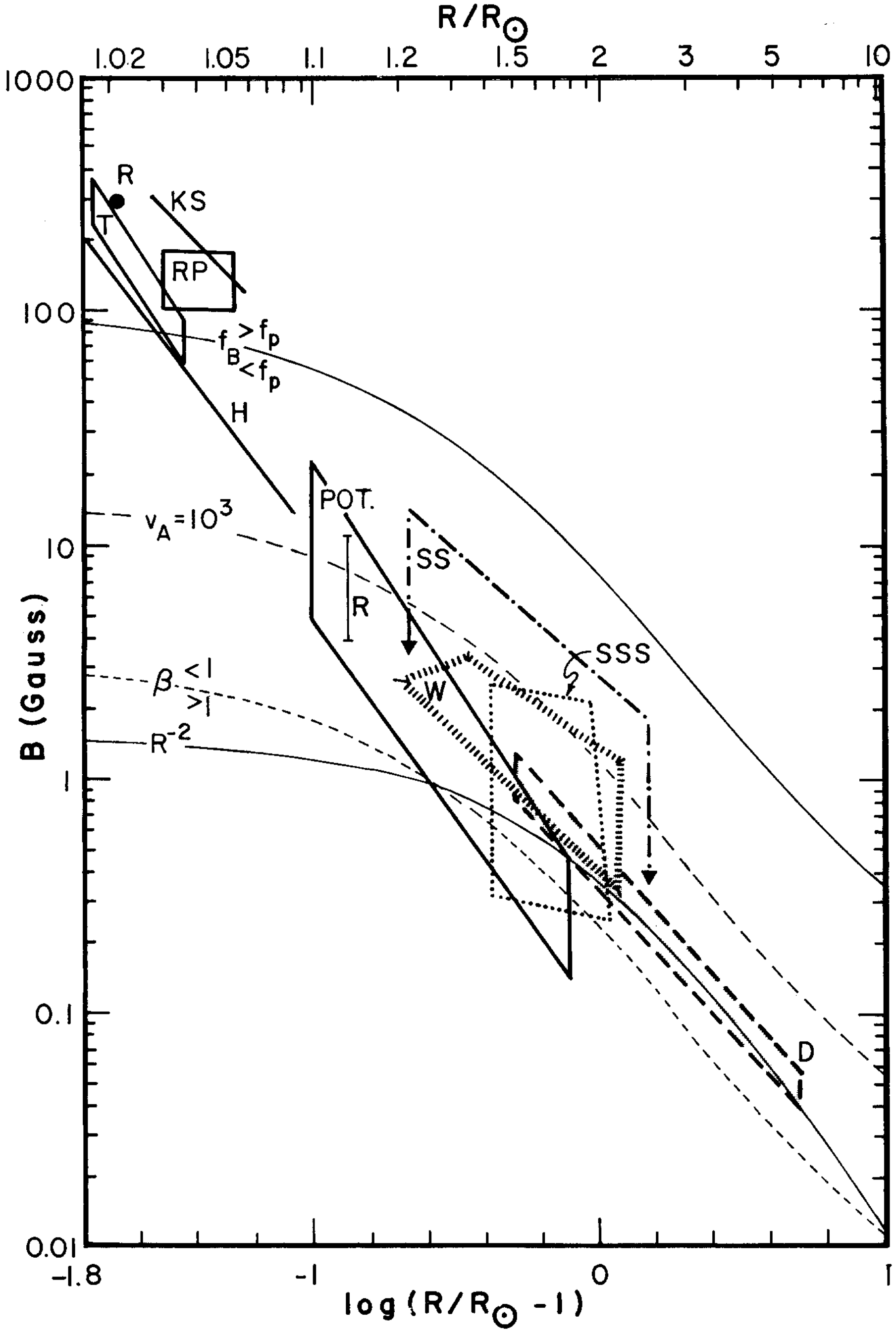

Fig. 1. Magnetic field strength vs height above active regions. A coronal density model twice that given by Newkirk (1967) or Saito (1970) for the equatorial corona at sunspot minimum has been assumed. (This assumption affects only the positions of boxes 'SS', 'SSS' and 'W', and the curves for $f_B = f_p$, $v_A = 10^3$ km s^{-1} and $\beta = 1$.) The various lines and boxes are identified in the text.

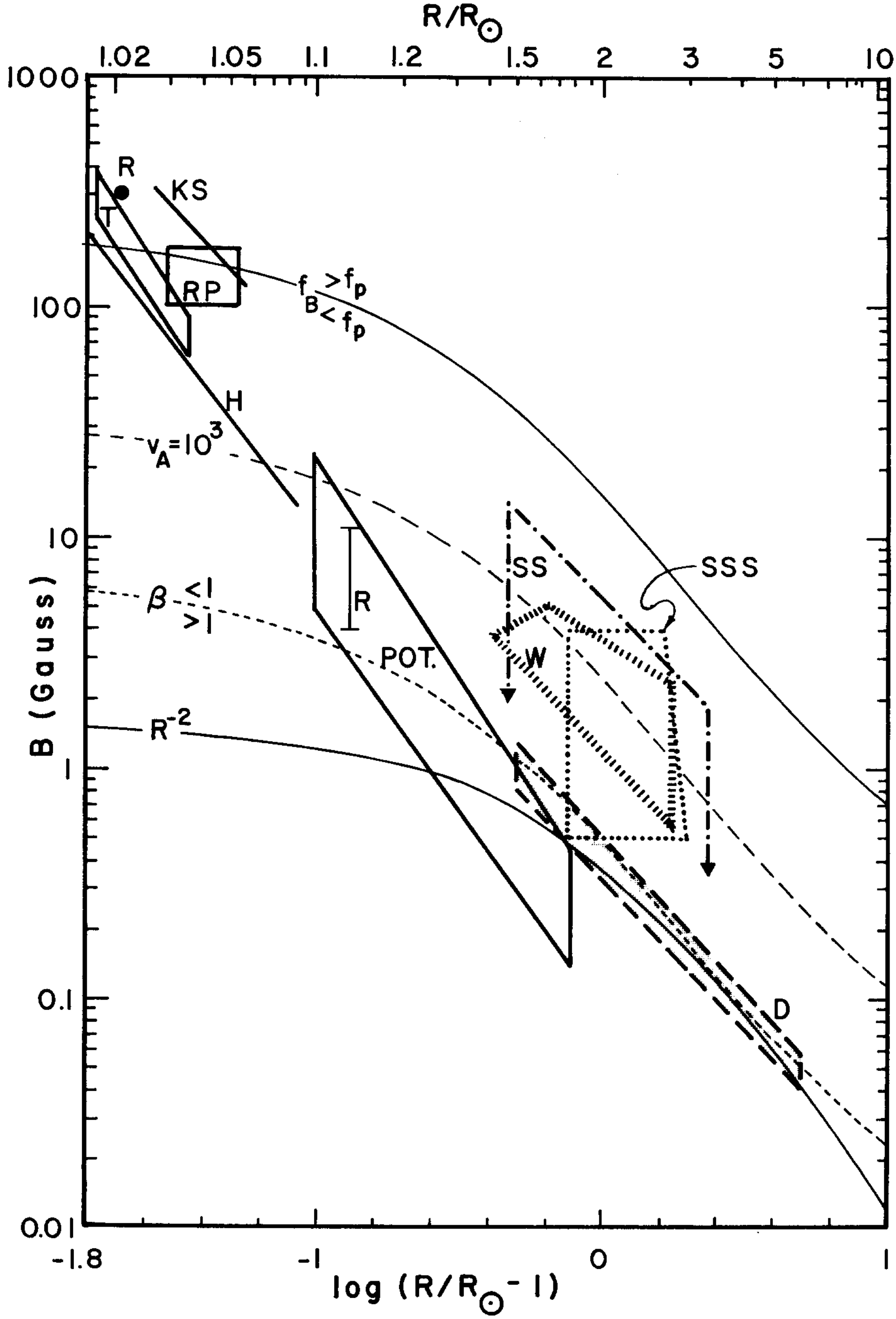

Fig. 2. Same as Figure 1 but for a coronal density model eight times that given by Newkirk (1967) or Saito (1970). Note that the box 'D' has been included for reference although it is inconsistent with the high density model adopted for this figure; it was derived using an observed (low) density distribution.

5 AU and shows that the radial component of magnetic field, which is the only component of interest for solar wind data, can be fitted by the function

$$B_r = 3.0 \times 10^{-5} (R/216)^{-2}\,\mathrm{G}, \tag{2}$$

where R is in solar radii. When extrapolated to the solar surface, this formula gives $B_r \approx 1.4$ G; however, the observational uncertainty in the coefficient and exponent make this number uncertain to about a factor of two.

We would not expect the R^{-2} law to apply low in the corona, below about two radii, because of the influence of closed magnetic structures and the nonradial divergence associated with coronal holes (e.g., Munro and Jackson, 1977). These effects would imply that the exponent should be larger than 2 below $R \approx 2R_\odot$; a recent analysis of Faraday rotation from Helios as it was occulted by the corona seems to be consistent with these expectations (Volland *et al.*, 1977).

The R^{-2} law is plotted in Figures 1 and 2. For reference, we also plot three other curves, one which corresponds to equal magnetic and thermal energy density (i.e., $\beta = nkT/(B^2/8\pi) = 1$, where k is the Boltzmann's constant, $n = n_e + n_i \approx 1.92 n_e$, and T is taken to be 1.5×10^6 K), a second curve which corresponds to $v_{\mathrm{A}} = 1000\,\mathrm{km\,s^{-1}}$, and a third which corresponds to $f_B = f_p$. Each of these latter curves involve the density model as well as field (Equation (2)), so are different on the two figures. The similar form of these three curves is no coincidence: from Equations (1b) and (1d), $\beta \approx 4.0 \times 10^4 / v_{\mathrm{A}}^2 \approx 10^{-3} (f_p/f_B)^2$ for $T = 1.5 \times 10^6$ K.

The existence of the well-defined arches and loops seen below $R \approx 2$ both in quiet and in active regions (eclipse photos, Hα, green line, X-rays) is usually taken to imply that $\beta < 1$; thus we can consider the $\beta = 1$ curve in the figures to be a lower limit to the magnetic field.

B. ZEEMAN EFFECT IN ACTIVE REGION PROMINENCES

The magnetic field in active region prominences has been inferred from several indirect and direct methods; requirements for stability (e.g., Kippenhahn and Schlüter, 1957), thermal insulation from the surrounding hot corona (Rosseland *et al.*, 1956), form of loops, curvature of trajectories of prominence material (e.g., Idlis *et al.*, 1956; Warwick, 1957), filament oscillation (Hyder, 1966), polarization of emission lines (e.g. Hyder, 1964), and Zeeman effect in emission lines (Zirin and Severny, 1961; Zirin, 1961; Ioshpa, 1963; Rust, 1966; Malville, 1968; Harvey, 1969; Tandberg-Hanssen, 1970; Tandberg-Hanssen and Malville, 1974). Of these methods, the most reliable is the Zeeman effect. Because of this and because the other methods give, in most cases, similar results, we confine our discussion to Zeeman technique.

The earliest observations of active region prominences with magnetographs tended to give the highest magnetic fields, about 200 G, while later observations indicated that few or no prominences have >150 G. Harvey (1969) found that the median longitudinal field in his 172 observations was 26 G and that the maximum field decreases with height according to the relation

$$B_{\max} = 6.2 \times 10^8 \, h^{-1.6} , \tag{3}$$

where h is in km. We plot this relation in Figure 1, labelled '*H*'.

While the relation (3) is an upper limit in that it represents the maximum fields observed, it must be remembered that only the longitudinal component of the fields were measured and that the prominences were observed above the limb. Thus it is possible that significant field components were unrecorded, in particular the vertical components which may be the dominant ones.

Attempts have been made to measure the field in the hot, coronal material above active regions using the Zeeman splitting of the green line of Fe XIV (e.g., Harvey, 1969). The results have not been conclusive, partly because of the large noise level in the observations and partly because the large aperture (required because of the low light level) and the long line of sight through the corona could easily have contained fields of opposite polarity.

C. EXTRAPOLATIONS FROM PHOTOSPHERIC MAGNETIC DATA

This is now possibly the best source of information on coronal magnetic fields in the range 1.1 to about $1.4R_\odot$. Early attempts to calculate potential fields above active regions (e.g., Schmidt, 1964) and compare them with observations (Rust, 1966; Harvey, 1969; Rust and Roy, 1970) were confronted with measured fields about ten times larger than those calculated. However, the situation is now changed because of the introduction of high resolution magnetographs with a large dynamic range (Livingston and Harvey, 1971; Livingston *et al.*, 1976) and improved methods of computations, using global data and much higher resolution (Adams and Pneuman, 1976; Altschuler *et al.*, 1977).

Pneuman and Hansen (private communication) have kindly provided us with maps of the computed field strength at heights in the corona ranging from 1.1 to $2.5R_\odot$. For each of about 10 solar rotations in 1973–74 we identified the field strength above the active regions (about 4 per map) at each of several heights. We plot the results on Figures 1 and 2 in the form of a box (labelled 'POT') which represents the average field strength plus and minus one standard deviation.

One difficulty that arises in these global computations of coronal field is where to place the artificial 'source surface' which simulates the volume distribution of currents in the corona and forces the field to be radial beyond $R \approx 2R_\odot$. While the placement hardly affects the computed field below $R \approx 1.4$, a change from 1.8 to 2.5 radii causes the calculated fields at, say $R \approx 2$ to decrease by a factor of about three. Pneuman (private communication) finds the best agreement between calculated fields and observed forms of coronal features occurs when the source surface is placed at $R \approx 1.8$, so we use that placement in deriving the results of Figures 1 and 2.

We note that the results plotted in the figures have a steeper slope than either the R^{-2} curve or the $\beta = 1$ curve, and fall below those curves at $R \gtrsim 1.4R_\odot$. Because of the problems regarding (1) the applicability of potential field analysis when $\beta \gtrsim 1$, and (2) the position and artificiality of the source surface, we must suspect the potential calculations above $R \approx 1.4$.

D. MICROWAVE RADIO EMISSION

Microwave radio emission, both the slowly-varying component and flare-associated bursts, have been used to estimate the magnetic field strength in the low corona above active regions. One of the first estimates was by Kakinuma and Swarup (1962) who studied the intensity spectrum and polarization spectrum of the slowly-varying component. They based their study on observations of ten active regions in the year 1960 at wavelengths between 3 and 21 cm. They concluded that the properties of the radiation could be explained only by invoking gyroresonance absorption at low harmonics (first and second) of the gyrofrequency, and thus deduced that the average magnetic field over the active region varied from about 600 G at 2×10^4 km to 250 G at 4×10^4 km. Subsequent work (e.g., Takakura, 1967; Holt and Ramaty, 1969; Takakura, 1972; Ramaty and Petrosian, 1972) has indicated that gyroresonance absorption can be important also at the third harmonic and perhaps at the fourth, so we suggest that Kakinuma and Swarup's values of magnetic field should be approximately halved. The diagonal line labelled 'KS' in the upper left corner of Figures 1 and 2 gives these halved values.

The uncertainty in the estimate of the magnetic field just derived is about 50% due to the question about gyroresonance absorption at the fourth harmonic. Further, there are variations in the properties of the slowly-varying component from one active region to another which would imply fields that differ by at least a factor of 3. Of possibly greater importance is the uncertainty in the height from which the radiation comes. In Figures 1 and 2 we have used the values quoted by Kakinuma and Swarup, but they admit to considerable scatter in height measurements. Thus a displacement of the 'KS' curve in the figures to lower heights, say to the left margin, would not be unreasonable.

The spectral properties of the polarization and intensity of flare-associated microwave bursts have been used by a number of workers to estimate the magnetic fields in active regions (Takakura, 1960; Cohen, 1961; Takakura, 1967; Kai, 1968; Takakura *et al.*, 1968; Holt and Ramaty, 1968; Ramaty and Petrosian, 1972; Takakura, 1972). Much of the work before about 1968 ignored several mechanisms which turned out to be important in forming the observed intensity and polarization spectra. In particular, gyrosynchrotron self-absorption, free-free absorption, and gyroresonance absorption are usually important and the Razin-Tsytovich effect may sometimes be important (e.g., Ramaty, 1973). Therefore, we present only the results published by Ramaty and Petrosian (1972) and by Takakura (1972).

Ramaty and Petrosian (1972) considered three flares with a 'flat' microwave spectrum, i.e., with nearly constant flux density at wavelengths shorter than about 15 cm. They found that the flat spectrum requires both free-free and self-absorption of the gyrosynchrotron emission to be important. They were able to deduce average properties of the emitting region, including limits on the magnetic field: $100 \lesssim B \lesssim 180$ G at the position where $n_e \approx 2 \times 10^{10}$ cm^{-3}. There is no direct measurement of the height to which this field estimate pertains. Also, the density at low heights during a flare is likely to be considerably higher than at other times (e.g., de Feiter, 1974). Thus we have used Švestka's (1976) Figure 29 to estimate that the pertinent height is between 2 and 3×10^4 km. We plot on Figures 1 and 2 a box labelled 'RP' to denote the field estimated by Ramaty and Petrosian and the height range estimated by us.

Takakura (1972) considered the radio emission emanating from a non-uniform flare region, where the emission at different wavelengths arises from regions of different height, different densities and different magnetic field strengths. He computed the gyrosynchrotron emission at several wavelengths, taking self-absorption into account, and compared the computed intensity and polarization spectra with observations. Although his results are somewhat model dependent, Takakura deduced that the observations require the magnetic field to be in the range 220–370 G at 1.3×10^4 km (the effective height of 9.4 GHz radiation) and in the range 60–90 G at 2.5×10^4 km (the effective height of 2 GHz radiation). The box labelled '*T*' in Figures 1 and 2 shows these results. Using another model of an active region which also could satisfy the observations, Takakura derived values of field which were lower by a factor of about 1.1 to 2 than those just given.

E. BUSTS AT DECIMETER WAVELENGTHS

At decimeter wavelengths, dynamic spectra show interesting and complicated structures. One common variation, 'fiber bursts' has a drift rate which is intermediate between those of type II and type III, and has an emission 'ridge' at a slightly higher frequency than an accompanying absorption 'ridge'. These bursts have been studied by Kuijpers (1975), who suggests that they result from coupling between whistlers and Langmuir waves to produce transverse waves. In Kuijpers' theory, whistlers with a certain speed, 21.5 to 28 times the Alfvén speed, are needed to explain the observed drift rates, and the whistler frequency must be between 0.1 to 0.5 of the gyromagnetic frequency in order to explain the frequency separation of the emission and absorption ridges. Both of these properties can be used to estimate the magnetic field; the former gives tighter limits which are completely consistent with the latter. The results as given in Kuipers' Table III are presented here in Table I, where we have added columns giving electron density and plasma beta.

We note that the magnetic field strengths derived in Table I are considerably smaller than those inferred from microwave bursts for a similar height or density range. Also, the resulting $\beta \gtrsim 1$ would seem to be in conflict with the existence of discrete looplike structures in active regions.

While Kuijpers' work represents an interesting application of plasma theory and it is one of the first attempts to explain the fiber bursts, its reliability as a means of estimating coronal fields is suspect and therefore we have not included the results

TABLE I

Magnetic field strength derived from intermediate drift bursts[a]

f_p (MHz)	n_e (cm^{-3})	B(G)		β
		(1)	(2)	(2)
900	1.0×10^{10}	7.2–36	15–11.5	0.5–0.8
320	1.3×10^{9}	1.1–11	3–2.3	1.5–2.5
160	3.2×10^{8}	0.36–1.8	0.66–0.51	7.5–12.6

[a] Adapted from Kuijpers (1975).

(1) Determined from instantaneous ridge separation assuming that $\Delta f = 0.1\text{–}0.5 f_B$.

(2) Determined from observed drift rates.

on Figures 1 and 2. There are numerous other plasma mechanisms besides coupling between Langmuir waves and whistlers which might explain the bursts, but none has yet been explored in detail. Examples include particle streams, electron cyclotron waves, Bernstein waves, Z-mode waves, hydromagnetic waves other than whistlers, etc. In fact, it is interesting to note that in Figures 1 and 2, the height range relevant to decimeter bursts, about $R = 1.05$ to $1.1R_\odot$, is just where $f_B \approx f_p$. This suggests that wave modes which involve both the plasma frequency and the electron gyromagnetic frequency might be promising candidates for explaining various kinds of decimeter bursts.

F. BURSTS AT METER WAVELENGTHS

Type I Bursts

Type I storms, consisting of many short-lived bursts superimposed on a background continuum, are closely associated with active regions which contain large sunspots (Payne-Scott and Little, 1951; Le Squeren, 1963). Both the bursts and the continuum are generally strongly circularly polarized, of the order of 70 to 100%, and the sense of polarization is that of the ordinary mode (Fokker, 1960; Suzuki, 1961; Le Squeren, 1963; Dulk and Nelson, 1973; Kai and Sheridan, 1974). It seems probable that when we understand this type of burst it will provide a useful estimate of the magnetic field strength in the source region.

However, at the present time, there are many theories of type I emission (see, for example, the summaries in Elgaroy, 1977). Of these, one of the more interesting is that of Takakura (1963) and Kai (1970) which leads to rather high estimates of field. We have not included these estimates, nor any based on type I emission, because of major uncertainties in the theories. Moreover, because the radiation at each frequency probably originates near the plasma level, the interpreter of the observed polarization must take into account the effects of propagation through the plasma, effects which are difficult to estimate without a detailed knowledge of the geometry of the magnetic field and electron density distribution near the source.

Type II Bursts

It is generally accepted that type II bursts are the radio emission from magnetohydrodynamic shock fronts in the solar corona and that the emission process, basically the same as for type III bursts, produces radiation at the local plasma frequency and at approximately twice that frequency. Without going into the detailed theory, we can obtain an estimate of the ambient coronal magnetic field near the shock front as follows: given a model for the electron density $n_e(r)$ as a function of radial distance, r, from the center of the Sun, we can relate emission frequency to height, and hence frequency drift rate to radial velocity, v_r. The requirement that the emission originate in a shock front is equivalent to the requirement that the Alfvénic Mach number, defined by $M_A = v/v_A$, be greater than some limit M^*, say, of order unity. Here v_A is the local Alfvén speed (Equation (1)), v is the speed of the disturbance, and M^* is a critical Mach number which must be exceeded if radiation is to result. Except if the direction of motion of the disturbances departs significantly from radial, this implies the approximate relation

$$v_r \geq M^* v_A = 1.9 \times 10^4 \, M^* B/f_p \,,$$

where both v_r and the plasma frequency, f_p (MHz), can be found from the observations. This technique was used first by Takakura (1964) and Weiss (1965), who assumed $v_r = v_A$ and thus obtained an upper limit on B.

The field estimated by putting $v_r = v_A$, although an upper limit, is probably quite good because the shock waves which produce type II bursts are generally weak shocks, i.e., $M_A \lesssim 1.5$. One reason for believing that these shocks are weak is that type II fundamental radiation is generally not observed at frequencies higher than about 100 MHz, corresponding to a height of a few tenths of $R_\odot$ in the solar corona. Fomichev and Chertok (1965) suggested that this is because the Alfvén speed in the low corona above active regions is greater than typical disturbance speeds. Thus the emission is first observed from the height at which the Mach number of the disturbance exceeds unity. Fomichev and Chertok used this argument to estimate the field at the starting heights of type II bursts. There are, however, reasons to believe that type II shock fronts continue to be weak throughout their duration and so we have utilized data for the whole duration of the large set of type II bursts measured by Weiss (1965). We have assumed $v_r = 1.2 v_A$ in our derivation of the magnetic field, the results of which are given as the box labelled 'W' in Figures 1 and 2. The vertical extent of this box represents a real variation from burst to burst. The uncertainty in the field strength resulting from the uncertainty in the Mach number is not great, perhaps 30%. Another uncertainty results from the possibility that for some shocks the motion may have been nonradial, particularly at low heights; this would cause an underestimate of the field strength in those cases by up to a factor of 2, but the average effect on the whole data set would be far smaller. Of more importance is the uncertainty in the height to which the magnetic field pertains; this is due to our lack of an accurate density model. The magnitude of the uncertainty is evident from a comparison of Figures 1 and 2.

A somewhat different approach to finding the magnetic field in the vicinity of type II shock fronts was introduced by Smerd *et al.* (1974). Their approach is based on the not-uncommon feature of type II bursts that both the fundamental and second harmonic emission components are split into twin bands. Smerd *et al.* (1974) suggest that the lower frequency bands originate just in front of the shock front, while the higher frequency bands originate in the denser plasma just behind the shock. Using the Rankine-Hugoniot relations for a one-dimensional shock, they are able to deduce the Alfvénic Mach number, M_A, from the frequency split, and hence by the arguments already presented, the ambient magnetic field. They deduce values of M_A which are mostly in the range 1.2 to 1.5, further supporting the idea that type II shocks are weak.

The magnetic field strengths they deduced are indicated in Figures 1 and 2 by the box labelled 'SSS'. The differences between the boxes 'W' and 'SSS' result from the selection of different data sets and from the range of values of Mach number which emerge from the analysis. While in general the two are consistent, the lower left corner of the box 'SSS' has no counterpart in 'W'. In looking closely at Smerd *et al.*'s data, we find that our lower left corner represents not more than one or two bursts which had exceptionally low drift rates. A low drift rate need not represent a low shock velocity (and hence by interpretation a low magnetic field), but possibly the non-radial propagation of the shock or its encountering a region of exceptionally low density gradient. Not knowing for certain, we have retained the data in Figures 1 and 2.

Type III Bursts

It is now well established that type III bursts result from streams of fast electrons moving out from active regions along open magnetic field lines. At each height, the electron streams generate intense Langmuir waves at the local plasma frequency, and some of the energy of the Langmuir waves is scattered into electromagnetic waves at both the fundamental and second harmonic of the local plasma frequency. The presence of the background magnetic field affects the properties of the Langmuir waves, the conversion processes, and the escaping radiation, resulting in a net degree of polarization for the escaping radiation. The theory has been discussed in general by Melrose and Sy (1972) and in more detail, for second harmonic emission, by Melrose *et al.* (1977).

Although there have been occasional reports of polarized type III harmonic bursts before (Komesaroff, 1958; Enome, 1964; Sheridan *et al.*, 1973; Takakura and Yousef, 1975; Santin, 1976), it is only recently that there have been reliable measurements of the polarization of large numbers of type III bursts along with a careful separation of fundamentals from second harmonics. Suzuki and Sheridan (1977) used a swept-frequency polarimeter operating between 25 and 220 MHz and measured the degree of circular polarization of 94 fundamental-harmonic pairs. They found that both the fundamental and harmonic radiation is often polarized. The degree of polarization of the harmonic radiation (a) averages about 0.13 and is almost always less than 0.3, (b) is approximately 30% of that of the fundamental, (c) is always in the same sense as the fundamental, and (d) is approximately independent of frequency between 25 and about 200 MHz.

The interpretation of the polarization of *fundamental* radiation is not straightforward. As has been shown by Kai (1970) and by Melrose and Sy (1972), if propagation effects are ignored, the relatively low degree of polarization observed, $\lesssim 0.5$, implies a very low field strength in the source region, e.g., $\lesssim 0.1$ G at about $1.2 R_\odot$. However, propagation effects are undoubtedly very important for fundamental radiation, especially near the plasma level where the index of refraction is very small. Mode-mode coupling in quasi-transverse regions is likely to alter the polarization significantly (e.g., Melrose, 1975, 1977) especially when scattering from coronal inhomogeneities is taken into account. Therefore, we concentrate our attention on the harmonic bursts, where these effects are much less important.

The degree of polarization of second harmonic radiation is given by (Melrose and Sy, 1972; Melrose *et al.*, 1977)

$$r = a(\theta) f_B / f_p ,$$

where $a(\theta)$ is a slowly-varying function of the angle θ between the magnetic field direction and the viewing direction, and for Langmuir waves confined to a small cone centered on the field direction is in the range $0.4 \lesssim a \lesssim 1.0$ for $20° \lesssim \theta \lesssim 70°$. For present purposes we take $a = 0.63$ which pertains to $\theta = 45°$, where maximum power is radiated. Then the observed mean value $r = 0.13$ leads to values of B ranging from 7.2 G at the 100 MHz plasma level to 0.9 G at the 12.5 MHz plasma level. The maximum polarization observed leads to field strengths about twice as large; we take these as upper limits and plot them in Figures 1 and 2 labeled ‘SS’. The lower limits are not well determined because the minimum polarization observed is zero, but only to an accuracy of about 5%.

We consider that observation of harmonic type III polarization promises to be one of the best ways of estimating coronal magnetic field strengths. The theory is now well-developed, propagation effects are likely to be small, and appropriate instrumentation is just becoming available. However, the initial observations of Suzuki and Sheridan (1977) were not ideal for the purpose. First, their discrimination of the degree of polarization was less than desirable for observations of harmonic bursts. Second, their polarimeter observations were not supplemented with heliograph or other information on the location of the burst sources. This is important because of the factor $a(\theta)$ above; for quasi-radial open field lines, one would expect θ to be small when bursts occur near the center of the disc and to approach 90° for bursts occurring near the limb. A possible reason for the rather high polarization ($\gtrsim 0.2$) of some bursts observed by Suzuki and Sheridan is that they originated near the limb; by using $a = 0.63$, rather than say $a \gtrsim 1$, we may have over-estimated the field by nearly a factor of 2.

Eventually, the only limitation we foresee to the application of this type of observation to the measurement of coronal fields, is that the height of the emission is uncertain. This problem will be discussed further in Section 3.

Type IV Bursts

When observed with dynamic spectrographs, type IV emission appears as continuum radiation with a frequency spread of at least 2 to 1. In the original observations by Boischot (1957), who first aplied the term type IV, the radiation was at meter wavelengths and came from a moving source. Unfortunately the term was later extended to all wide band continua radiated from stationary or moving sources and observed anywhere in the radio frequency range. Thus it now applies to burst sources of very different physical characteristics. However, in this section we will confine our attention to two varieties: (a) meterwave continuum from stationary sources, and (b) moving type IV sources.

(a) Meterwave continuum from stationary sources is often designated Flare Continuum if it occurs in association with the flash phase of flares (i.e., type III and/or type II bursts) and Storm Continuum if it occurs late in a flare in association with development of a type I storm (e.g., Wild, 1970). Because type I bursts were discussed earlier, we will not discuss Storm Continuum any further.

Flare Continuum bursts have recently been studied by Robinson and Smerd (1975), Magun *et al.* (1975), and Robinson (1977). It seems that there are several subspecies of Flare Continuum bursts, and it may turn out that each will give information on coronal magnetic fields. But as yet, for only one event has the available information been sufficient to allow an estimate of the coronal magnetic field. This event, reported by Dulk *et al.* (1976), was of the variety termed Slow Drift Continuum because in such events the continuum typically has a low frequency cutoff which drifts from high to low frequencies at a rate which is similar to that of type II bursts. It was a special event because it occurred in association with the coronal transient event of 14–15 September, 1973 and was observed not only with the Culgoora radioheliograph, but also with the white light coronagraph on Skylab. Thus there was a considerable variety of complementary information available and this permitted an extensive examination of the physical nature of the event.

The event of 14–15 September, 1973 occurred about 25° behind the west limb. No type II burst was observed, presumably because it was so far behind the limb. But it was surmised that a shock front did exist, partly because the white light data indicated the presence of a bow wave, but mainly because the bright radio emission required the presence of non-thermal electrons as produced in collisionless shocks. Then knowing that the Alfvénic Mach number was $M_A \geq 1$, an upper limit to the ambient field strength could be deduced, as explained earlier in the section on type II bursts. The properties of the radio burst, assumed to be gyrosynchrotron emission which was suppressed at low heights by the Razin-Tsytovich effect, gave estimates of the plasma density and magnetic field in the compressed plasma behind the bow wave. Knowing the compression factor and assuming that the ambient field was directed about 30° from the shock normal, an approximate lower bound to the ambient field strength was obtained. (A strict lower bound based on an unrealistic assumption that the ambient field was perpendicular to the shock normal, is about a factor of 2 lower.) The upper bound and this approximate lower bound are labelled 'D' and plotted in Figures 1 and 2 for the range of the radio and/or white light observations, 1.5 to $6R_\odot$. If, instead of gyrosynchrotron emission, the radiation is assumed to be plasma radiation at the second harmonic, the measured degree of circular polarization ($\sim 5\%$) gives a lower bound on the coronal field strength which is about half of that just given.

To our knowledge, this is the only estimate of field strength anywhere between about $3R_\odot$ and $60R_\odot$, which is based on observations. It is interesting that the values so derived are close to the curve for R^{-2} and correspond to $\beta \approx 0.3$ (Figure 1) or $\beta \approx 1$ (Figure 2). In fact, the near agreement with the R^{-2} curve is satisfying because, at those heights, the radial field should be dominant and thus the coronal field should be compatible with interplanetary data.

(b) Moving type IV sources, especially the most common variety termed 'Isolated Sources' (e.g., Smerd and Dulk, 1971), characteristically develop a high degree of circular polarization as they move outward to as much as $6R_\odot$. The accepted radiation mechanism for these sources is gyrosynchrotron, and the field strength within the sources can be estimated from the polarization and brightness. In order to explain the high degree of circular polarization observed, usually $\gtrsim 0.7$, a high magnetic field strength is required, ~ 10 G at $R \approx 1.5R_\odot$, and ~ 2 G at $R = 4R_\odot$ (e.g., Dulk, 1973; Robinson, 1974, 1977). It is surmised that these fields are transported from the low corona in the form of plasmoids, self-contained configurations of magnetic field, electric currents, perhaps some thermal plasma, and a small number of mildly relativistic electrons. Because these sources are not usually present in the corona above active regions, but are only occasional transient disturbances following flares, we do not include them on Figures 1 or 2.

3. Summary and Conclusions

It is gratifying to see in Figure 1 that the various sources of data on coronal magnetic fields are in general agreement with one another. The range of variation is less than a factor of 10, compared to a factor of 100 or more in the reviews of Newkirk (1967, 1971), and much of the variation undoubtedly results from real differences in field strength from one active region to another.

By contrast, however, in some parts of Figure 2 the range is still about 100 : 1. We note that the estimates of magnetic field derived from type II (boxes 'W' and 'SSS') and type III (box "SS') bursts depend on the electron density model adopted, whereas the other available estimates do not, and that in Figure 2 the former are systematically higher, by about a factor of 10, than the others. This inconsistency in Figure 2, contrasted with the consistent picture presented in Figure 1, suggests to us that the lower density model is more likely to be correct. Therefore, for the remainder of this discussion we will concentrate on Figure 1.

The improved agreement in Figure 1 compared with earlier reviews results largely from our elimination of a number of sources of data which involved an interpretation in terms of outmoded, incorrect, or inapplicable plasma physical concepts. Plasma emission at the fundamental is an important example where the emission and propagation processes, especially mode coupling, are so complicated and so dependent on the detailed geometry as to make most interpretations untrustworthy.

The largest field strengths in the height range above about $1.1R_\odot$ were derived from measurements of the polarization of type III harmonic bursts. At present the observational evidence is not sufficient to be able to judge whether the bursts with highest polarization emanated from regions of abnormally high field strength, came from regions where the magnetic field was at large angles to the line of sight and hence was overestimated, or possibly indicate that there is a flaw in the theory. We expect that more complete observations will allow us to choose among these possibilities and perhaps to make possibie definitive observations of coronal field strength.

Almost all of the data in Figure 1 are consistent with the usual belief that the corona is magnetically dominated, i.e., $\beta < 1$. The exceptions are the calculations of potential field above about $1.4R_\odot$ and some of the data derived from measurements of the band splitting and drift rate of type II bursts. The potential field calculations are suspect above $R = 1.4R_\odot$ because of the uncertainties mentioned earlier regarding $\beta \gtrsim 1$ and the positioning of the 'source surface' which is intended to simulate the volume distribution of currents in the corona. Further work needs to be done to investigate the applicability of potential field calculations at high altitudes. (In Figure 2 most of the potential field box lies in the region $\beta > 1$; we consider this to be a further reason for preferring the low density model used for Figure 1.) The other exception, the lower left corner of the box representing the fields derived from Type II band splitting and drift rates, may have resulted from one or two shocks whose propagation was at a large angle from radial and thus violated one of the important assumptions of the analysis. We note the inconsistency of the portion of the box 'SSS' with box 'W' which was derived from a much larger sample of type II bursts.

The values of inferred field strength in Figure 1 can be fitted by a straight line. The empirical formula

$$B = 0.5(R/R_\odot - 1)^{-1.5}\ \mathrm{G} \qquad (1.02 \lesssim R/R_\odot \lesssim 10)$$

fits all of the data presented to about a factor of three. This is probably as good a single parameter formula as is possible given the undoubted inhomogeneity and variability of the coronal magnetic field of active regions.

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