Interplanetary magnetic field and its possible effects on the mid-latitude ionosphere II

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Abstract
Using critical frequencies, f_0F2 from the Uppsala, Lannion and Dourbes ionosonde stations, the possible effects of the orientation of the IMF on mid-latitude ionosphere are further investigated. For this purpose, the regular diurnal, seasonal and solar cycle variations in the f_0F2 data were removed by subtracting the mean of f_0F2 for the same UT on all the magnetically quiet days ($A_p < 6$) within 15 days around the IMF B_z turnings. This yields the deviation from the average quiet-time value δf_0F2. The data are sorted according to the polarity of the IMF B_z and the effects of the southward turnings are discussed. Hapgood *et al.* (1991), Tulunay *et al.* (1991), Tulunay and Rahman (1992) investigated the possible effects of the IMF on mid-latitude ionosphere by employing the Slough and Argentine Islands f_0F2 data. In order to facilitate a comparison the same method of analysis is being adopted again. However, in the present work the southward polarity changes in IMF B_z with no consideration of the IMF sector structure were considered only.

Key words *IMF – variability – critical frequencies*

1. Introduction

Radio waves of a wide range of frequencies, from very low frequency (VLF) to high frequency (HF) (broadly 3 kHz to 30 MHz) can be propagated to great distances via the ionosphere. The day-to-day variability of the height distribution of F-region ionospheric electron densities greatly influences the propagation characteristics of HF waves. Of particular importance is the peak density of the ionospheric plasma, which is proportional to the square of the «critical frequency» of the F layer. f_0F2 (the largest frequency of the ordinary wave which the F-layer reflects back to a vertical-incidence sounder). The f_0F2 value can be used to compute the «maximum usable frequency» (MUF) of HF waves using a so-called M-factor (*e.g.* Lockwood, 1983). The day-to-day variability of f_0F2 has remained unpredictable, despite many scientific studies to find its origins (Aravindan and Iver, 1990). This unpredictable variability greatly limits the efficiency of operation of communication, radar and navigation systems which employ HF radiowaves (Bradley, 1991; Lockwood *et al.*, 1993).

The objective of this paper is to search further the possible effects of the orientation of the interplanetary magnetic field (IMF) on the critical frequency of the ionospheric F-layer at mid-latitudes. The IMF is known to exert a controlling influence on the magnetosphere and high-latitude ionosphere. Of primary importance here is the north-south component of the IMF, in accordance with magnetic reconnection being the dominant mechanism by which energy, mass and momentum are transferred from

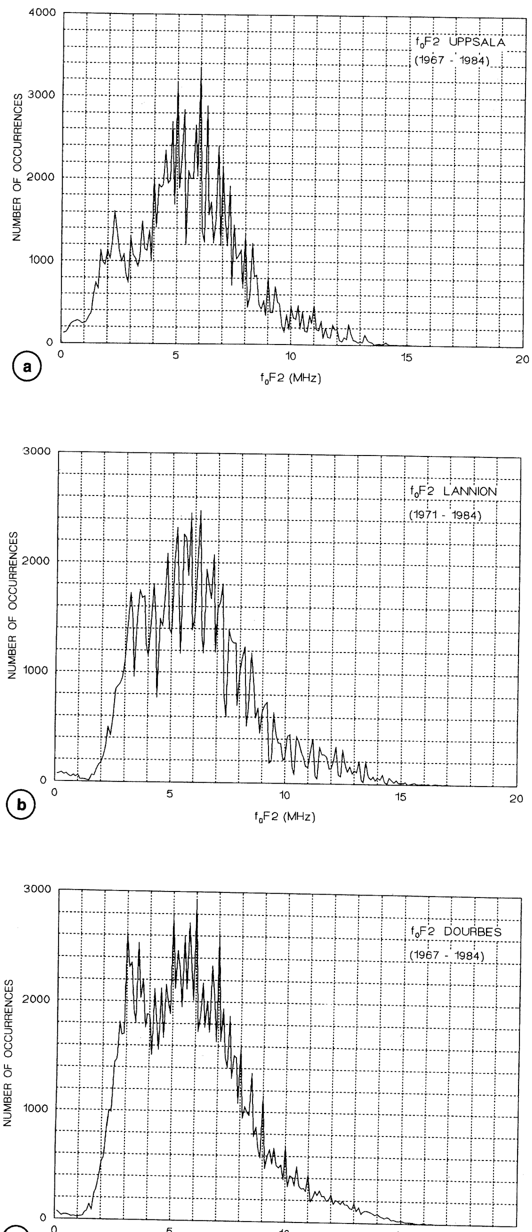

Fig. 1a-c. Distribution of all critical frequencies, f_0F2, from a) Uppsala (1967-1984); b) Lannion (1971-1984); c) Dourbes (1967-1984) for which simultaneous IMF and solar wind data are available.

the solar wind flow into the Earth's magnetosphere, as first suggested by Dungey (1953, 1961). The thermospheric winds driven at high latitudes can propagate across magnetic field lines. Such winds, which are mostly seen in the «storm time circulation» pattern, and the composition changes observed in the neutral thermosphere due to the high latitude heating by auroral particle precipitation are known to exert a strong influence on the peak density of *F*-region plasma. The winds blow the plasma up the magnetic field lines for the equatorward and down the magnetic field lines for the poleward winds to altitudes of lower/greater plasma loss. The changes in the ratio of molecular to atomic density of the neutral species may result some induced changes in the balance between plasma production and loss (see for example, Risbeth *et al.*, 1989; Lockwood, 1991). Even though, most of the features of the Earth's magnetosphere and high latitude ionosphere which are controlled by the IMF B_z component are confined to high-latitudes, via the action of the neutral thermosphere the IMF controlled flows at high latitudes are expected to have some influence on the *F* region ionosphere (see for a full discussion by *e.g.* Lockwood *et al.*, 1993). This paper includes some more results of the recent work conducted by employing the Uppsala Lannion and Dourbes ionospheric critical frequencies between 1967 and 1986. The critical frequencies are studied in conjunction with simultaneous satellite measurements of the IMF. In particular, significant effects of polarity changes of IMF B_z (in GSM) are revealed once more. The seasonal dependence on the results were briefly investigated in Tulunay and Rahman (1992). However, in order not to deal with a statistically smaller subset, the IMF B_z turnings, key data have not been subdivided further into seasons.

2. The data sets

The data concerning the interplanetary medium used in this work have been taken from a compilation of solar wind plasma and

Table I. Some statistical results.

Station names Geographic coordinates Data coverage	Critical frequencies (MHz)				δf_0F2 (MHz) major southward IMF B_z turnings		
	Extreme values	Median and mode	Upper decile	Lower decile	Upper decile	Lower decile	Mode
Uppsala (49.8 N, 17.6 E) (1967-1984)	0.1-15.1	5.3 6.3	8.6	2.3	0.8	−2.1	0.0
Lannion (48.7 N, 356.5 E) (1971-1984)	0.1-17.0	5.8 6.2	9.2	3.2	0.9	−2.1	−0.6, −0.3
Dourbes (50.1 N, 4.6 E) (1967-1984)	0.1-16.3	5.6 6.0	9.2	3.0	0.8	−1.9	−0.3

IMF data prepared by the US National Space Science Data Center (NSSDC). The data were supplied by a number of experimental groups and they were recorded by a number of spacecraft close to the Earth: IMP-1, IMP-3 to-8, AIMP-1 and-2, OGA-5, HEOS, VELA-2 to-6, ISEE-1 to 3 (Couzens and King, 1986). The data were stored on-line in a number of data bases which operated under a formal management system called R-EXEC. This system was developed at Rutherford Appleton Laboratory (RAL) for the manipulation of geophysical data (Hapgood *et al.*, 1991). The IMF data were transformed into the GSM co-ordinate system because, as discussed above, that is the most relevant to transfer of momentum and energy from the interplanetary medium into the ionosphere. The IMF data set available covers a period from 2 November 1963 to 31 May 1987. This period covers two complete solar cycles. That is numbers 20 and 21. Within this period, only the cases for which both simultaneous plasma and magnetic field data were available were examined and the results of a survey of these data concerning the interplanetary medium have been published by Hapgood *et al.* (1991). This restricted the analysis to the period 27 November 1963 to 4 April 1986. Within this period, there were 101 558 hourly values available out of a total 195 960 h possible, *i.e.* there is an average availability of IMF data of 52%. Figure 1a-c of Hapgood *et al.* (1991) gives the distributions of the relevant interplanetary parameters (solar wind speed and density, and IMF strength and B_z component) for this period (Lockwood, 1991; Lockwood *et al.*, 1993).

The ionospheric critical frequency data used here were taken from the COST 238:PRIME data base at the CNET Laboratories (Hanbaba and Sizun, 1993). The critical frequencies were obtained from the ionosonde stations at Uppsala, Sweden (geographic (G), latitude 59.8°N, geographical (G) longitude 17.6°E); Lannion, France (48.7 GN, 356.5 GE); Dourbes, Belgium (50.1 GN, 4.6 GE).

At a given time-of-year and phase in the solar cycle, the ionosphere exhibits regular diurnal variations at mid-latitudes as the plasma co-rotates with the Earth. In order to study the day-to-day variability of the ionospheric densities about these regular diurnal variations, some form of «quiet-time» diurnal variation must be subtracted from the variations observed. In order to achieve this, for each hourly value of f_0F2 all quiet-time soundings with 15 days of the sounding in question were identified: quiet-time values were defined as when the simultaneous magnetic A_p index was less than 6. The mean quiet-time value at the same UT, the

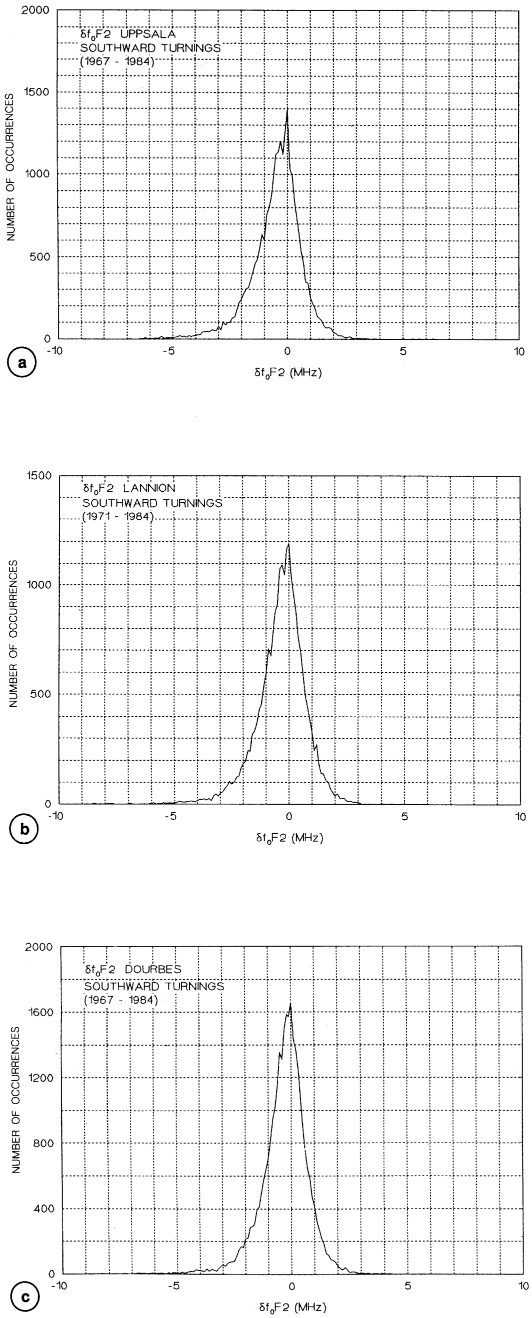

Fig. 2a-c. Distribution of the deviation from quiet-time averages, δf_0F2, for the same data set as fig. 1 during the southward IMF turnings.

quiet-day control value, was then subtracted from the value actually observed: the resulting value is here termed δf_0F2. Only ionospheric data which were available in digital form were employed and that further restricted the period studied to (1967-1984) for Uppsala; (1971-1984) for Lannion and Dourbes. Figures 1a-c and 2a-c show the distributions of f_0F2 and δf_0F2, for the entire period. Table I summarizes some statistical results about these f_0F2 and δf_0F2 values.

As seen from table I and from fig. 1a-c f_0F2 varied between 0.1 MHz and 15.1 MHz for Uppsala; 0.1 MHz and 17.0 MHz for Lannion; 0.1 MHz and 16.3 MHz for Dourbes. Figure 1a-c includes the regular diurnal and annual/seasonal variations as well as variations due to any other causes which are grouped under the term «day-to-day variability». Figure 2a-c shows the distribution of the δf_0F2 values which correspond to the major southward IMF B_z turnings. These distributions are skewed with the most common values of 0.0. MHz for Uppsala; 0.6 and -0.3 MHz for Lannion; -0.3 MHz for Dourbes. The upper and lower decile values as listed in table I range between 2.7 and 3.0 MHz. Hence the day-to-day variability, not accounted for by regular quiet-time variations (as described earlier) amounts to a spread between 2.7 and 3.0 MHz for the data under consideration. 2.7 and 3.0 MHz when compared with the most common values of f_0F2; *i.e.* 6.3 MHz, 6.2 MHz, 6.0 MHz, it becomes apparent that the day-to-day variability presents an important problem in practice.

3. Definition of IMF events

In order to study the effects of IMF B_z polarity changes, the data were searched for all southward and northward turnings (in GSM). Following Hapgood *et al.* (1991), a reversal of the polarity of the IMF B_z component between hourly data points was named an «event» (with start time t_1 and finished time $t_2 = t_1 + 1$ h) provided that $| B_z |$

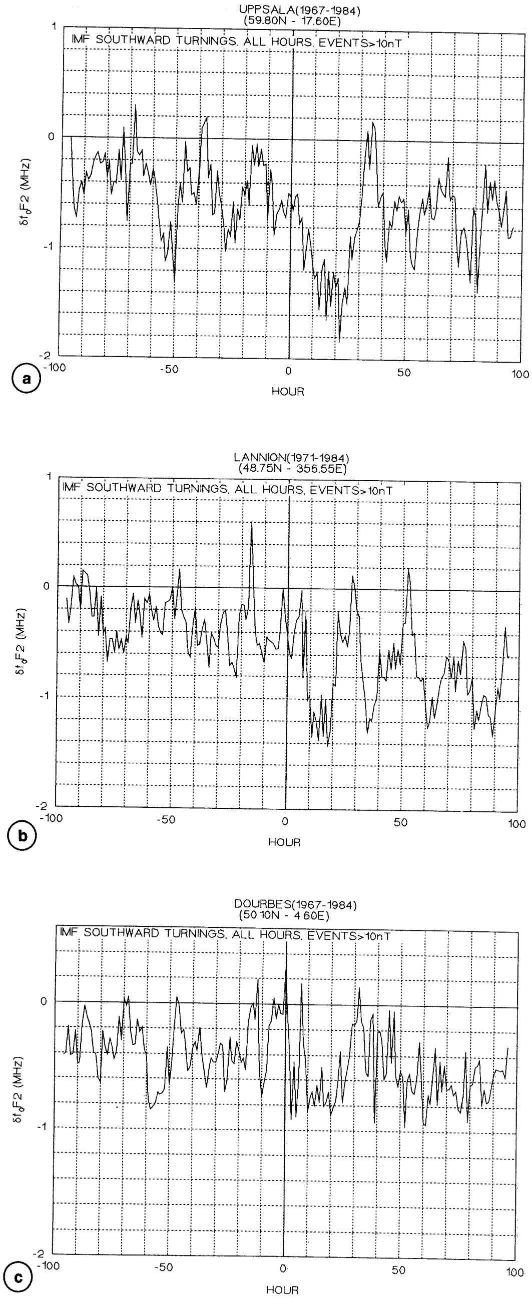

Fig. 3a-c. Superposed-epoch plots of mean δf_0F2 as function of event time. Event time zero is the time of southward turning events of the IMF B_z.

> 1 nT for both these two data points. Hence the IMF B_z was required to change polarity and to change in magnitude by at least 2 nT. A total of 6 018 events were defined in this way.

The numbers of events for various categories can be summarized as follows:

1) about 49% of all the events were northward an 51% of them were southward turnings of the IMF;
2) for 24% of the events neither B_x nor B_y polarity reversals took place during the period of 8 h around the B_z reversal (*i.e.* from (t_1-3) h to (t_2+3) h) (T or A events);
3) for 42% of the events there was a reversal of either B_x or B_y during a B_z reversal, while the other component kept the same sign for the 8 h period;
4) for 3% of the events there were reversals of both B_x and B_y during the B_z reversal;
5) for 31% of the events there were either data gaps in the 8 h period or there were multiple B_x and/or B_y crossings.

It is interesting to note that in only 3% of cases does a B_z change accompany a garden-hose orientation sector boundary crossing and 24% of B_z changes did not relate to any change in polarity of either of the other 2 components.

The well-defined cases (2, 3 and 4) do show the predominance of the garden-hose orientation, as at the time t_1, they fall into the following classes:

1) 47% had B_x positive and B_y negative;
2) 42% had B_x negative and B_y positive;
3) 5.5% had B_x positive and B_y positive;
4) 5.5% had B_x negative and B_y negative.

Hence in 89% of these well-defined cases, the garden hose orientation applied before the B_z polarity change. In addition, various sub-set of events were considered. For example, events for which the IMF retained its B_z polarity for extended periods about the change were considered. For this class of event it was required that the IMF B_z polarity was the same for both 4 h before

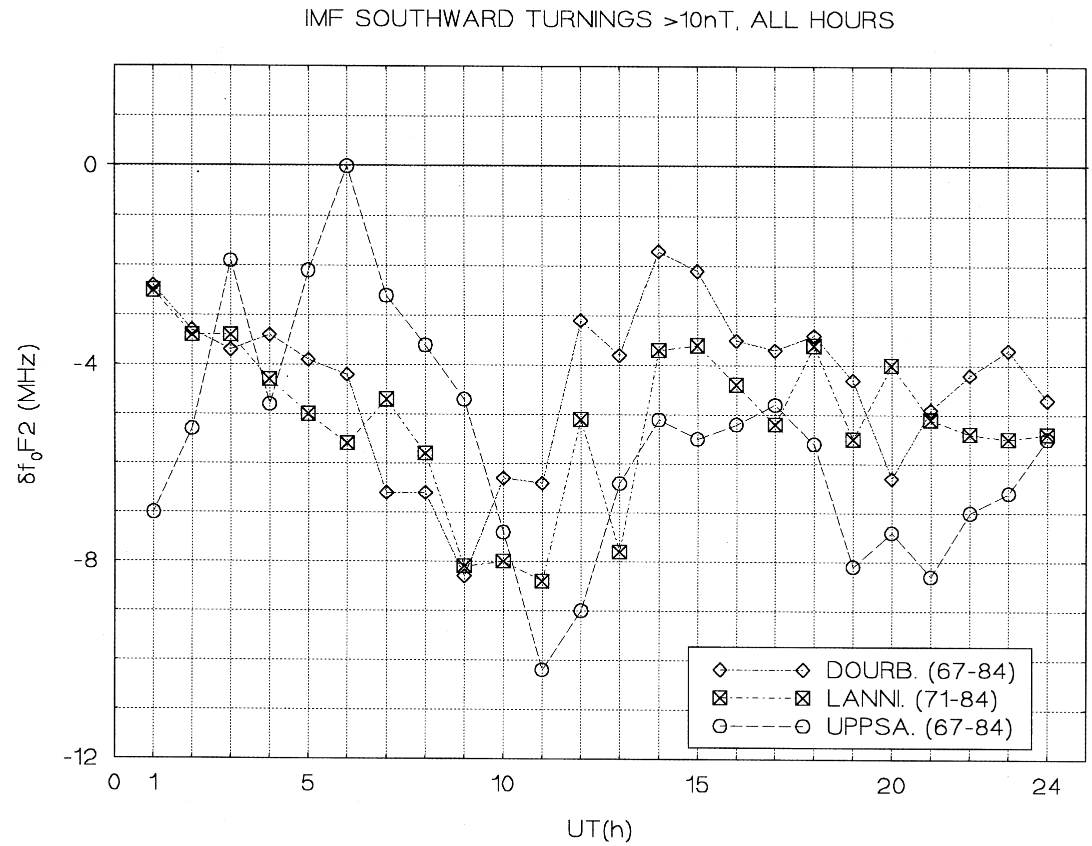

Fig. 4. Diurnal variation of all the $\delta f_0 F2$ data for Uppsala, Lannion and Dourbes in the period 1967 to 1984: the deviation of the critical frequencies from quiet-time values algebraically are greater near dusk than those of near dawn in general.

and 4 h after the turning (*i.e.* B_z had the same sense for soundings at (t_1-3) to t_1 h and for t_2 to (t_2+3) h, inclusive. In total there were 310 events out of the 6 018 with continuous data over an 8 h period and for which this condition was met. Hence summarizing, we divide the data into two classes:

1) data for 8 h periods around the UT of a southward turnings of the IMF. By the end of these periods, there may have been some initial effect of the southward IMF orientation, and at the start there will have been some which were influenced by southward IMF at earlier times. These are therefore termed the $\Delta B_z<0$ data (160 southward turning);

2) the second class are for 8 h periods around the northward IMF turnings. These are classed as $\Delta B_z>0$ data (150 northward turning).

The results presented in this paper belong to the «$\Delta B_z<0$» data. Events were further classified according to the size of the change of B_z (the minimum value is 2 nT). In order to study the effects of major B_z changes, a set of very large events, where the IMF change $|\Delta B_z|$ exceeded or equal 10 nT, were defined. The choice of this threshold for ΔB_z is inferred from Lockwood *et al.* (1993). A total of 20 such events were defined out of the full number of 160 with continuous data over 8 h periods. These events are referred to as $|\Delta B_z| \geq 10$ nT events, or alternatively, the «major events».

4. The effects of the southward IMF B_z-turnings on the mid-latitude ionosphere

Figure 3a-c shows the results of superposed epoch studies for the $|\Delta B_z| \geq 10$ nT events described above. In all plots the IMF change occurred at time zero. The horizontal axis gives the time (in hours) relative to the IMF B_z polarity change, and the vertical axis shows the mean value of $\delta f_0 F2$. Figure 3a-c shows clear minima in the average $\delta f_0 F2$ during the day after the southward IMF turnings. These minima are at $\delta f_0 F2$ of -2.0 MHz in the Uppsala; -1.8 MHz in the Lannion and -1.1 MHz in the Dourbes results. The values before the events are, however, not always zero, indicating that many non quiet-day values are present. The peak change in $\delta f_0 F2$ which can be attributed to the southward IMF B_z turnings are approximately 1.5 MHz for the Uppsala, 1.4 MHz for the Lannion and 0.7 MHz for the Dourbes results. The mean values before the events are assumed to be -0.5 MHz, 0.4 MHz, and -0.4 MHz for Uppsala, Lannion and Dourbes $\delta f_0 F2$ respectively. Since the magnitude of the changes described here, 0.7 MHz - 1.5 MHz, are a large part of the total variability shown in fig. 2a-c, the results imply that the southward turnings of the IMF B_z can contribute in day-to-day variability of the mid-latitude densities.

Figure 4 exhibits the diurnal variation of the average Uppsala, Lannion, and Dourbes $\delta f_0 F2$ values for all observations in the periods of interest. It is interesting to note that algebraically the peak deviation of the critical frequencies from quiet-time values occurs near dusk, whereas the smallest average deviation is near dawn.

5. Conclusions

This study of critical frequencies from Uppsala, Lannion, Dourbes reveals that much of the day-to-day variability of the mid-latitude ionosphere may be related to the orientation of the southward IMF B_z. The results can be summarized as follows:

1) the distribution of $\delta f_0 F2$, the deviation from quiet-time critical frequencies of Uppsala, Lannion and Dourbes show a decile range between 2.7 and 3.0 MHz. The upper decile is about 0.85 MHz, whereas the lower decile is -2.03 MHz. The corresponding values for a decile range, upper decile and lower decile were 2.3 MHz, 0.70 MHz and -1.60 MHz respectively for the distribution of $\delta f_0 F2$ of the Slough data (Tulunay and Rahman, 1992). The results exhibit similar tendencies in general;

2) significant depressions, similar to those of the Slough $\delta f_0 F2$ data, of over 1 MHz are found in the average critical frequencies, employed in this work, for 1-2 days following a southward turning of the IMF B_z;

3) the mean critical frequencies differ from the quiet-time values most at dawn and least at dusk which also agree with the diurnal variation of the mean Slough critical frequencies which were reported as the first of the series of such papers;

4) it is hoped that similar work when completed with a larger data groups will enable one to employ such results for modelling and prediction purposes.

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