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COSMIC RAY DECREASES AND MAGNETIC CLOUDS

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Abstract

A study has been made of energetic particle data, obtained from IMP 8, in conjunction with solar wind field and plasma data at the times of reported magnetic clouds. It is shown that magnetic clouds can cause a depression of the cosmic ray flux but high fields are required. A depression of 3% in a neutron monitor requires a field of about 25 nT. Such high fields are found only in a subset of coronal ejecta. The principal cause for Forbush decreases associated with energetic shocks is probably turbulence in the post-shock region although some shocks will be followed by an ejecta with a high field. Each event is different. The lower energy particles can help in identifying the dominant processes in individual events.

1. INTRODUCTION

The term 'magnetic cloud' was introduced by Burlaga and co-workers (Burlaga et al., 1981; Burlaga and Behannon, 1982; Klein and Burlaga,1982 and Zhang and Burlaga, 1988) to describe structures in the solar wind having a magnetic field which changes direction smoothly through a large angle and has an enhanced intensity and a plasma temperature and beta that are of a low value. About a half of such structures were found to follow shocks. It is now commonly accepted that magnetic clouds are a subset of ejecta in the interplanetary medium (e.g. Gosling, 1990).

Recently there have been a number of studies dealing with the role of magnetic clouds in causing decreases in the cosmic ray intensity, with conflicting conclusions. Badruddin et al. (1985), Zhang and Burlaga (1988), Badruddin et al. (1991) and Lockwood and Webber (1991a) attribute the decrease of cosmic rays to turbulent magnetic fields in the sheath between the shock and the associated magnetic cloud. The argument is based on the observation that the decrease commences at the time of shock passage and continues after the cloud has passed by, and that clouds without shocks are associated with small or non-detectable cosmic ray decreases. Lockwood and Webber (1991a) concluded that "the role of magnetic clouds in producing Forbush decreases is relatively unimportant". Note that Lockwood and Webber apply the term 'Forbush decrease' only to those cosmic ray decreases which have an "asymmetric shape" i.e. a rapid decrease followed by a more gradual recovery.

Sanderson et al., (1990a) have approached the problem in the context of the 'two-steps' seen in some cosmic ray decreases. Barnden (1973) first pointed out that some decreases have two steps and associated the first step with the shock and the second step with the 'driver gas surface'. Sanderson et al. (1990) found that in 18 out of 19 events the second decrease was larger than the first. In another study Sanderson et al. (1991) examined diffusion coefficients in the post-shock regions of shocks associated with 8 decreases and concluded that "the turbulence in the post shock region is not always sufficient to produce a Forbush decrease". In this later paper an alternative location/mechanism for excluding cosmic rays was not proposed. In the earlier paper it was proposed that drifts in the cloud could cause the decrease. Drifts in magnetic 'blobs' as a cause of Forbush decreases was first discussed by Barouch and Burlaga (1975).

It is important to note that Sanderson et al. (1990a, 1991) looked at decreases that occurred at the times of low energy (35-1000 keV) proton bi-directional flows reported by Marsden et al. (1987). These bi-directional flows were interpreted by Marsden et al. (1987) to be another signature of coronal ejecta and in fact approximately a third (12/29) of their shock-related events are also 'magnetic clouds'. From previous work (e.g. Cane, 1988) it is apparent that only one event included in the Sanderson et al. (1990) study was associated with a large, energetic shock. This is the one event for which Sanderson et al. found a large change in the diffusion coefficient at the shock and at which the decrease commenced at shock passage.

There is an important observation that has not been taken into account in recent work on Forbush decreases. Rao et al. (1967) showed that 'energetic storm particles' exist during the onset of Forbush decreases. The rapid increase of low energy particles coincides with the first step and a rapid decrease occurs at the second step. They proposed that the particles are accelerated by the shock. However the idea that the mechanism which accelerates the low energy particles is intimately connected with the mechanism that depletes high energy particles was not explicitly mentioned. In recent work (e.g. Lockwood and Webber, 1991b) the enhanced particle intensities at the onset of Forbush decreases have been treated as 'interference'. Yet scattering in turbulent fields is a favored mechanism for both particle acceleration at shocks (e.g. Jones and Ellison, 1991) and for producing Forbush decreases. It should be possible to use the low energy particles to distinguish which processes are occurring during Forbush decreases and within individual decreases. This has been done in the present paper using data from Goddard Space Flight Center instruments on IMP-8 to address the question of the role of magnetic clouds.

In this study time histories of particles in the energy range 1 MeV to about 5 GeV are examined at the times of the passage of magnetic clouds. It is shown that the high field in magnetic clouds does cause a depression in the cosmic ray intensity.

2. RESULTS AND DISCUSSION

The energetic particle data for this study were obtained from the Goddard Space Flight Center experiments on IMP 8 (McGuire et al., 1986). Besides the differential intensities, the rate from the plastic scintillator anticoincidence guard (G) on the medium energy telescope was also examined. This provides an integral rate for energies greater than about 60 MeV/nuc. This is a very sensitive method for looking at the small decreases in clouds because of a) the lower cut-off rigidity compared with a neutron monitor and b) the absence of diurnal anisotropies which can obscure the onset of the decrease and fine structure within the decrease.

Field and plasma data, obtained from the NSSDC OMNI database, were studied in conjunction with the IMP 8 data for 16 clouds from the Zhang and Burlaga list. From the original list of 19 clouds two events (April 3, 1979 and September 17, 1979) were excluded because of solar particles and another (September 18, 1981) because of an IMP 8 data gap. Only two events (January 4, 1978 and December 19, 1980) can be associated with solar events based on the onset of associated energetic particles (see Cane, 1988).

Figures 1 to 4 show particle and solar wind data (1 hour averages) at the times of four clouds. In addition to the IMP 8 data (30 minute averages) pressure corrected count rates from the Mt. Wellington neutron monitor (1 hour averages) are also shown. Each figure shows from the top to bottom: (a) intensities in the energy ranges 0.9 -1 and 6-11 MeV, (b) and (c) the Mt Wellington neutron monitor and IMP 8 G count rates expressed as a percentage of the pre-event level (d) the field magnitude, (e) the field elevation, and (f) the solar wind speed. Vertical lines indicate the shocks and the boundaries of the clouds.

Figure 1 shows a period in January 1978 when an energetic shock was seen at a number of spacecraft (Burlaga et al., 1981). The cloud following the shock arrived at Earth at 1200 UT on January 4 according to Zhang and Burlaga (1988). However the data in Figure 1 suggest that the cloud may have arrived slightly earlier at 1030 UT. Between the time of shock passage and this time, the low energy ion intensities (illustrated on a log scale) show an enhancement above a long term increase commencing on January 1 and ending after January 7. The G rate, shown on a linear scale, is off-scale during this enhancement. It should be noted that while the G rate has a median response of about 1 GeV, increases in the counting rate are mainly due to particles with energies less than 80 MeV. The G rate shows a minimum level, below pre-event levels, inside the cloud suggesting that cosmic rays are partially excluded from this region. The low energy particles also show evidence of partial exclusion from this region. The neutron monitor data are difficult to interpret in isolation. However, in combination with the lower energy data there is evidence for about a 2% reduction in the cloud preceded by a larger reduction in the post-shock region.

Figure 2 illustrates a different kind of event. The flow and field jumps at the shock are rather small and the field magnitude does not fluctuate very much in the post-shock region. The rms of the magnetic field components is large during the period when the field is fluctuating as can be seen from Figures 6 and 7 of Zhang and Burlaga (1988). For the event in Figure 2 the field reaches a maximum in the cloud. Consistent with the lack of turbulence in the field, and that it is a weak shock, is the absence of any low energy particles. The minima in the two high energy rates are clearly in the cloud.

Figure 3 shows an event in which the cloud and the post-shock region probably are equally important but the data gaps make it difficult to determine. It is clear that the decrease of high energy particles starts at the shock but that there is a further decrease in the cloud. The field is highest in the post-shock region and is very turbulent. The intensity of the lowest energy particles is high and is off-scale.

Figure 4 illustrates another event in which the field is a maximum in the cloud. The data are consistent with a cloud arrival time slightly earlier than that given by Zhang and Burlaga (1988). An arrival time of 0000 UT on February 12, rather than 0300 UT, was also suggested by Sanderson et al. (1990b). In this event the neutron monitor and G rate decreases do start before the cloud but clearly most of the decrease can be attributed to the cloud. There are some shock accelerated particles superimposed on an increase (partially off-scale) related to a solar event that was not associated with the shock and cloud. Events of Figures 2, 3 and 4 originated in solar ejections that had no obvious electromagnetic signatures.

The remaining 12 events show similar features but with variations. Three events show no decreases in the period before or during the passage of the cloud and these were the ones with the smallest field magnitude in the cloud. It is clear that in the other events the count rate decreases on entry to the cloud but most are preceded by another decrease that starts with the shock. The relative sizes of the decreases seem to correlate well with relative strengths of the field in the post-shock region and the cloud and on the amount of turbulence in the post-shock region.

For those events with a maximum field and a clear depression in the cloud, the depression was estimated based on levels in the G rate just before entering the cloud and the minimum rate in the cloud. By correlating the percentage decrease and the field strength in the cloud (see Figure 5) it can be deduced that a 6% decrease for the IMP-8 G rate requires a field of about 25 nT. From a study of the neutron monitor and G rates a 6% decrease in the latter corresponds to about a 3% in the former. For the 12 events in Figure 5 the depression and the field magnitude are reasonably well correlated with a correlation coefficient of 0.86.

The important result of this study is that high fields and turbulent fields can both cause a depression of cosmic rays. The relative contribution of each process will depend on the particular event. Since one of the criteria Klein and Burlaga (1982) used for defining 'clouds' was a high field strength, (the mean value for the Zhang and Burlaga (1988) clouds is 18 nT), it is the high field strength which is more relevant for the majority of these events. Magnetic clouds are a subset of those ejecta which propagate in the direction of the Earth. The majority of energetic shocks are not followed by high field regions. Perhaps the ejecta in energetic events do not have high fields. Certainly only in some events will the ejecta be intercepted. In other events the turbulence will be more relevant for the depression of cosmic rays. The majority of the shocks studied by Sanderson et al. and Zhang and Burlaga were not major shocks or major Forbush decreases.

Support for the important role of turbulence in major Forbush decreases can be inferred from the fact that large, energetic shocks responsible for major Forbush decreases also accelerate particles to high intensities and relatively high energies. Furthermore the two events in the Sanderson et al. (1991) study with the greatest change in the diffusion coefficients at the shock are the two with the highest fluxes of low energy particles.

3. CONCLUSION

It is concluded that magnetic clouds do play a role in the depression of cosmic rays. The depression is related to the strength of the field with a 3% decrease in a neutron monitor requiring a field of about 25 nT. Generally such high field regions are not observed and so, for the majority of cosmic ray decreases, turbulent fields in post-shock regions are more important. The relative contributions of particular mechanisms will vary from event to event, depending on the maximum field strength in the ejecta, the shock strength and possibly other parameters too.

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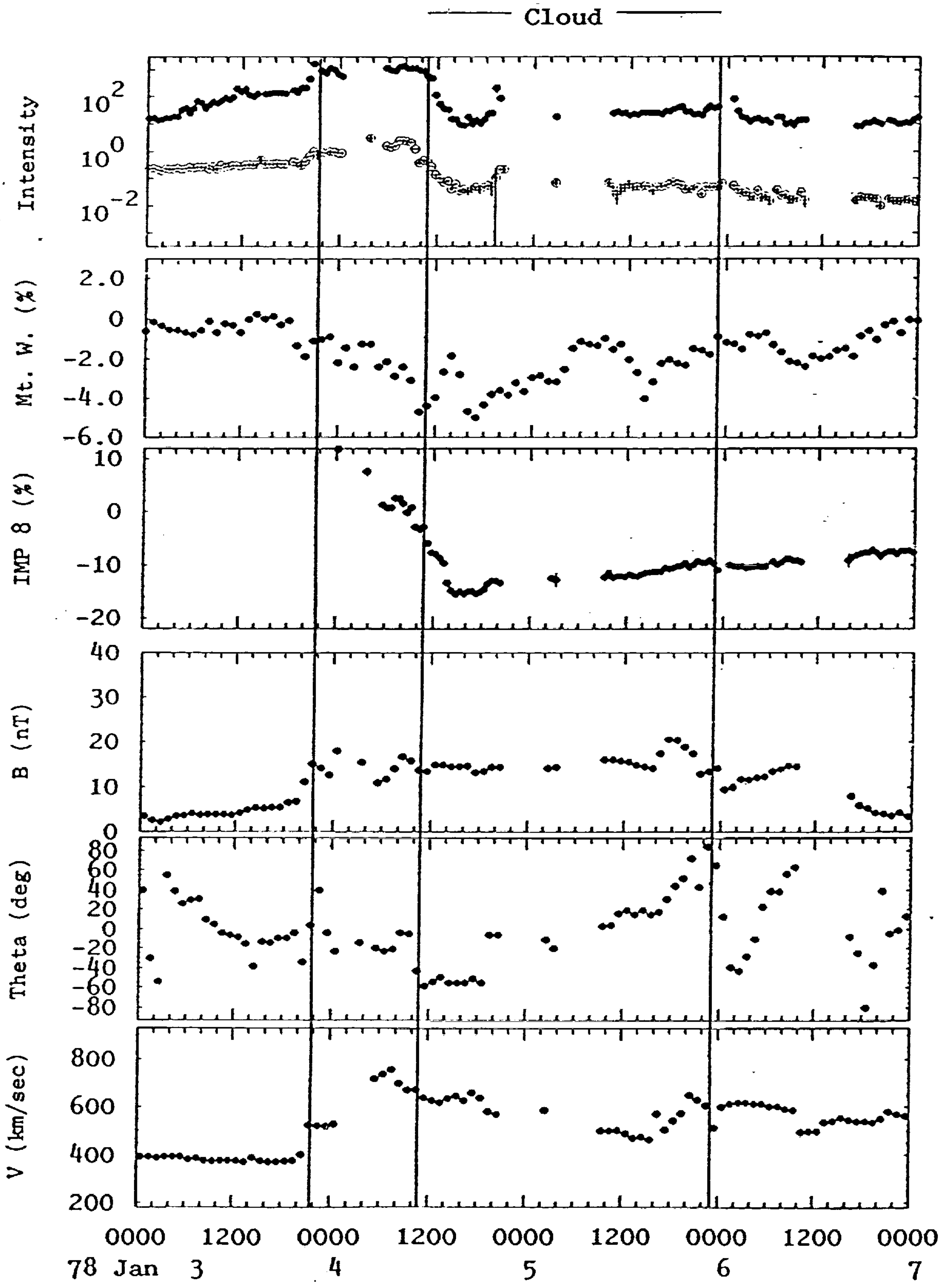
FIGURE CAPTIONS

Figures 1-4. Energetic particles recorded at the time of the passage of a shock followed by a magnetic cloud. From top to bottom: (a) intensities (particles/(cm^2 sec ster MeV)$^{-1}$ in the energy ranges 0.9-1 and 6-11 MeV, (b) and (c) the Mt Wellington neutron monitor and IMP 8 G count rates expressed as a percentage of the pre-event level (d) the field magnitude, (e) the field elevation, and (f) the solar wind speed. Vertical lines indicate the time of shock passage and the boundaries of the cloud.

Figure 5. Percentage depression of the IMP 8 G rate as a function of the maximum magnetic field measured in associated clouds.


Cloud
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-4.0
-6.0
IMP 8 (%)
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-10
-20
B (nT)
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Theta (deg)
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V (km/sec)
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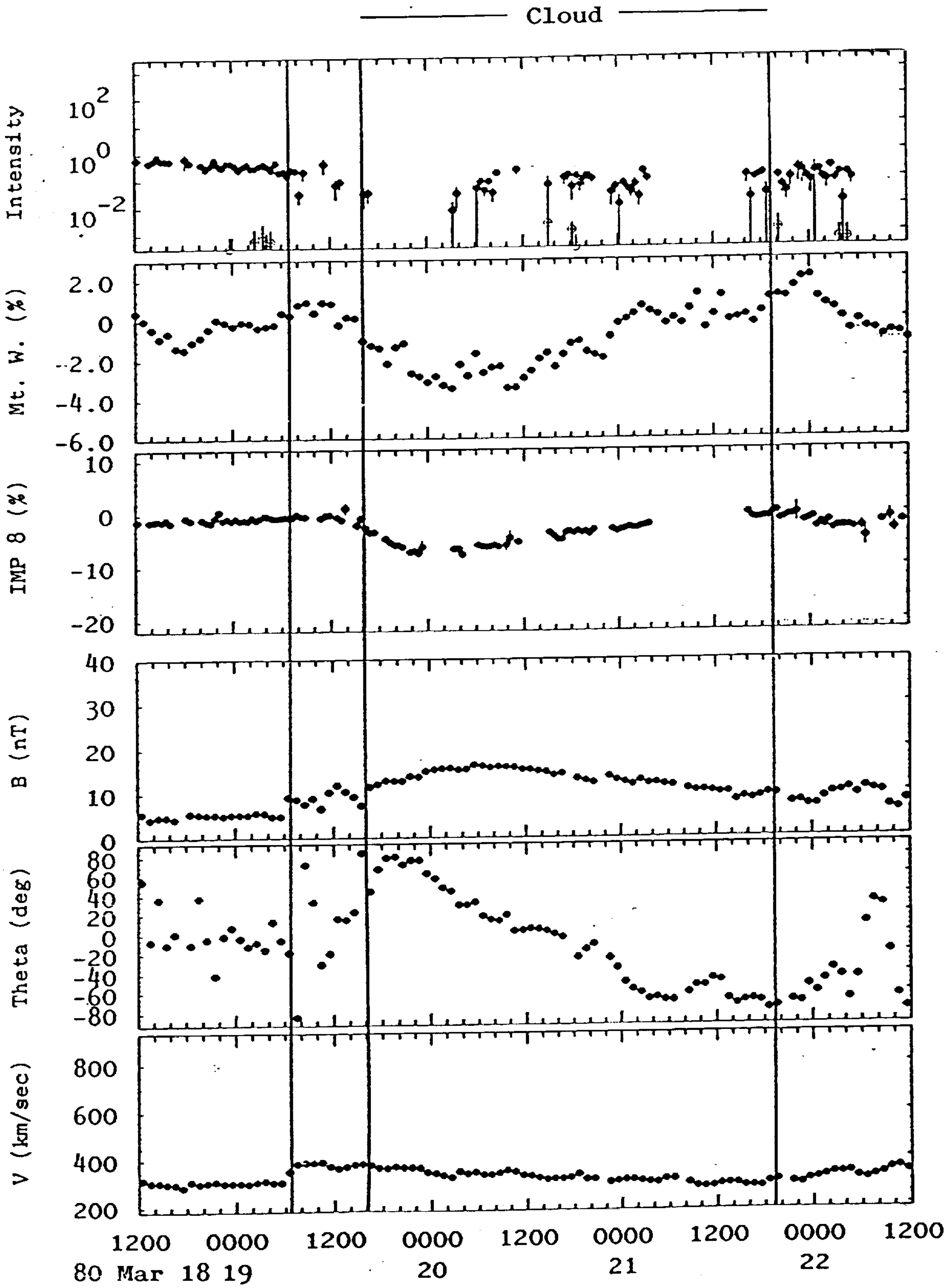
Cloud
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Mt. W. (%)
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B (nT)
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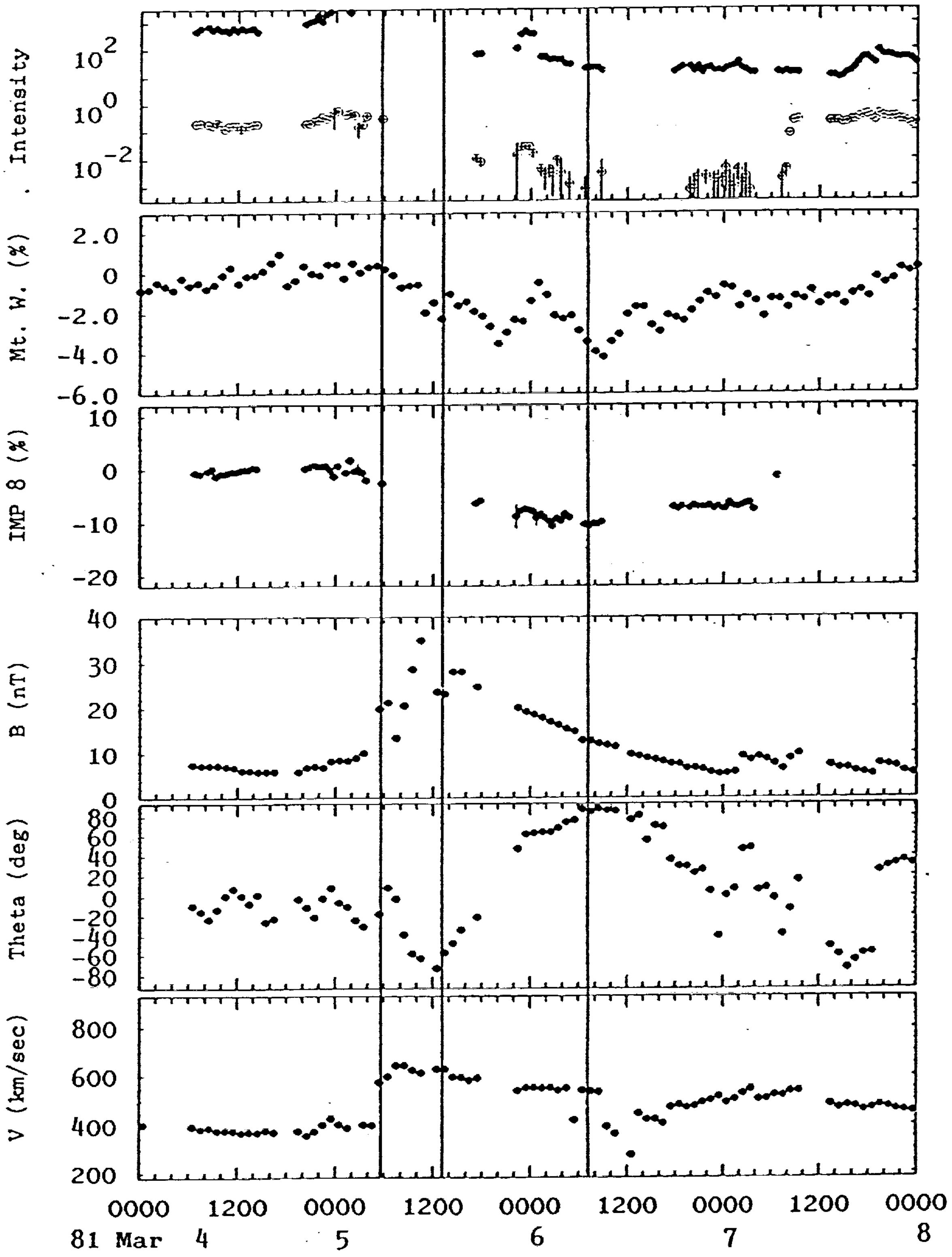
Cloud



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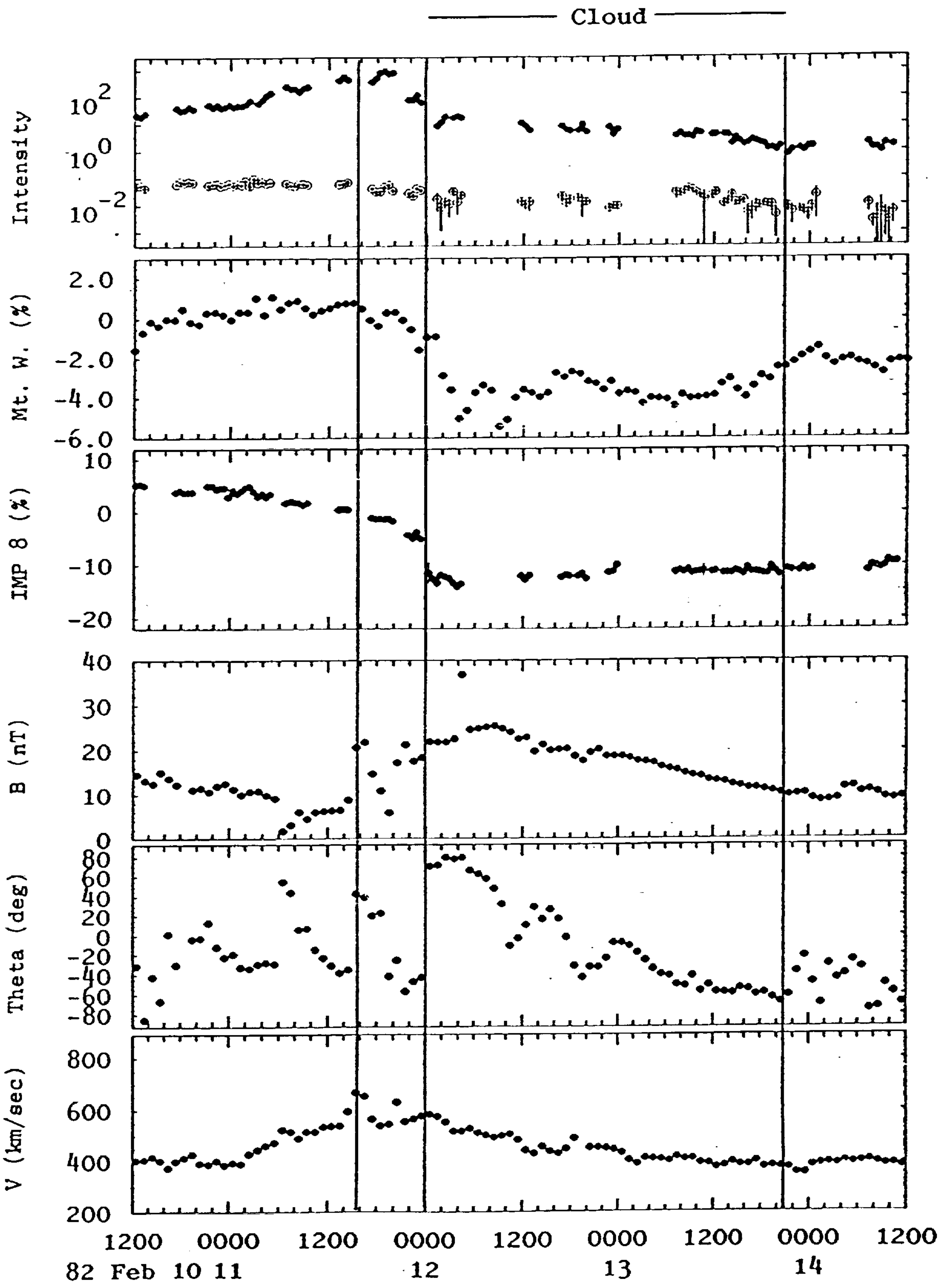
Cloud
Intensity
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10^0
10^{-2}
Mt. W. (%)
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IMP 8 (%)
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B (nT)
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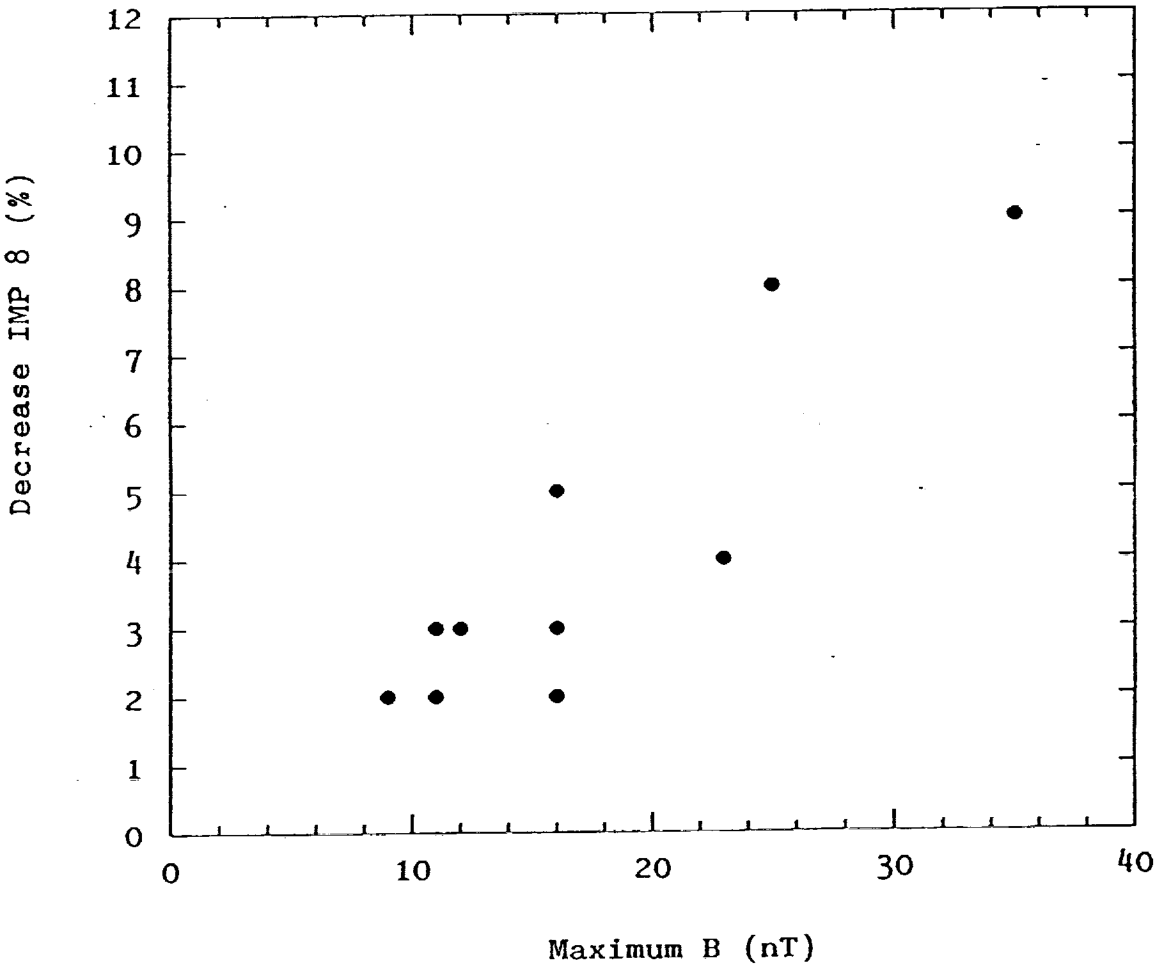

Decrease IMP 8 (%)
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1
2
3
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6
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9
10
11
12
0
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20
30
40
Maximum B (nT)