A Study of the Relationship Between Micropulsations and Solar Wind Properties

by

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Submitted to the
Department of Physics in Partial
Fulfillment of the Requirements
for the Degree of

Bachelor of Science in Physics

at the

Massachusetts Institute of Technology

May 1989

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Abstract

Long-term correlations between solar wind parameters obtained from the MIT experiment on IMP-8 and micropulsation measurements made by the Università dell'Aquila have shown a correlation between solar wind speed and micropulsation activity in the period range from $\sim$37s to $\sim$16s with a correlation coefficient greater than 0.7 for zero delay. For the period range from $\sim$16s to $\sim$6s, a higher correlation is found between the time derivative of the solar wind speed and the micropulsation activity than between the speed and micropulsation activity. A specific event where there are clear dynamic pressure pulses in the incoming solar wind has been examined to study the onset of micropulsations. This onset does not appear to be as sudden as one might expect.

Thesis Supervisor: Alan J. Lazarus
Title: Senior Research Scientist

to My Mother

Contents

Chapter 1

Introduction

It is generally agreed that variations in the incoming solar wind have an effect on the earth's environment. There is less agreement as to what variations have what effect.

Periodic oscillations of magnitude about one part in 10^6 and of periods on the order of minutes, such as the example shown in Figure 4.1, have been seen in the earth's magnetic field since Stewart's report in 1861 (as referenced by *Saito,* 1969). It is not known exactly how these pulsations are generated. *Vellante et al.* (1988) found that there seem to be two classes of micropulsation frequencies. The primary mode appears to be the resonant frequency of the local field line and a second mode, about half that frequency, is an "outside driver." The resonant frequency of the local field line is determined by propagating an Alfvén wave along the magnetic field line that emerges from the earth at that magnetic latitude, in effect putting a kink in the local field line and finding the resulting frequency. At L'Aquila, where our experiment is located, that frequency is about 13 $\pm$ 2seconds.

A flux-gate magnetometer experiment was installed near L'Aquila, Italy, in 1983 by the Gruppo Italiano di Fisica Cosmica (GIFCO) at the Università dell'Aquila. This experiment continues to measure variations in the local magnetic field.

In 1972, MIT flew a Faraday cup experiment on the IMP-8 spacecraft. This experiment measures parameters of the solar wind such as velocity, density, and temperature.

Professor Umberto Villante, of the Università dell'Aquila saw a unique opportunity to relate, on a statisitical basis, data from these two experiments. Pooling their data together, the two groups were able to examine observations from the entire year of 1985 in terms of how the solar wind affects the earth's magnetosphere. Previously, this kind of comparison had been done only on a small scale: a few "good" events or statistically for a few weeks. This is the first analysis to compare data from a solar wind plasma experiment with an Earth-based magnetometer for the period of an entire year.

Using this extended data base, we determined correlations of plasma parameters with micropulsation activity. The remainder of this paper examines this analysis in further detail. We found, as have others, that the velocity of the solar wind correlates well with micropulsation activity, however we have also found that it is the time derivative of the velocity that actually drives pulsations in some frequency bands.

Chapter 2

History and Theory

There is still disagreement as to the origins of micropulsations in the magnetosphere. Most daytime activity is currently thought to be related to waves generated upstream of the bow shock by protons reflecting off the shock and creating conditions for cyclotron waves as they interact with the incoming wind (*Gul'elmi*, 1974). Supporting this theory, the relationship $T \sim 1/B$ between the strength of the Interplanetary Magnetic Field (IMF) and the frequency of ground pulsations has been reported by some observers (*Troitskaya et al.*, 1971, *Gul'elmi et al.*, 1973, *Yumoto et al.*, 1984).

As these waves propagate into the magnetosphere, they excite the fundamental frequencies of the local field lines (*Yumoto and Saito* 1983). Two frequency ranges would be measured at an Earth-based magnetometer under these conditions: an irregular wave form dependant on the IMF, and a regular oscillation with a lattitude dependence. This pattern of oscillations has been shown to exist by *Vellante et al.*, (1988).

An examination of the history of micropulsations and theories about what governs them, especially micropulsations of interplanetary origin, is given in the review *Odera* (1986). Much of what follows in this chapter is based on this work. References not explicitly cited in the bibliograph can be found there.

Some features of micropulsations, that might be indicative of their origin, were found long ago. *Saito* (1964) showed that pulsation activity correlates well with solar wind speed. This work was later corroborated by *Greenstadt and Olson* (1976, 1977).

The IMF orientation was shown to have an effect on the occurrence of pulsations by *Playsasova-Bakunina* (1971). She found that pulsations occur most often when the IMF is very nearly toward or away from the sun. Later work also showed the same results. *Greenstadt and Olson* (1976) introduced the "cone angle," the angle between the IMF direction and the Earth-Sun line as a measure of how close the IMF and the Earth-Sun line are. The cone angle has been found to be related to the production of pulsations in that this production tends to occur when the cone angle is small.

There have historically been two explanations for the generation of micropulsations. Generation through Kelvin-Helmholtz instability at the magnetopause, and through what has been called "quasi-parallel shock structure."

The Kelvin-Helmholtz instability develops when there is relative motion at the interface between two plasmas. Like "wind over water," waves are likely to develop at this interface. In the situation of the magnetosphere, the waves would be generated on the sides of the magnetopause where the interplanetary solar wind passes by the relatively stationary plasma of the magnetosphere. These waves are amplified when the relative velocity exceeds a critical value. So large amplitude waves are more likely to be driven by high speed solar wind, but smaller waves will be driven all the time.

There are some problems with the model involving Kelvin-Helmholtz instability generation of micropulsations. One problem is the fact that micropulsations are not observed continuously. The prediction based on this model would be that the micropulsations would be observed as long as there is a difference in the velocities of the plasmas at the interface. The solar wind does blow continuously. There is no explanation in this model of the observed relation of the period of micropulsations to the magnitude of the IMF. Lastly, and perhaps most convincingly, *Green* (1979) found that the waves propagated from the night side to the day side, that is to say, the wrong way.

Greenstadt (1972) suggested that waves already in the solar wind can interact with the magnetosphere and generate waves that would propagate down to the surface. An IMF perpendicular to the bow shock would provide the best circumstances for the transfer of oscillations to the magnetopause. Upstream waves are generated when protons reflect off the bowshock and go upstream. This results in cyclotronic plasma instability that can generate waves.

For small cone angles, the waves can more easily be transmitted into the magnetosphere, and conversely, an IMF parallel to the magnetopause would make it very difficult to transmit waves. The cyclotronic instability would generate oscillations related to the IMF by $T \sim 1/B$.

Vellante et al. (1988) did a careful statistical analysis of the frequencies that are observed at the ground based magnetometer station in L'Aquila, Italy, during 1985. What they found was that events tend to occur in two separate ranges, $P_1 = 25 \pm 5$s, and $P_2 = 13 \pm 2$s. The spectra appear consistent with a wide source spectrum peaked at P_1 from waves originating outside the magnetosphere and with a resonant mechanism at P_2 roughly the fundamental resonant period of the local field line.

Supporting this hypothesis are the observations that the events of period P_2 are strongly monochromatic as would be expected for standing oscillations of local field lines, and tend to occur along the east-west component, the component which is generally observed to be related with field line resonance phenomena. P_1 events, on the other hand, are much less monochromatic and tend to perturb both the east-west and and north-south components and are more often observed in the morning, implying that they are driven by the solar wind.

Chapter 3

Experiments and Results

The two experiments used to provide data for this experiment are the Earth-based magnetometer experiment in Preturo, Italy, and the plasma science experiment on the IMP-8 spacecraft.

The magnetometer measures variations of the earth's local magnetic field in three orthogonal directions. Periods of less than about 10 seconds are filtered out of the measurement chain. These data were then reduced to show the electromagnetic power as a function of time in sixty bandwidths whose frequencies f in Hz are given by: $f = n/265$ where n represents the band number. So, for example, band 1 corresponds to 256 sec. and band 60 to about 4.3 sec.

The sixty bands were clustered into seven larger bands to make some of the initial analysis of the data a bit less clumsy. When we began to see some results emerge, we regrouped the bands in a way that corresponded to effects we saw in the phenomenology. This phenomenology and the resulting groupings are described below and shown in Figure 4.4.

The source of the solar wind data was the plasma science experiment on the IMP-8 spacecraft launched in 1972. The experiment provides measurements of velocity, temperature and density of the passing plasma. The spacecraft makes a circular orbit around the earth at about 30 Earth radii and passes through the magnetotail.

The time resolution of the magnetometer data is about one second. For the plasma data, it is at best about one minute. In both cases, for the majority of the work done, daily and hourly averages of both data sets were used over the time period of 1985.

It has been shown that, in small samples and on individual bases, high velocity solar wind is highly correlated with the onset of micropulsation activity. We attempted to verify this conclusion on a statistical basis covering all of 1985 as our information base. Using hourly averages, we ran Pearson cross correlations with time lags ranging from -48 hrs. to $+48$ hrs.

We found, as expected, that the speed of the solar wind is clearly correlated to micropulsation activity in all of the frequency bands. The best correlation coefficients ($p = 16 - 36$ sec) were greater than $r = 0.7$. In some frequency bands however, ($p = 6 - 16$ sec) the peak occured not at zero or a positive lag time, but rather at a negative lag time, implying that the micropulsations *preceded* the increases in solar wind speed by about 25 hours.

Figure 4.2 shows that lag in the peak of correlation. Bands 4 and 6, representing the periods from 11s to 16s and 6s to 10s, are peaked at a lag of one day and band 5 ($p = 10 - 11$s) is peaked at $\Delta T = 2$ days.

We theorized that the micropulsations were not induced by simple high velocity streams, but rather by the increases in the velocity. The implication is that when the shape of the magnetosphere is changing, it generates micropulsations, and that these changes in shape correspond to changes in solar wind speed.

We switched our analysis from one hour resolution to one day resolution because the features we saw in the correlations were on a timescale of longer than a day. Doing so also made the data significantly easier to handle and improved our correlation somewhat.

To verify this possibility, we looked for a correlation between the velocity temporal gradient and the pulsation activity. To determine the velocity gradient on day n, we simply subtracted the speed of day n from the speed on day $n + 1$. Correlating these velocity gradients with pulsation activity, we found the correlations themselves to be lower but peaked at $\Delta T = 0$ days for all periods but that from $p = 16 - 36$ seconds. Figure 4.3 is a plot of the correlation between the temporal gradients of velocity and the micropulsation activity. The peaks nearly all fall at time $\Delta T = 0$. The peaks are also sharper.

The correlation with velocity gradients suggests a few things. First, we know that velocity gradients occur most often in stream interaction regions. It seems a likely possibility that the strong correlation with the velocity gradient is related to a strong correlation with some other feature of these interaction regions. We also feel intuitively that it is not simply the velocity of the wind which drives the pulsations, rather it seems it should be the dynamic pressure or energy flux, ρv^2 or ρv^3 that drives the changes.

We explored these possibilities by determining these parameters and testing their correlation with pulsation activity in the same manner we used for the velocity and the velocity gradient.

Some of the features characteristic of stream interaction regions are an increase in density and temperature and a small shift in the angular direction. We found the correlation with the density ρ to be strongly negative $\sim$0.5, with a lag time similar to the velocity and that with the thermal speed, w, and change in angular direction, $|\frac{d\theta}{dt}|$, to be very small. The strong negative correlation with the density is to be expected if the velocity is positively correlated because the flux, ρv, generally remains constant.

Neither form of pressure is well correlated with micropulsation activity, and neither are their time derivatives. This is not a surprising result considering that the density, ρ, is negatively correlated and the velocity, v, is positively correlated.

Other investigators have reported anecdotal evidence that the "cone-angle," $\phi = \arccos \frac{B_x}{|B|}$, of the magnetic field is related to micropulsation activity. What has been witnessed is that the onset of micropulsation activity is accompanied by sharp increases in the cone-angle of the B field. In an attempt to verify this on a statistical basis, using the same methods as above, we found that the correlation is very small, at least on the timescale of one day.

In an effort to see, in a high resolution example, the effect we had been studying on a statistical basis, we examined data from day 203 (July 21) of 1988. The day was remarkable because the effects of a large solar flare were becoming visible. There were two large pulses that day. The first at 0600 UT was primarily a jump in velocity and the second at 1330 was primarily a pressure (ρv^2) jump.

As we see in figure 4.5 the first pulse, the jump in velocity, is accompanied by a strong increase in pulsation activity. Later in the day, after the pulsations have settled down a bit, the strong pressure pulse is accompanied by little to no increase in activity.

This supports what we have been seeing statistically. The increases in velocity generate micropulsations and the increases in pressure do not.

Chapter 4

Conclusions

We have found that the correlation between the solar wind velocity temporal gradient and micropulsations of the magnetosphere is sharply peaked at $\Delta T = 0$. Previously it had been observed that the solar wind velocity drives micropulsations. However it seems that it is the change in velocity which is the critical factor.

This correlation with the gradient of the solar wind suggests that the micropulsations are a feature of stream interaction regions. However, this does not seem to be the case. Examination of other parameters related to interaction regions, such as an increase in density or temperature, or a change in direction, all produced no correlation except for the density which was correlated negatively, the opposite of what we would expect from stream interaction regions. Thus, as they do not occur in tandem with features of interaction regions, micropulsations are probably not a product of stream interaction regions.

The accepted models that describe the generation of magnetospheric micropulsations suggest that waves are generated either through Kelvin-Helmholtz instability or through cyclotronic instability produced in quasi parallel shock structure. A Kelvin-Helmholtz instability would not generate pulsations exclusively when the wind speed was increasing nor would it generate waves fitting the relationship $T \sim 1/B$ which has been seen by some other observers (not in the present experiment).

A cyclotronic instability would explain the relationship to $T \sim 1/B$ but not necessarily to the speed gradient. Theses findings cast some doubt on the models which we have constructed for micropulsation activity.

An examination of day 203 of 1988 shows an example of the effects we have been studying. An increase in solar wind speed accompanied by an increase in micropulsation activity and an increase in pressure without and accompanying increase in pulsations.

This work presents the result that the temporal gradient of the solar wind velocity drives magnetospheric micropulsations. These increases are not related to pressure or energy flux changes, or changes in the cone angle of the IMF, nor are they connected to any other features of stream interaction regions. The implications are that our present model explaining micropulsations may need to be reworked.

Acknowledgements. First and formost, I want to thank my boss, thesis advisor and sailing buddy, Alan Lazarus. Al, your patience and guidance through two and a half years has been exceptional. You really make research fun.

Thanks are due to Dr. George Gordon, Pamela Milligan and Joan Quigley for all their help in finding my way around the computers and the data at CSR, and to Louis Villanueva for staying on my back and nagging me about getting this thing done, to Anne Bowes for remaining calm and keeping this place working amid all the chaos, to Ken Dinndorf for keeping me company and making me feel like I wasn't working hard enough. And of course thanks to the whole bunch in the Space Plasmas group at CSR for being friendly and supportive.

I also have to thank the group in L'Aquila, Italy under the direction of Umberto Villante, for introducing me to a beautiful land. Grazie a Massimo, Ermanno e Umberto.

Of course I owe thanks to all my neighbors at La Maison Française for being wonderful friends and throwing great parties. Thanks too to all my fellow seniors who helped me raise the load on Project Athena while working on *their* theses.

Thanks to Project Athena and the Student Information Processing Board for not breaking too often and helping me when it did respectively.

And of course thanks to my parents for being the supportive parents that they have always been and for getting me through this place. Mom, Dad, thanks.

This work was supported in part by the National Aeronautics and Space Administration through Grant NAG 5-584 (GSFC-IMP 8). Thanks to NASA to for supporting my research in L'Aquila.

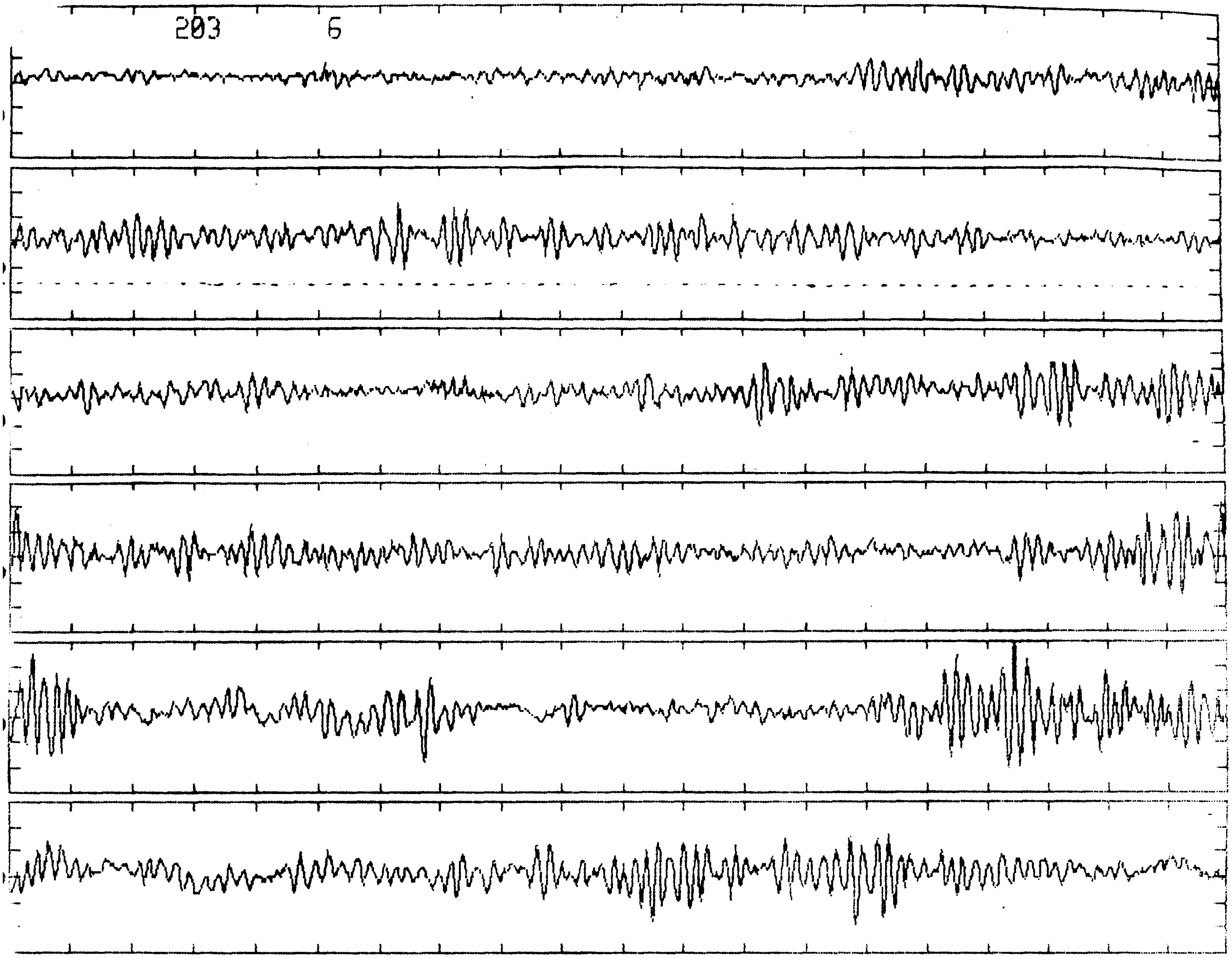

Figure 4.1: Example of a micropulsation event from 0600 to 0800 of day 203 of 1988. Each horizontal band represents 20 minutes and each tick mark represents one minute. Full scale on the vertical axis is one gamma.

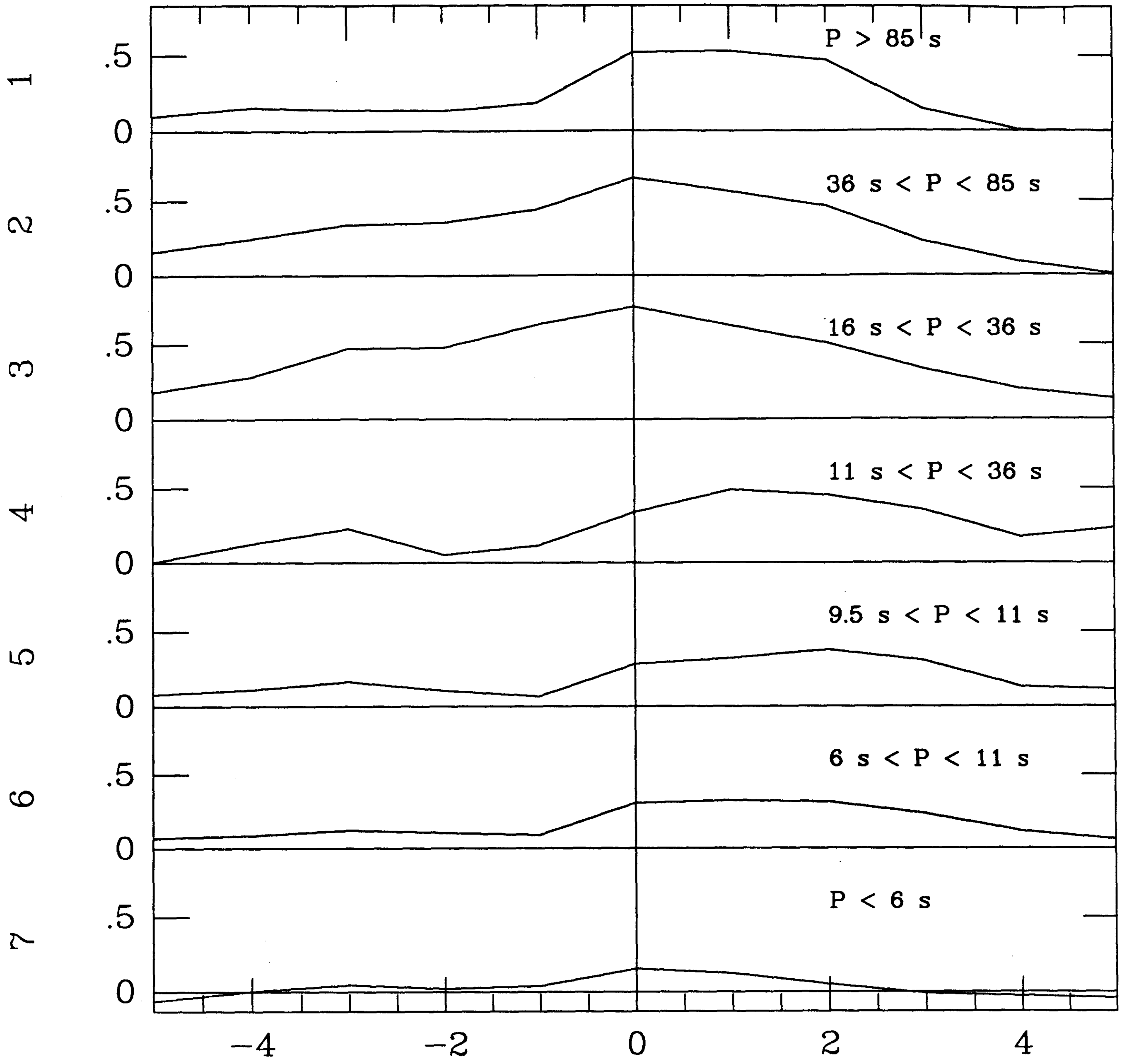

Figure 4.2: Correlation of velocity with micropulsation activity in various bands for a range of time lags. Band 1 is the lowest frequency band from $p = 85$sec to longer periods. High correlations at positive time lags imply that micropulsation activity leads high speed solar wind.

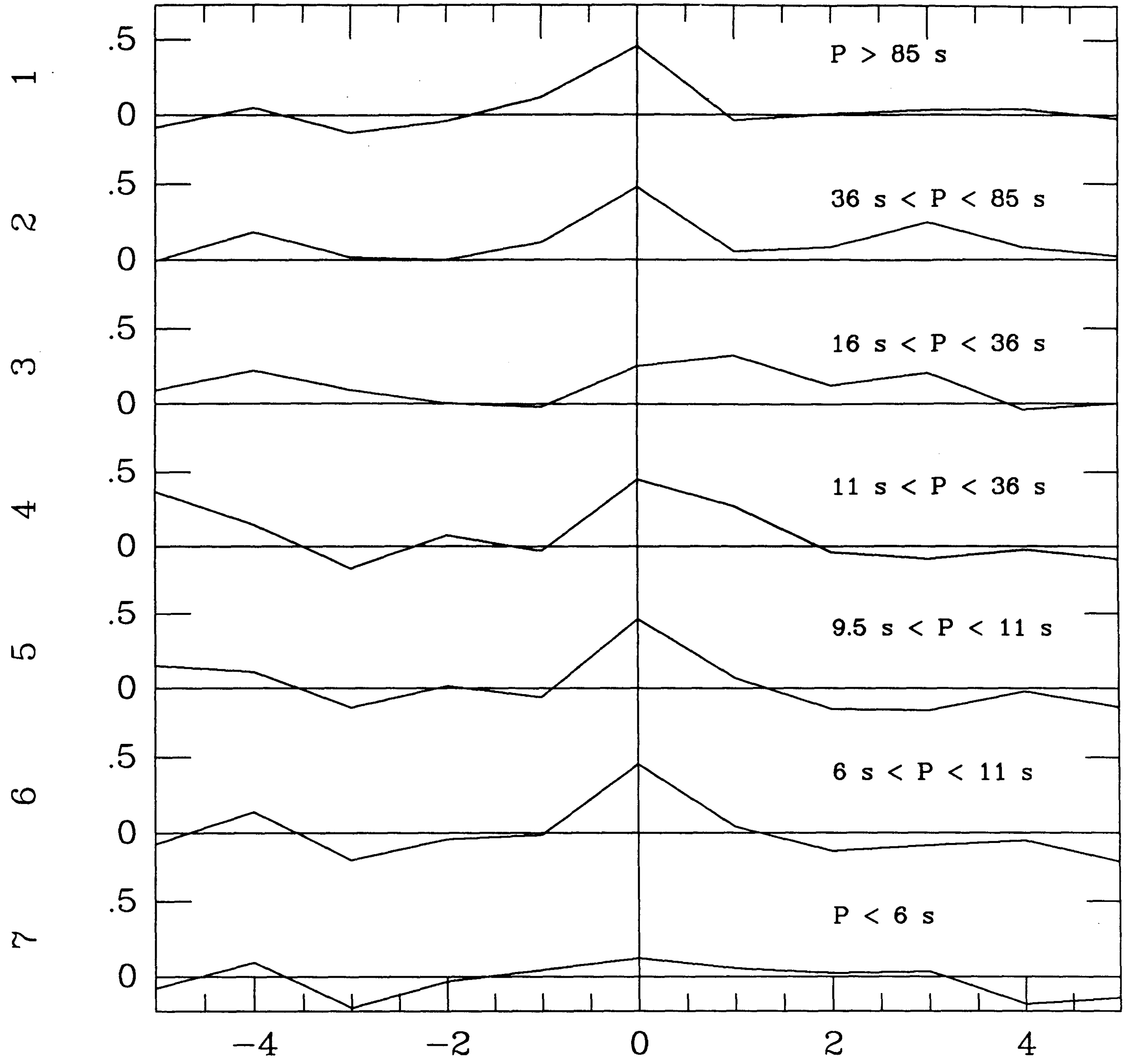

Figure 4.3: Correlation of velocity temporal gradient with micropulsation activity in various bands for a range of time lags. Band 1 is the lowest frequency band from $p = 85$ sec to longer periods. The correlation is sharply peaked at $\Delta T = 0$

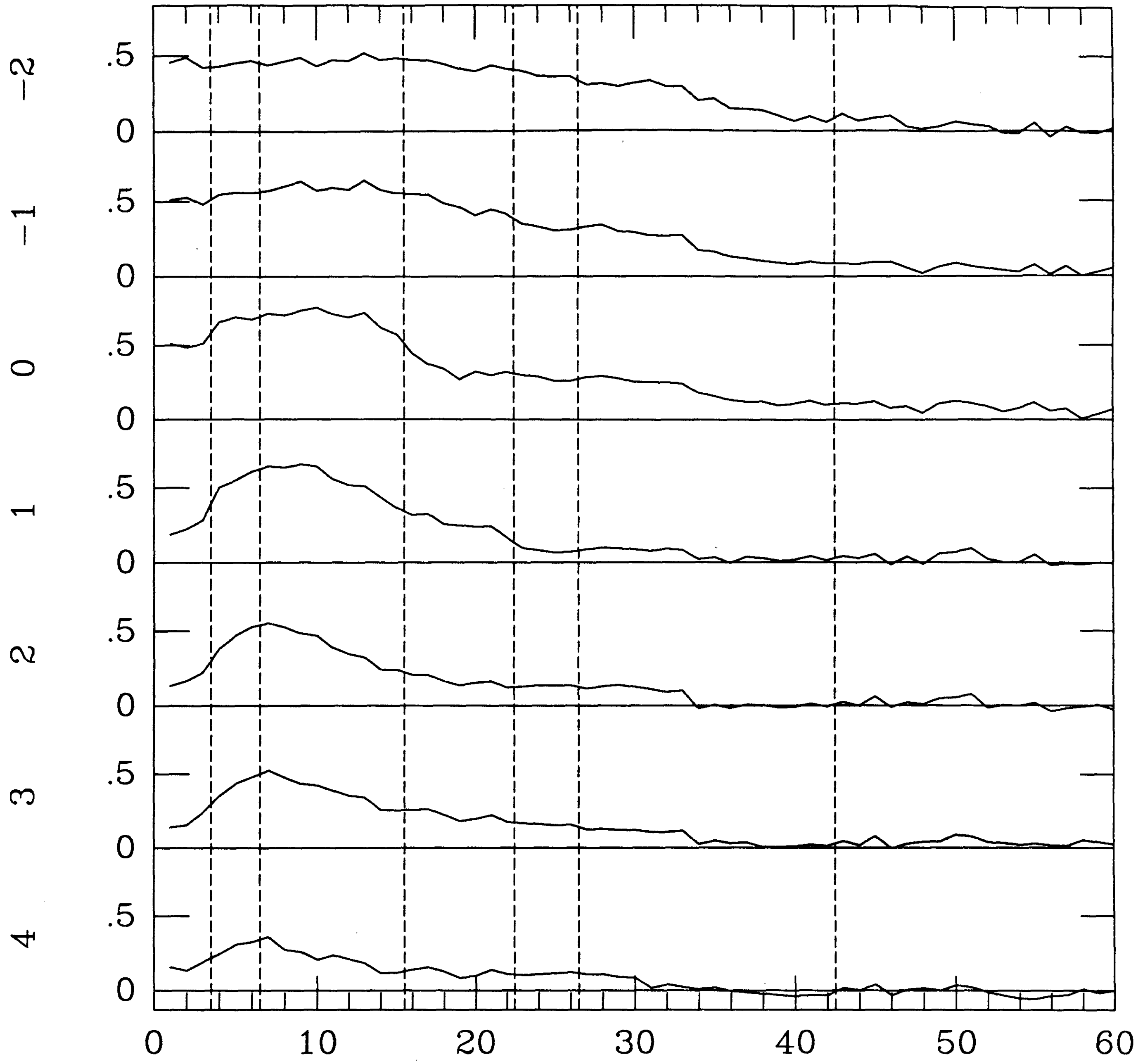

Figure 4.4: Correlation of high resolution frequency bands with velocity for lag times from -2 days to +4 days. The y-axis represents correlation coefficient and the x-axis represents the band number. The dashed lines represent the breaks between frequency bands that were chosen for further analysis. Note that in bands 4 and 5 lags of $\Delta T = 1$ or 2 have higher correlations. Frequency f is related to the band number n by the relation $f = n/265$.

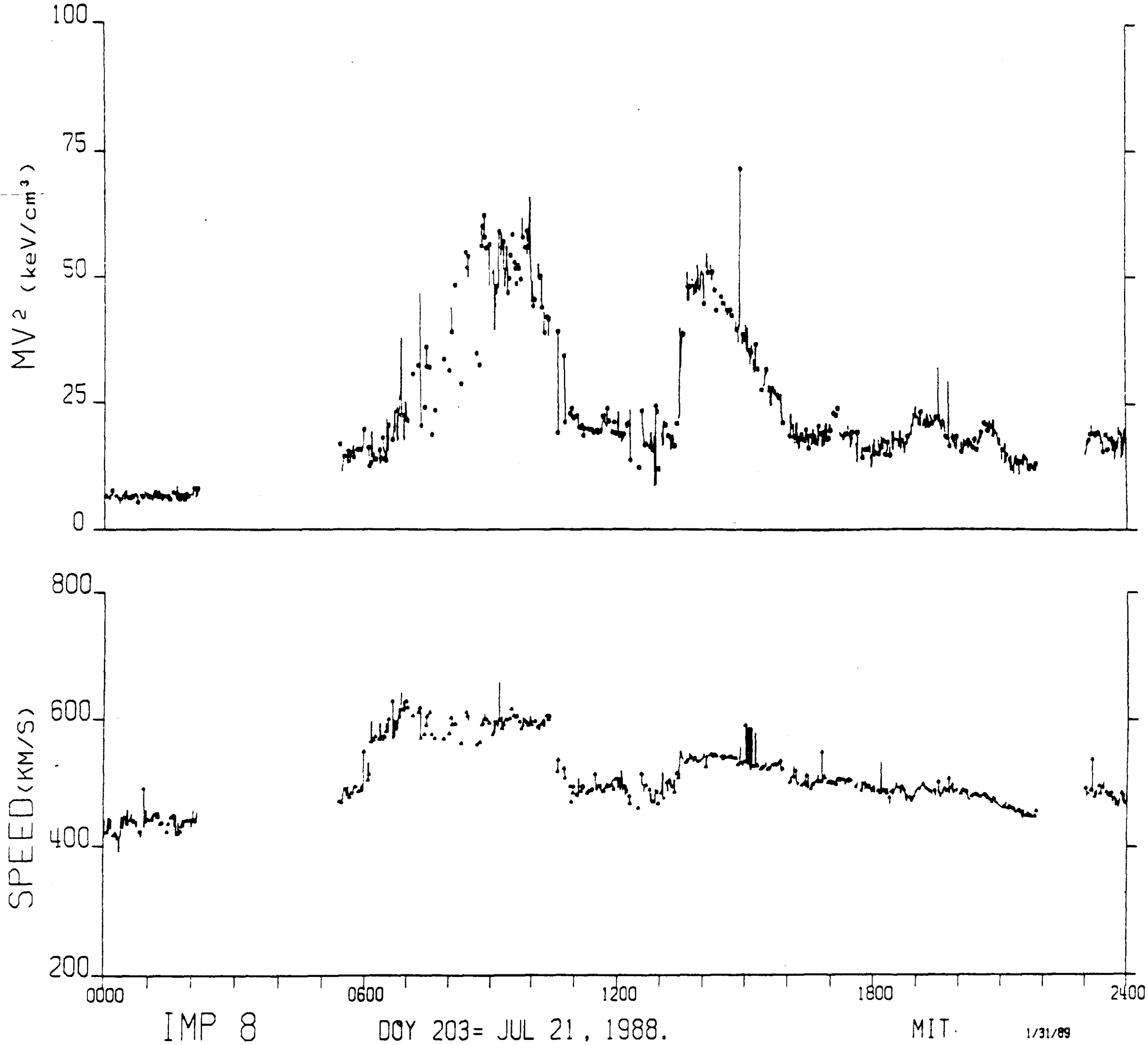

Figure 4.5: Plasma parameters from day 203 of 1988. At ~0630 we witness a pulse in velocity and at ~1330 we see a pulse in pressure. The large increase in activity shown in figure 4.1 occurs at about 0630 and around 1330 we see no such activity.

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