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A comparison of midlatitude Pi 2 pulsations and geostationary orbit particle injections as substorm indicators

T. K. Yeoman,[1] M. P. Freeman,[2] G. D. Reeves,[3] M. Lester,[1] and D. Orr[4]

Abstract. Both the injection of energetic particles at geostationary orbit and ground magnetic observations of Pi 2 wave activity are characteristic indicators of the onset of the substorm expansion phase. Occurrence statistics for the appearance of electron and proton particle injection at three geostationary spacecraft and for the detection of midlatitude magnetic Pi 2 pulsations in a 3-hour local time sector have been compiled from 240 hours of data. Throughout this interval a signature was detected on one or more of the instruments on average every 65 min. It is demonstrated that the detection of geostationary orbit particle injections and the detection of ground-based Pi 2 pulsations are correlated at a very high significance level, and that both appear to be effective substorm indicators. However, a small percentage of events (~10% in each case) may be identified as a Pi 2 event but not as an injection event or viceversa, without any obvious explanation, such as the local time of the observing instrumentation. A number of possible explanations for the discrepancies between the two data sets are discussed.

Introduction

Understanding the magnetospheric substorm is probably the most important goal of current research in magnetospheric physics, playing as it does a fundamental role in magnetosphere-ionosphere coupling. Much of the research toward this aim employs substorm indicators, such as Pi 2 pulsations or particle injection signatures, to determine the timing and possibly also the location of substorm onset.

Mid-latitude Pi 2 wave bursts have long been recognized as a characteristic signature of the substorm expansion phase [e.g., *Saito et al.*, 1976; *Rostoker et al.*, 1980]. Pi 2 waves are known to be optimally observed in the premidnight sector, near 2300 local time [*Jacobs and Sinno*, 1960], but are visible over most of the nightside magnetosphere at mid-latitudes, although their higher latitude and space signatures are frequently more localized around the midnight sector [*Singer et al.*, 1983; *Gelpi et al.*, 1985].

Since the advent of in situ measurements of the magnetospheric plasma by spacecraft instrumentation, it has been established that an enhancement ("injection") of energetic particle flux (both electrons and protons) at geostationary orbit is also a characteristic feature of the substorm expansion phase [e.g., *Lanzerotti et al.*, 1971; *Belian et al.*, 1981].

The aim of the present study is to offer a comparison of the Pi 2 and injection substorm indicators to assess the efficiency, differences, and relative advantages and disadvantages of the two techniques.

[1]Department of Physics & Astronomy, University of Leicester, Leicester, United Kingdom.
[2]British Antarctic Survey, Cambridge, United Kingdom.
[3]Los Alamos National Laboratory, Los Alamos, New Mexico.
[4]Department of Physics, University of York, Heslington, York, United Kingdom.

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Motivation and Instrumentation

This study derives from ongoing research by a larger group of scientists into bursts of high-speed ionospheric flow on the nightside [*Williams et al.*, 1990, 1992; *Lewis et al.*, 1993; *Morelli et al.*, 1993]. These scientists have assembled a database from a wide range of instrumentation covering the same time intervals. A knowledge of the relationship between flow bursts and the substorm cycle is necessary in order to understand the flowburst phenomenon, and cannot properly be achieved without an understanding of the substorm indicators derived from that data set.

We study here a subset of the available instrumentation, but over the whole time span. Ten days (240 hours) were selected on the basis that at some time during them flow bursts [*Williams et al.*, 1990, 1992; *Lewis et al.*, 1993; *Morelli et al.*, 1993] had been observed in the European Incoherent Scatter (EISCAT) radar [*Rishbeth and Williams*, 1985] CP 2 programme data. Such a data interval represents an interval of higher than average magnetic activity. This introduces a systematic bias into our analysis when compared to the much larger and more randomly selected database that has been employed to examine the statistics of the geostationary particle injection data alone [Borovsky *et al.*, 1993]. We shall comment on this comparison later. However, it is reasonable to assume that the current data set does allow a comparison of the two substorm indicator techniques, since it comprises a reasonable number of events for each instrument over the same (albeit geomagnetically active) interval. Furthermore, the authors are aware of no similar comparative statistical study between geostationary spacecraft particle injections and ground-based observations of Pi 2 pulsations which has previously been attempted.

The occurrence of Pi 2 wave bursts is measured here by the ground-based U.K. Sub-Auroral Magnetometer Network (SAMNET) [*Yeoman et al.*, 1990]. SAMNET is a mid-latitude array of flux gate magnetometers covering 54° - 65° geographic latitude and 3 hours LT in the European sector, with a sampling interval of 5 s. Geostationary orbit electron and proton injections are monitored via three Los Alamos National Laboratory (LANL) spacecraft [*Belian et al.*, 1978; *Higbie et al.*, 1978; *Baker et al.*, 1979], which, during the period of this study, were situated at UT - 10 hours, UT + 5 hours, and UT + 1 or UT - 2 hours. In this study, 1-min time resolution data are employed, with integrated fluxes between 30 and 300 keV for the electrons and 100 and 600 keV for the protons being investigated. The electrons are counted at 0°, ±30°, and ±60° from the spacecraft spin plane, and the protons in the equatorial plane of the spacecraft only. For the interval under study here, the three spacecraft and seven ground magnetometer stations were, on average, each individually operational for ~80% of the time. The locations of the various instruments employed in this study are illustrated in Figure 1.

Results

Occurrence Statistics

In the following sections, first, a presentation of the occurrence statistics for the ground-based Pi 2 and the spacecraft particle injection events will be given independently. Second, the statistical relationship between the two phenomena will be explored, and third, three examples of simultaneous geostationary orbit particle flux and ground-based data will be presented. In the subsequent sections the following definitions are used:

1. Pi 2 pulsations are defined here as waves in the Pi 2 frequency band (periods of 40-150 s), of duration 200-900 s. These waves are subdivided into two classes by magnitude on the lower-latitude SAMNET chain data, after a band-pass filter of 200-20 s has been applied. Large Pi 2 pulsations are defined as those with a peak-to-peak amplitude of 10 nT or greater, the remainder being defined as small. Where a wave train in the Pi 2 frequency band was observed, events were counted as distinct if wave amplitude increases were separated by 10 min or more. An observation of such a wave in one or more SAMNET station is identified here as a "Pi 2 event."

2. Injections are similarly subdivided into two classes: large injections involving an increase in particle flux of greater than a factor of 10 and small injections involving an increase of a factor of 10 or less. Both dispersionless and dispersed injections are considered, with a requirement that the flux rose with a time scale of 20 min or less in one or more energy band. An observation of

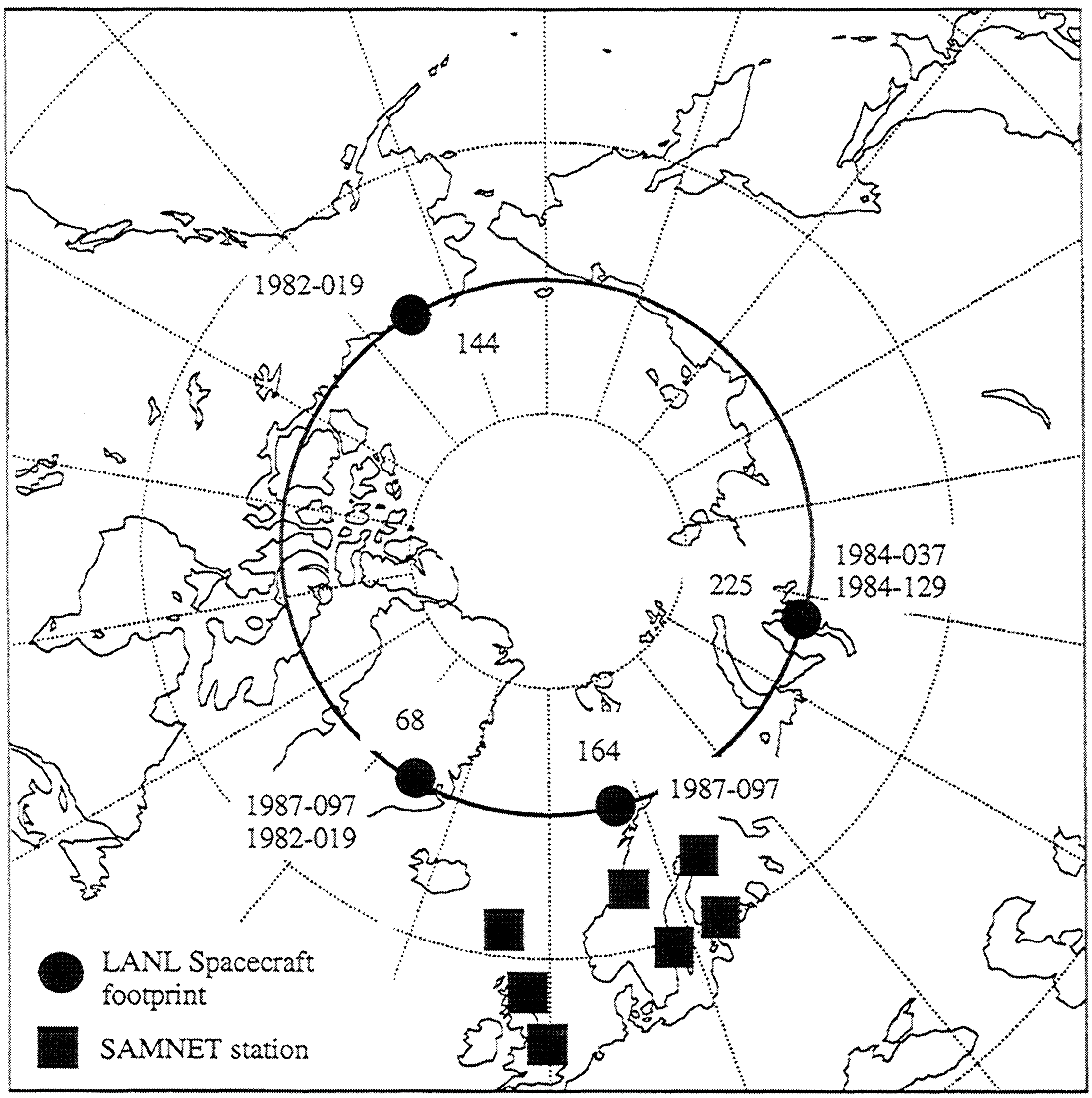

Figure 1. Locations of the SAMNET ground magnetometer stations and LANL spacecraft footprints during this study. The spacecraft identification and the number of hours of data for each location are shown. Note that at any one time, data from only three spacecraft are available.

such an injection in either or both of the LANL electron and proton detector instruments on one or more spacecraft is identified here as an "injection event."

Initially, features were identified which occurred as an injectionlike structure in any of the six spacecraft instruments (three spacecraft with electron and proton detectors), or on the low latitude SAMNET chain with a band-pass-filtered amplitude of 1 nT or more.

Figure 2a presents occurrence statistics for Pi 2 events, ordered by the local time of the center of the SAMNET array. As expected, the distribution is centered near local midnight [*Jacobs and Sinno*, 1960]. A fairly broad distribution is observed, with Pi 2 waves being observed during the 10-day data interval at local times as early as 1500 LT and as late as 1000 LT.

The corresponding occurrence statistics for particle injection events (electrons and protons for all three spacecraft) are displayed in Figure 2b. Again the overall distribution is centered around local midnight, as expected. In the case of the injections, however, a very broad distribution is observed, with injections observed at all local time bins. This is a consequence of the large azimuthal drift (~12 hours local time) which a particle of energy 150 keV or more can achieve in a 20-min interval. In addition, Figure 2b illustrates a systematic effect whereby proton injections are observed predominantly in the pre-local midnight sector and electron injections are observed predominantly in the post-local midnight sector. This is a consequence of the eastward (westward) gradient-curvature drift of the injected electrons (protons) in the geomagnetic field [see *Reeves et al.*, 1990, 1991]. The total number of injections observed in the electron detectors exceeds that in the proton detector instruments. This is most likely a consequence of the energy ranges of the instruments concerned.

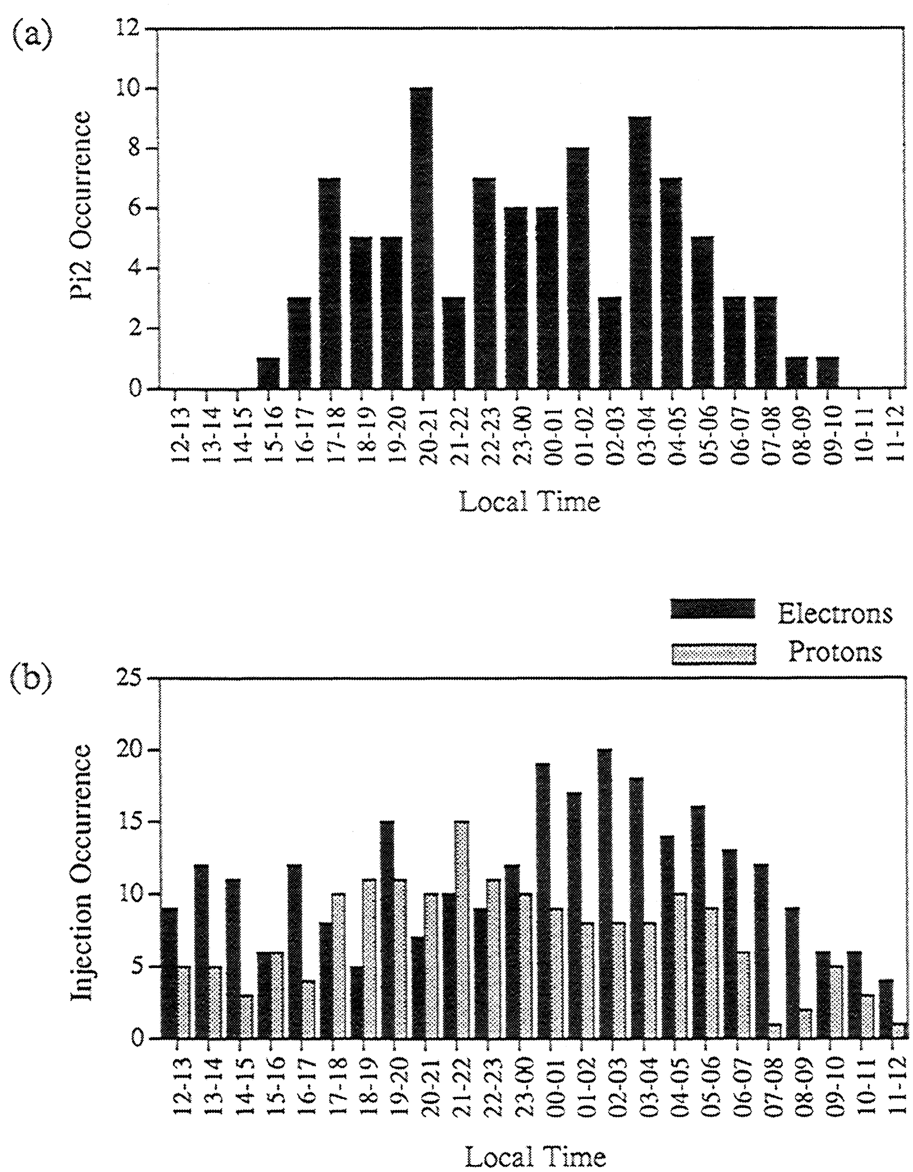

Figure 2. (a) Local time distribution of all Pi 2 events observed on the SAMNET array during the study. (b) Local time distribution of all electron and proton injections observed on the three LANL spacecraft particle detectors.

Case Studies

Before presenting simultaneous observations of Pi 2 pulsation and particle injection data, the relationship between the Pi 2 and particle injection signatures needs to be established. This is done here via a two-way contingency table (Table 1). The 240-hour interval is divided into 720 20-min trials, in which 195 particle events and 99 Pi 2 events were observed. Such a table gives a χ^2 value of 123.8, which leads, at 1 degree of freedom, to the conclusion that the Pi 2 and injection observations are related at a significance level of much less than 0.1%. Thus there is overwhelming evidence for the close connection between the Pi 2 and injection phenomena.

Near-simultaneous events on the various instruments, defined as events occurring (in the magnetometer data and/or in one or more energy bands for the spacecraft data) within 10 min for dispersionless injections and within 20 min for dispersed injection signatures, have been grouped into "substorm events." Such an analysis has identified 221 events observed on at least one spacecraft instrument or at least one ground magnetometer, or both, in the 240-hour interval (on average one event every 65 min).

Out of the 221 events, a total of 73 events were detected with near-simultaneity on the two instrument classes. Figure 3 illustrates an interval from 0000 to 0300 UT on March 20, 1990. A clear Pi 2 burst is observed in the 200- to 20-s band-pass-filtered *H* component magnetogram from the SAMNET KVI station at 0030 UT. This signature coincides with a sharp, dispersionless injection in both the protons and electrons observed in the LANL spacecraft 1982-019, located near local midnight at a local time 2 hours earlier than UT. The same injection feature is observed as a dispersed injection of electrons which have gradient-curvature drifted to the east from local midnight to the LANL spacecraft 1984-129 located 7 hours later in local time. No signature is observed in the proton detectors at this spacecraft, the protons having gradient-curvature drifted westward from the injection region. Thus this event illustrates coincident substorm expansion phase signatures from the ground-based magnetic field and the spacecraft particle detecting systems.

The remainder of the 221 events were only observed in one set of instrumentation. There were 26 occasions when a Pi 2 was observed, but with no corresponding injection; thus 74% of the 99 Pi 2 events were accompanied by "objective" evidence of particle injection. Further examination of the database revealed some small signature in the particle data corresponding to a clear signature in the Pi 2 data set. Here, these are termed "subjective events," because they would not have been identified from both data sets if used individually. Such an analysis revealed that on a further eight occasions when a Pi 2 was observed there was a small (subjective) particle injection. This suggests that in total, 82% of the Pi 2 events were accompanied by some evidence of particle injection. The division of events between "subjective" and "objective" signatures is clearly very dependent on the criteria employed in injection and Pi 2 classification.

As an example, in the event observed on August 29, 1989, between 2100 and 0000 UT, a clear Pi 2 pulsation was observed at NOR at 2250 UT (Figure 4). However, neither LANL spacecraft 1987-097 (LT = UT + 1 hour) nor spacecraft 1984-129 (LT = UT + 5 hours) observed a significant injection of electrons. A slight enhancement of the electron flux is seen at low energies, but such enhancements are commonly observed during nonsubstorm intervals. This event would thus be classified as a subjective injection event. The proton detectors on both spacecraft (not shown) detected no increase in particle count rates. In this case study therefore, although the magnetic signature of the substorm expansion was observed, the corresponding particle signature was weak or largely absent.

In contrast, there were 122 occasions when an injection signature was observed with no corresponding Pi 2. Thus for the 195 cases of clear particle injection activity, only 37% were objectively selected on the grounds of Pi 2 activity. In the event observed on June 14, 1988, between 0000 and 0300 UT (Figure 5), localized Pi 2 wave enhancement events were observed at FAR at 0200 and 0245 UT. On the LANL spacecraft 1987-097 (LT = UT - 2 hours), however, a sequence of small injection events was observed, starting as early as 0120 UT, before the first sign of Pi 2 activity. Low-energy electron counts on spacecraft 1984-037 (LT = UT + 5 hours) started to pick up in response to this activity as early as 0030 UT. Thus for this event, geostationary particle injection signatures were observed with no corresponding magnetic field signature on the ground until $1^1/_2$ hours after the onset of the first injection event.

Again, it is possible to increase the number of coincident events by making a subjective search, in this case for Pi 2 activity. When including the 28 further cases which such a search reveals, 52% of clear particle injection events are accompanied by some evidence of Pi 2 activity on SAMNET.

Table 1. A two-way contingency table for the Pi 2 and Injection Events

	Pi 2	No Pi 2	Total
Injection	73 (26.8)	122 (168.2)	195
No injection	26 (72.2)	499 (452.8)	525
Total	99	621	720

720 20-min trials are assumed in the 240 hours of data. In these trials 195 particle events and 99 Pi 2 events were observed. Expected values for independent phenomena are given in parentheses. It is concluded that Pi 2 and injection phenomena are related at a significance level of less than 0.1 %.

Discussion

The overall statistics of substorm indicator occurrence in this study have revealed that 221 substorm events are observed by the combined SAMNET and LANL instrumentation over the 240-hour interval. Thus a minimum of one substorm onset is indicated every 65 min. In principle the data presented here could be used to calculate a larger "corrected" event total. Information on intersubstorm intervals is an important constraint on substorm models [*Klimas et al.*, 1992]. *Farrugia et al.* [1993] recently observed an average delay between substorms of ~1 hour during a magnetic cloud interval. Such an intersubstorm gap is supported by the observations made in the present study, over a geomagnetically active interval much longer than that studied by *Farrugia et al.* [1993]. In contrast, *Borovsky et al.* [1993] observed an average interval between substorms of 2-4 hours over an interval which was even longer, and presumably of a more average geomagnetic activity. Clearly, the precise definition of what constitutes a substorm indicator will also affect the number of substorm expansions identified in a given interval.

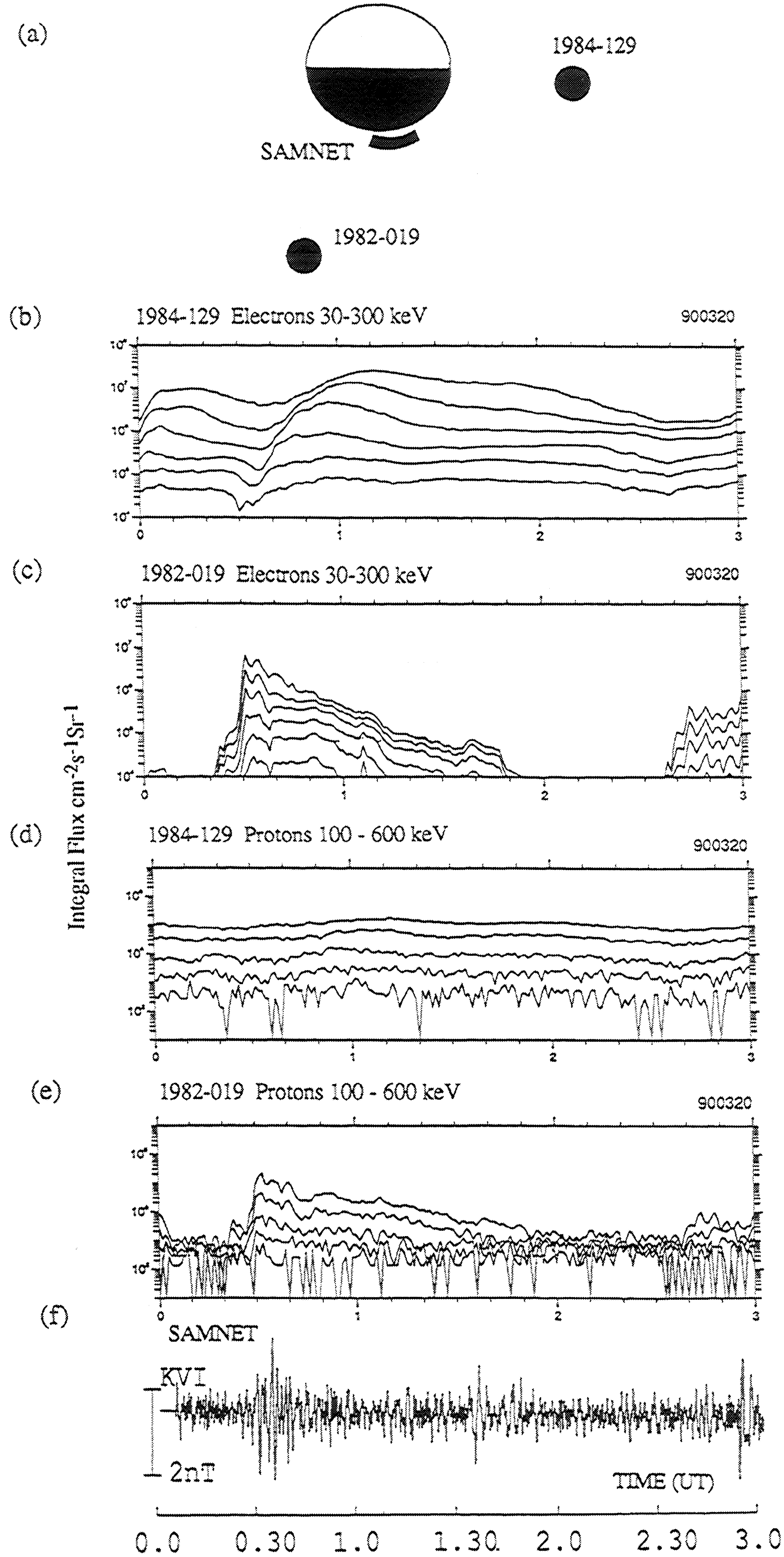

Figure 3. March 20, 1990. (a) Orientation of the instrumentation at 0030 UT. (b) Integrated electron fluxes from spacecraft 1984-129 (30-300 keV). (c) Integrated electron fluxes from spacecraft 1982-019 (30-300 keV). (d) Integrated proton fluxes from spacecraft 1984-129 (100-600 keV). (e) Integrated proton fluxes from spacecraft 1982-019 (100-600 keV). (f) Ground-based *H* component magnetic field from the SAMNET KVI station, band pass filtered between 200 and 20 s.

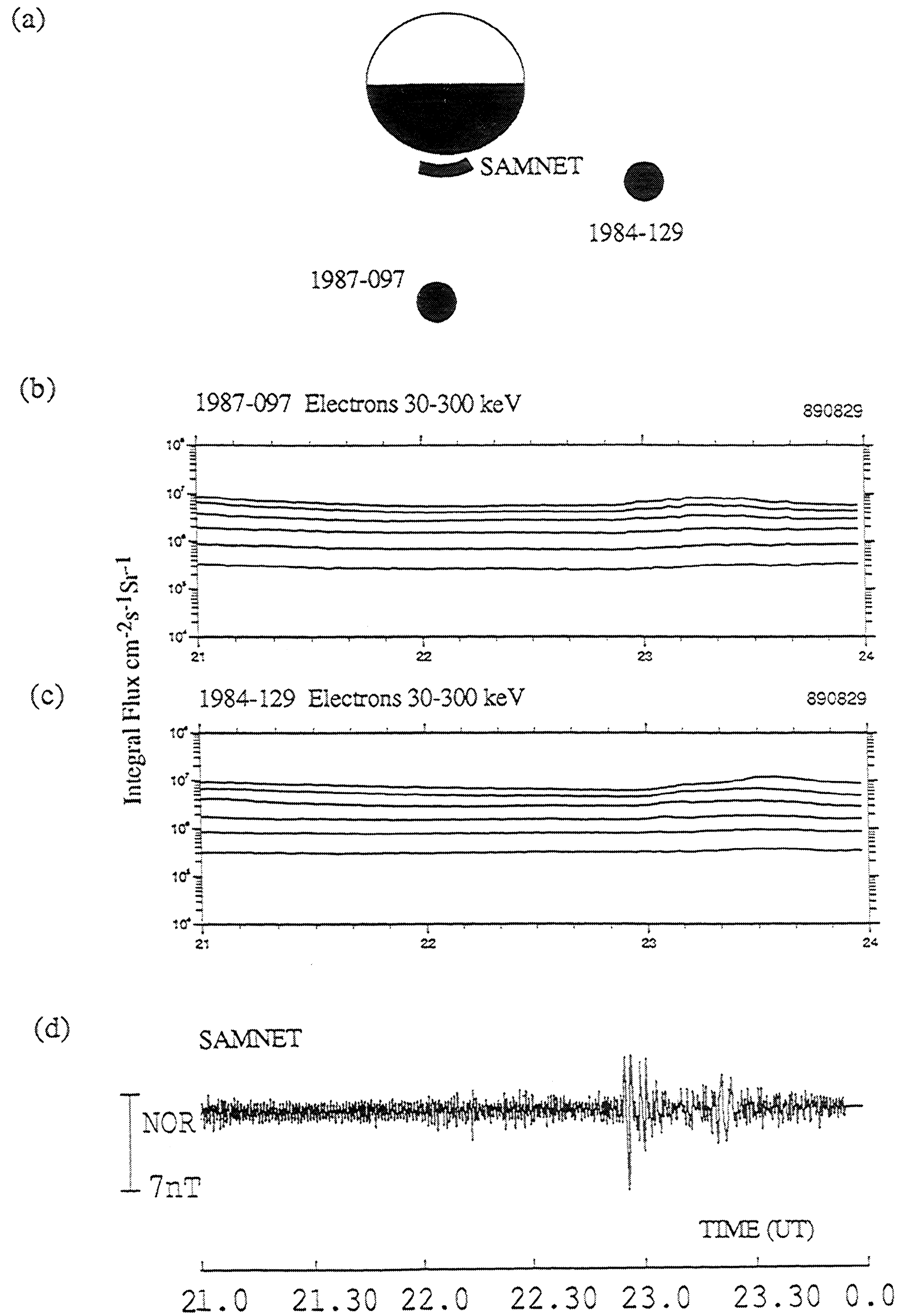

Figure 4. August 29, 1989. (a) Orientation of the instrumentation at 2300 UT. (b) Integrated electron fluxes from spacecraft 1987-097 (30-300 keV). (c) Integrated electron fluxes from spacecraft 1984-129 (30-300 keV). (d) Ground-based *H* component magnetic field from the SAMNET NOR station, band pass filtered between 200 and 20 s.

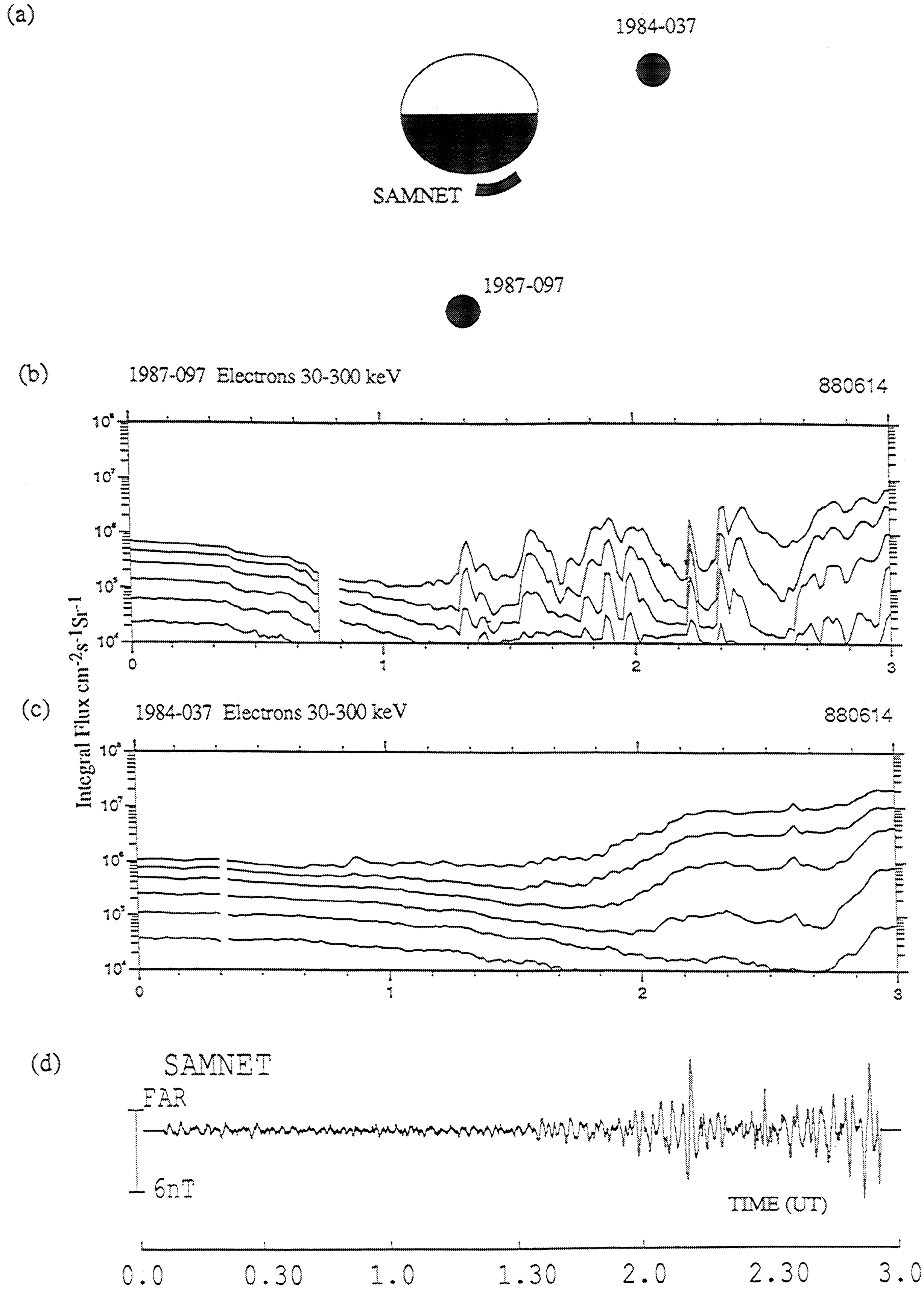

Figure 5. June 14, 1988. (a) Orientation of the instrumentation at 0200 UT. (b) Integrated electron fluxes from spacecraft 1987-097 (30-300 keV). (c) Integrated electron fluxes from spacecraft 1984-037 (30-300 keV). (d) Ground-based *H* component magnetic field from the SAMNET FAR station, band pass filtered between 200 and 20 s.

The occurrence statistics for Pi 2 and/or injection events are summarized in Figure 6. Of the total of 221 Pi 2 and/or injection events, 89% were identified objectively in the spacecraft energetic particle data, whereas only 45% were identified in the SAMNET ground magnetometer Pi 2 data. Thus we would conclude that the LANL three-spacecraft array is a superior substorm monitor to the SAMNET magnetometer array if used alone. Part of the explanation for events in which an injection is observed with no Pi 2 signature is that 40 of these events (18% of the total) occurred at a UT when the SAMNET magnetometer array employed in this study was poorly situated to observe Pi 2 signatures. From the data shown in Figure 2a we define this "blind spot" as 0700 - 1700 UT. It may be assumed that such events would have been detected had the magnetometer network been more widely distributed in local time, and the comparison of particle injections with wave data from a more global magnetometer array will form the subject of a further study.

Spatial coverage may also affect the sensitivity of the instrumentation to the Pi 2 and injection disturbance as the disturbance amplitude is likely to vary in local time, particularly in the case of the Pi 2 signature. On average the spacecraft array has more observing hours in a given LT sector than the SAMNET array. Consequently, 28 (13%) of the events had objective injections with only subjective evidence of a Pi 2, identified with hindsight. Conversely, eight (3%) events had objective Pi 2 signatures and subjective injections. In 53 (25%) events objective injections with no Pi 2 activity were observed, in spite of the magnetometer network lying in an apparently suitable local time, whereas 18 (8%) events had objective Pi 2s with no corresponding injections.

A subset of 29 of the 53 events for which there was no apparent Pi 2 activity were only observed as small injections. These events may have been due to nonsubstorm transients, such as magnetospheric compressions which cause fluctuations in the particle fluxes [*Wilken et al.*, 1982; *Farrugia et al.*, 1993], impulsive nonsubstorm reconnection in the distant magnetotail [*Sergeev et al.*, 1990], or some local plasma instability, not instabilities leading from or to substorm onset. Alternatively, weak substorm activity may not stimulate a full substorm signature [*Koskinen et al.*, 1993]. In other words, a subset of injection signatures may not have as a cause a substorm-associated geomagnetic field dipolarization. Unfortunately, the LANL spacecraft are not equipped with magnetometer instruments. In addition, a subset of these events may have been double counted, since low-energy particles gradient-curvature drifting relatively slowly around the Earth may be observed with a substantial time delay between two spacecraft (typical drift speeds ranging from 1.5° - 12° min^{-1} for 30- to 250-keV particles [*Reeves et al.*, 1990, 1991]), while the high-energy particle data may only observe a weak signature, and thus one injection could be erroneously identified as two substorm events rather than one.

	Objective Injection	Subjective Injection	No Injection
Objective Pi 2	73	8	18
Subjective Pi 2	28	...	...
No Pi 2	94	...	...

	Large Injection	Small Injection
Good LT	24	30
Bad LT	40	...

Figure 6. A summary of Pi 2 pulsation and particle injection occurrence statistics (see text for details).

Summary

It has been demonstrated that the detection of injected geostationary orbit particles and the detection of ground-based Pi 2 pulsations are highly correlated phenomena, and both appear to be effective substorm indicators. In both cases, however, a small percentage of events (~10% in each case) are detected as a Pi 2 event but not as an injection event, or detected as an injection event but not as a Pi 2 event, without any obvious explanation such as the local time of the observing instrumentation. Ideally, therefore, a variety of characteristic signatures should be sought to establish beyond doubt the onset of the substorm expansion phase. Although the results presented in this study only strictly apply to the two sets of instrumentation employed in the comparison, very similar conclusions would be expected to apply to other, similar instrument sets. In principle the data presented here could be used to calculate a "corrected" event total, of more than 221, which, statistically, should have occurred in the 240-hour interval. However, uncertainties in such a statistical analysis, and possible alternative Pi 2 and injection definitions, argue against an analysis of such detail for the current data set.

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M. P. Freeman, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, England, United Kingdom.

M. Lester and T. K. Yeoman, Department of Physics & Astronomy, University of Leicester, University Road, LEICESTER LE1 7RH, England, United Kingdom.

D. Orr, Department of Physics, University of York, Heslington, YORK YO1 5DD, England, United Kingdom.

G. D. Reeves, Los Alamos National Laboratory, Los Alamos, NM 87545.

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