SUSPECTED WAVE–PARTICLE INTERACTIONS COINCIDENT WITH A PANCAKE DISTRIBUTION AS SEEN BY THE CRRES SPACECRAFT


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ABSTRACT

On 1990 October 13 the Sussex Particle Correlator Experiment on the USAF/NASA Combined Release and Radiation Effects Satellite (CRRES) observed modulation in the onboard wave-particle correlation functions at frequencies between one third and one half of the electron gyrofrequency during the period from 14:45 UT to 15:45 UT. At this time the Iowa plasma wave experiment measured chorus emissions in the region of one third of the local electron gyrofrequency, and the Lockheed IMS-LO electron instrument observed an apparent velocity dispersion event in electrons between 770eV and 20 keV, beginning at about 15:12 UT. We describe the particle correlation technique, briefly present this event, and then describe an approach to testing the hypothesis that wave-particle interactions were responsible for the large modulation seen in the particle correlator. Recent work on the statistical analysis of such data is presented.

1. INTRODUCTION

An outstanding problem in space plasma physics is to demonstrate directly the occurrence of wave particle interactions (WPIs) in the magnetosphere, because of their expected importance in the transfer of energy and momentum in space plasmas, which are essentially collisionless. The family of particle correlation techniques all aim to perform in-situ measurement of linear, resonant wave particle interactions (WPI) in space plasmas. The particle autocorrelator (PAC) technique originated at Sussex /1/, and was first used on sounding rockets /e.g. 5/ although the earlier work of /2/ had measured the frequency spectrum of a fixed energy electron detector. The correlator concept was since developed and modified both at Sussex and at Berkeley - where it is also referred to as the phase correlator - (e.g. /3,4/ and references therein), the Max Planck Institute and the University of New Hampshire. All correlator designs have in common that they look for periodicities in the input of a particle detector that match those of a component or components of the input of a wave detector. What differentiates the second generation wave-particle correlators (WPCs) is that they use a wave detector as a predictive input, whereas the PAC, in calculating an autocorrelation function is estimating one of a more general class of structure functions on the particle time series produced by the detector. WPC designs differ in the type of amplitude and phase information they can return about the degree of particle modulation by the waves (e.g. the percentage of particle bunching if any).
From linear theory, for a wave mode of frequency $\omega$, resonance can occur only at specific electron parallel velocities $v_{||}$ in the electron frame, given by the resonance condition

$$v_{||} = \frac{(n\Omega_e + \omega)}{k_{||}}$$

where $\Omega_e$ is the electron gyrofrequency, and $n$ is an integer.

From quasi-linear theory, the consequence of near-resonance is bunching of the particles about a given phase $/\theta_0/$. The aim of the correlator is to evaluate a structure function (such as the auto-correlation function (ACF)), or an estimate of cross correlation on the available particle and wave time series, over given regions in energy-pitch angle space, in order to detect this bunching. As a low energy electron instrument samples a range of energies and pitch angles the WPC can, in principle, directly identify a region of phase space in which wave particle interactions are occurring. The resolution in phase space depends on how the electron instrument is dividing up the energy and pitch angle space, and on the $\Delta E/E$ of electron instrument, which governs the intrinsic resolution of $v_{||}$. One must also consider $\Delta \omega/\omega$ which is more subtle in effect and dependent on the mode in which the correlator instrument is being operated. The strengths of the instrument include that it can measure wave phenomena with intrinsic frequencies as high as 5 kHz in the cross correlation mode discussed in this paper, with a frequency resolution of 160 Hz. A general problem is that comparison of measurements made at different points in the energy-pitch angle space requires that the count rate must be high enough to allow statistically significant measurements. The counts will however, for a real particle distribution, depend on pitch angle, and so one cannot compare all of phase space in practice unless the particle counter provides enough counts at the lowest particle densities, unlikely for other than a dedicated particle instrument. Other limitations are specific to the type of correlator employed, in the case discussed below a cross correlation function is only capable of looking at linear relationship between waves and particles $/8/$. In our case we have a 64 point cross correlation function so significant $\sqrt{N}/N$ statistical noise is inevitable. Despite all these caveats the experiment can in principle perform in situ measurement of wave-particle interactions, and so represents a potential advance over the indirect methods used so far.

2. THE SPACE INSTRUMENT FOR CRRES

The SPACE experiment on CRRES was designed to perform in situ correlation of the particle counts from the Low Energy Plasma Analyser (LEPA) and the onboard wave signal from the Berkeley electric field/Langmuir probe instrument. The $E$ - field wave signal was taken in from the electric field experiment via a wideband (less than 30 kHz) filter and then put into an operational amplifier in order to extract the highest amplitude wave mode by clipping. The wave signal was then used as a predictive filter on the particle counts. In the mode considered here and at this stage in the mission LEPA detected electrons from $\approx 100$ eV to 20 keV. The correlator used fixed rate sampling of the square wave (at $10kHz$ in the mode considered here) to form a 1 bit time series corresponding to wave displacement. At this point several different types of correlation estimators were then possible, depending on the mode of operation.

We present observations from the correlator’s cross correlation mode, in which the raw particle counts including background, $C_p$, were recorded in 128 bins each $10^{-4}$ seconds in duration. At this point, provided that there was at least 1 count in each bin [corresponding to a count rate of $10^4$ per second] the average level was used to set the corresponding bit of $C_p$ high (1) if the counts in that bin were greater than the mean, low (0) if less than mean. The saturated wave input, $C_w$, was measured at the end of each time bin and wave bit set “high” if displacement was positive, zero otherwise. The result was two 1 bit time series which could be cross correlated. If counts were on average less than one per bin however the original time series was not replaced, but any $C_p$ that was greater than 1 was replaced by one. The count rate into what was not a dedicated particle instrument was usually less than $10^4$ per second including background and so this was usually the applicable regime.
CRRES Observation of Wave–Particle Interactions

Frequently the un-normalised linear cross-correlation function between these two time series would be estimated by (see for example, /8,9/):

\[ s^{(l)}_k = \sum_{i=0}^{128-|k|} C_{W_i+k} \]  

(2)

The notation \(|k|\) indicates that time lags of \(\pm k\) are defined, and \(k\) runs from 0 (the zero lag), to 127. This means that there will be \(2 \times 128 - 1\) i.e. 255 terms in the function. Unlike an autocorrelation function it will not be symmetric in \(k\). It also means that the \(k\)th term is formed from \(128 - k - 1\) terms. However, if we instead consider only positive lags up to 63 we can have an alternative one-sided direct one bit cross correlation function (CCF) where the 64 terms \(s^{(c)}_k, k = 1, 64\) are given by:

\[ s^{(c)}_k = \sum_{i=1}^{64} C_{W_i+k} \]  

(3)

These two estimators would be equivalent (see /6/ p.270) in the limit \(N \to \infty\). \(s^{(c)}_k\) is calculated on CRRES, and 23 of the above functions are then transmitted as 1 accumulated CCF denoted by \(S_k\), once per second i.e approximately 15 times per half spin. Note that the zero lag is not sent.

3. MODE 9 OBSERVATIONS OF WAVE PARTICLE INTERACTIONS

We will consider an example of an observation made by the Sussex Particle Correlator (SPACE) while operating in its wave-particle cross correlation mode. This was during orbit 194 on 1990 October 13. Figure 1 (a) the shows WPC survey data from orbit 194 with the corresponding Iowa wave instrument survey plot as Figure 1 (b). The energy of the particle input to SPACE from LEPA is shown plotted versus UT in the lowermost panel of figure 1 (a). We see that the instrument sweeps down from 20 keV to 10 eV in 120 steps dwelling on one energy level during each half spin (14.3 seconds). The top panel of figure 1 (a) shows the magnitude (the square root of the modulus squared) of the Fourier Transform of the summed CCFs (divided by 32) displayed on a plot of frequency (linear scale) versus decimal UT. This provides a measure of the relative spectral intensity of the wave particle correlations observed by SPACE The first WPC angular sector is omitted as the voltage is still stabilising in this period. Each vertical stripe is an average over 4 successive half spins, approximately 1 minute. It should be noted that the WPC did not always receive E-field input throughout this orbit, during some of which the Berkeley instrument was in Langmuir probe mode.

Strong chorus emissions below the electron gyrofrequency (the continuous dark line on figure 1(b)) appeared as early as 13:50 UT. The electromagnetic emissions fall in frequency as the spacecraft moves to increasing L value. The two highest values of the magnitude of the spectral density can be seen at 14:30 and 15:15 on figure 1 (a). In only one case, however, is the input into the correlator known to be a valid periodic wave signal, the later of the two points. The earlier is from the Langmuir probe. We want to determine if either of these two events is likely to be due to a wave particle interaction. Because the magnitude of the associated spectral power is not sufficient to discriminate (as borne out by the modelling performed in /11/) between these two cases, we seek a more unambiguous indicator.

4. ANALYSIS AND MODELLING

The WPC is operating in a regime where the ratio of count rate to characteristic wave frequency is less than or of order unity. The typical maximum quiet-time electron count rate for LEPA (including background) on CRRES was 2 or 3 times \(10^3\) per second, which has been established from a systematic survey of LEPA data. This implies that the instrument is usually in the second of the 2 regimes discussed above. Confirmation of this is the dependence of the mean value of the cross correlation functions on the energy of the electrons, and thus on the count rate, which can be seen
Figure 1: (a) Top panels: Sussex Correlator Survey data from Orbit 194. (b) Bottom panel: Iowa Wave Experiment survey data from orbit 194. The gyrofrequency is marked by a solid line.
in figure 1 (a).

We thus need to design a statistical test that will help us to decide whether the interactions apparently observed by the WPC are statistically significant. We test the hypothesis \( H_0 \) that the random arrival times of the particles are completely independent of each other against the hypotheses \( H_k \) that there is a modulation of period \( 2k \).

This can be done by calculating the set of test statistics

\[
t_k = \frac{(S_1 - S_k)^2}{S_1 + S_k}
\]

where the \( S_k \) are defined as above and \( k \) runs from 1 to 33. Preliminary testing using simulated data and 5 kHz modulation suggests that this is a valid approach \(^7\). This is now being generalised to other frequencies and to real WPC data from this and other events. The technique relies on our ability to independently estimate the \( k \) at which we should be testing, which we can do by examining the wave data. Providing that we can establish through simulation the characteristic distributions for values of \( t_k \) taken from unmodulated and modulated particle series, we should be able to compare these with the values obtained from real data and thus, by consideration of individual observations, ascertain whether there are indeed wave-particle interactions being observed. It is intended to report the detailed results of these tests, for several CRRES orbits, in a future paper.

More detailed analysis is required to determine the wave modes that could be in resonance with these particles, here the cross-correlation technique has been shown in use in the context of a possible wave-particle interaction events.

ACKNOWLEDGEMENTS

We would like to acknowledge the help of Chris Paranicas and Mark Popecki in producing the wave plot used as figure 1(b), and Kevin Kerns in analysing and reducing the LEPA data. NWW acknowledges the support of PPARC grant GR/J 02438 and NWW and CGM acknowledge the assistance of the USAF office of Aerospace Research under the Window on Science Programme.

This paper is dedicated to the memory of Peter Christiansen.

REFERENCES