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THE ROLE OF SCIENTIFIC BALLOONING FOR EXPLORATION OF THE MAGNETOSPHERE

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ABSTRACT

The magnetosphere is explored in situ by satellites, but measurements near the low altitude magnetospheric boundary by rockets, balloons and groundbased instruments play a very significant role. The geomagnetic field provides a frame with anisotropic wave and particle propagation effects, enabling remote sensing of the distant magnetosphere by means of balloon-borne and groundbased instruments. Examples will be given of successful studies, with coordinated satellite and balloon observations, of substorm, pulsation and other phenomena propagating both along and across the geomagnetic field. Continued efforts with sophisticated balloon-borne instrumentations should contribute substantially to our understanding of magnetospheric physics.

INTRODUCTION

Magnetospheric balloon studies started with Van Allen's discovery of auroral X-rays /1/ and with the pioneering flights of Winckler et al. /2/ and Anderson et al. /3,4/. The first stage of magnetospheric ballooning (MB) was concerned with the characteristics of X-ray events. Several types of X-ray bursts were defined. These can be divided in two main groups: fast burst-like events observed mainly in the evening and midnight sectors, and slowly varying events in the morning and daytime sectors.

During the second MB-stage X-ray events were related with other geophysical phenomena mainly observed from the ground: riometer absorption, magnetic disturbances and aurora, in general phenomena associated with magnetospheric substorms. Examples of large scale balloon campaigns during this stage were those carried out by the SBARMO and SAMBO organizations /5,6,7/. Balloon trajectories from a campaign carried out by some SBARMO member institutes in the summer of 1973 /8/, and from the SAMBO winter 1982 campaign balloons are shown in Fig. 1.

The third MB-stage is characterized by extensive coordination with not only groundbased but also satellite experiments. Geostationary satellites, magnetically conjugate with the region monitored by balloons, are particularly useful in this context. This stage is still going on. The two first stages were devoted to a general exploration and mapping of phenomena accessibe to balloon-borne instruments. A real understanding of the physics behind these phenomena is not possible without simultaneous studies of related phenomena at higher altitudes. Examples of results from such studies are given in a following paragraph.

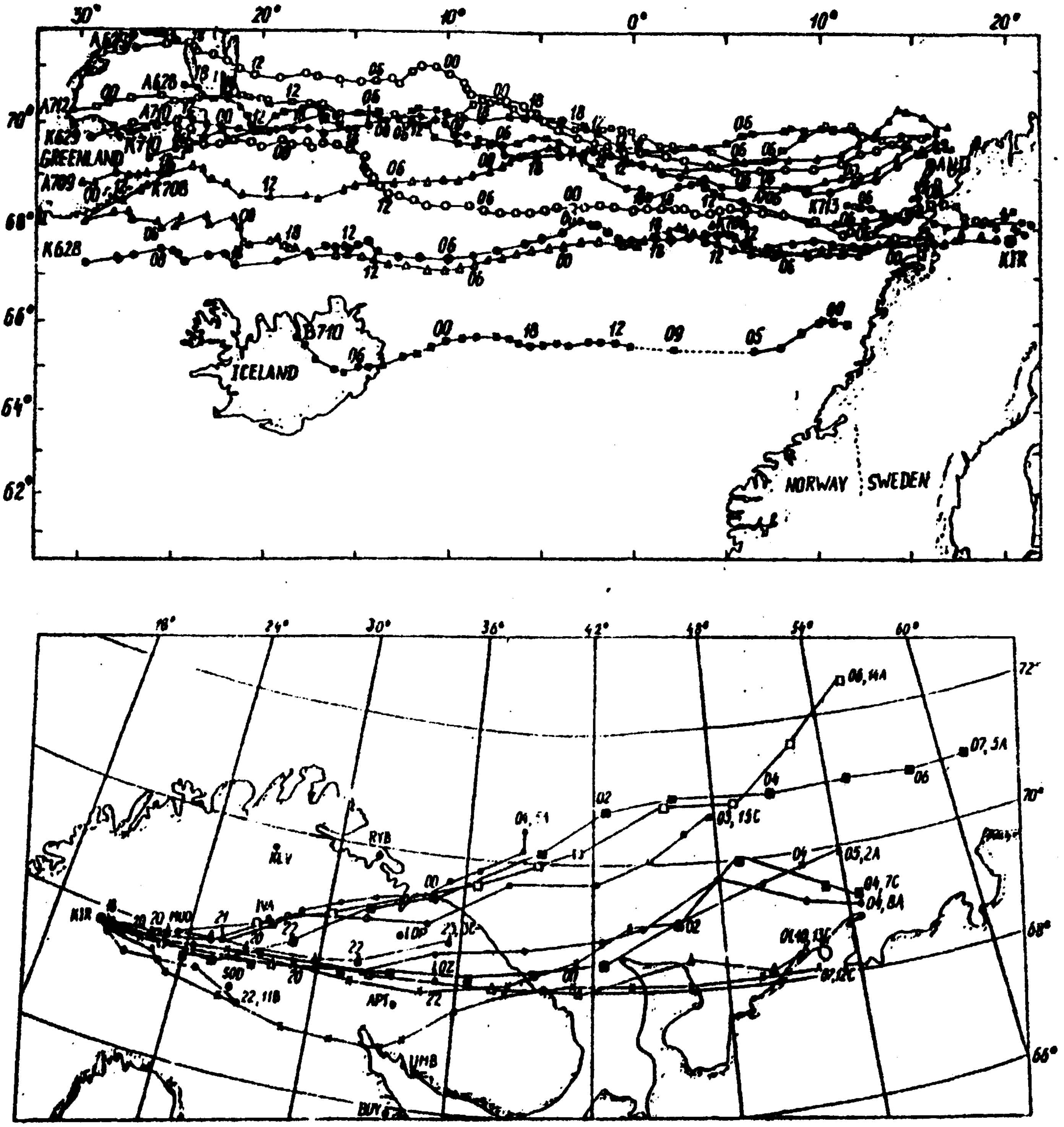

Fig. 1. Balloon trajectories during a summer 1973 campaign (top panel) and the SAMBO winter 1982 campaign (bottom panel).

INSTRUMENTATION

An example of a balloon payload is shown in Fig. 2. A typical payload may contain some or all of the following instruments.

X-ray detectors with one or several energy channels and in some cases also collimators providing some angular resolution. The detectors of the payload shown in Fig. 2 contain 7 collimated scintillation detectors. An X-ray pinhole camera with spatial resolution of about 15 km has also been developed and flown /8/.

VLF-antennas with a bandwidth of the order of 0.1 - 10 kHz.

Three-axis magnetometers recording slow geomagnetic variations.

Three-axis electric field detectors. The horizontal component represents the ionospheric electric field averaged over a distance of roughly 100 km. The vertical component measured on the balloon is an indicator of possible disturbances from atmospheric lightnings that may invalidate interpretation of the horizontal component.

Pressure and temperature sensors that are sufficiently sensitive to detect infrasonic waves.

Photometers that can record e.g. auroral emissions.

For future missions the use of optical imagers, sensitive for some strong auroral spectral line, has been discussed. It must of course be put on top of the balloon in order to have an unobscured field of view. Improved X-ray pinhole cameras with a spatial resolution of about 10 km and a field of view of approximately 100 km diameter at the X-ray production altitude are being developed /10/. Riometers may also be included in future payloads.

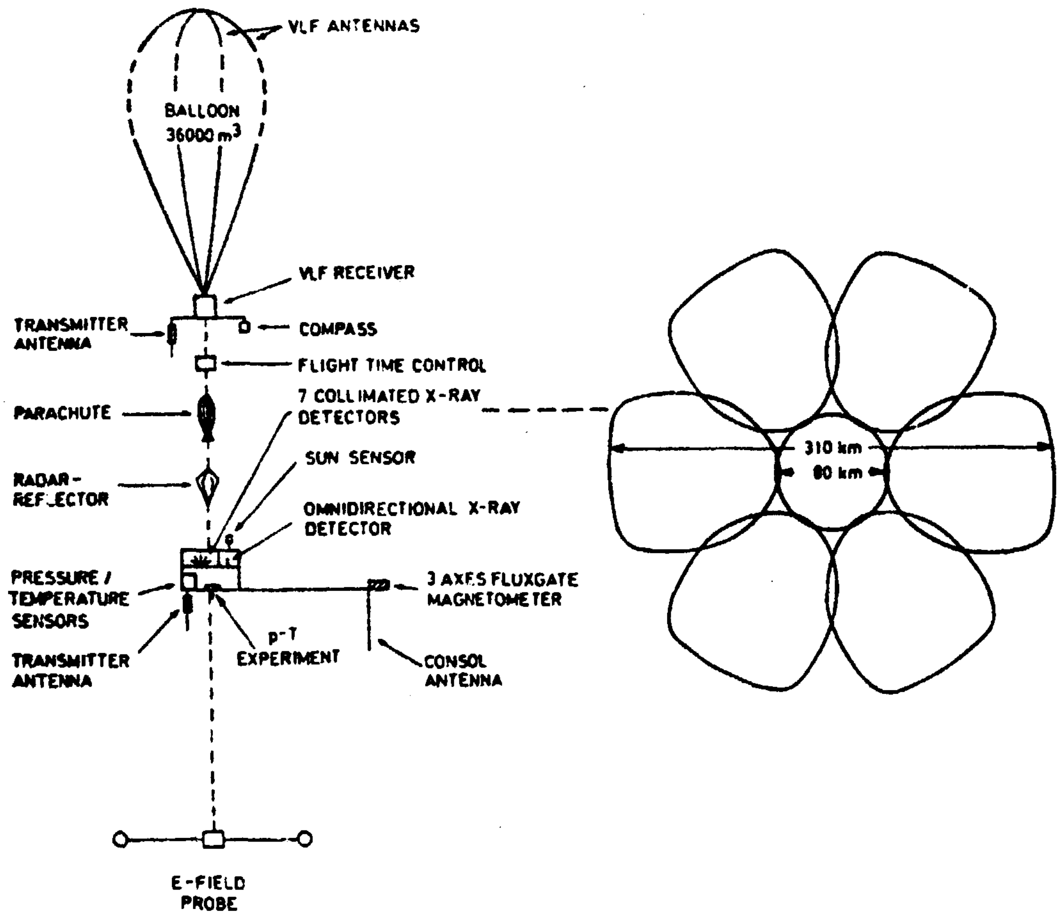

Fig. 2. Sketch of the configuration of a multi-experiment payload together with fields of view of the X-ray detectors. This payload was used in the SBARMO 1979 campaigns /6/.

Advantages of ballon-borne instruments

The cost per data byte is much lower for balloon-borne than rocket- and satellite-borne instruments but of course higher than for groundbased equipment.

The spatial resolution of groundbased instruments is limited by the separation between neighbouring instruments. Balloons may, especially over water, for limited time periods provide valuable complementary instrumentation of e.g. magnetometers and riometers. Furthermore, optical instruments are not obscured by clouds at balloon altitudes.

Geostationary satellites and rockets cannot discriminate between variations in time and space. It would be prohibitively expensive to launch large numbers of such vehicles with a spatial coverage comparable to that of a dozen simultaneous balloons and one magnetically conjugate geostationary satellite.

Balloons are particularly well suited for studies of phenomena with time scales comparable to and longer than that of a sounding rocket flight and shorter or of the same order as a typical satellite orbital period. These include such important phenomena as long period pulsations and substorms, where the entire time sequence can easily be monitored from a set of balloons.

X-rays cannot at all be measured from the ground due to absorption in the low atmosphere. Recently some experiments have been carried out with X-ray detectors on a satellite, providing mappings of the large scale spatial distribution of electron precipitation for short time intervals when the satellite passes the polar regions /11/. The results can be compared with balloon-borne detectors simultaneously providing continuous measurements with high temporal resolution at specific locations. Hence, balloons and satellites are complementary to each other. A limitation is that it is not possible to uniquely determine the causative electron precipitation spectrum from a measured X-ray spectrum.

Ionospheric electric fields can be measured by groundbased radars such as Chatanika, STARE, SABRE, and EISCAT, but only if they are above a certain minimum value of the order of 10 - 20mV/m, and only with poor time resolution, of the order of 10 seconds if measured at the same point each time, much longer if a larger area is scanned, cf. ref. /12/. Balloons can measure continuously with a time resolution as high as the telemetry permits. THE SBARMO electric field detectors measured a full field vector every 100 ms.

The reason why horizontal ionospheric electric fields averaged over about 100 km map down to balloon altitudes of 30 km, but not to the ground is the altitude distribution of electric conductivity, as shown by Atkinson et al. /12/.

SOME RESULTS

Substorm phenomena

Using several simultaneous balloons launched from northern Scandinavia during the summers of 1967 and 1968 Pytte et al. /14,15/ discovered certain characteristic features of X-ray (high energy electron) precipitation during magnetospheric substorms. The growth phase begins with precipitation at high L-values, which then moves southward with a velocity of about 10 km/min. At high L-values it ends well before breakup (negative bay onset), but at the lowest L-value reached (the southern part of the auroral zone) it merges with post-breakup precipitation, with a minimum just before or at breakup, presumably corresponding to the auroral fading discovered by Pellinen and Heikkila /16/. After breakup the precipitation moves quickly poleward and becomes much more intense and burstlike or impulsive, until it decays gradually during the recovery phase.

Later studies /17,18/ have confirmed the above results. Fig. 3, taken from reference /17/, illustrates the growthphase equatorward and post-breakup-phase poleward motion of the X-ray precipitation, including the brief minimum just before breakup. It also shows particle fluxes observed at the GEOS-2 satellite nearly conjugate with the KA-balloon. The X-rays on this balloon exhibit a clear correlation with the electron fluxes seen on the satellite.

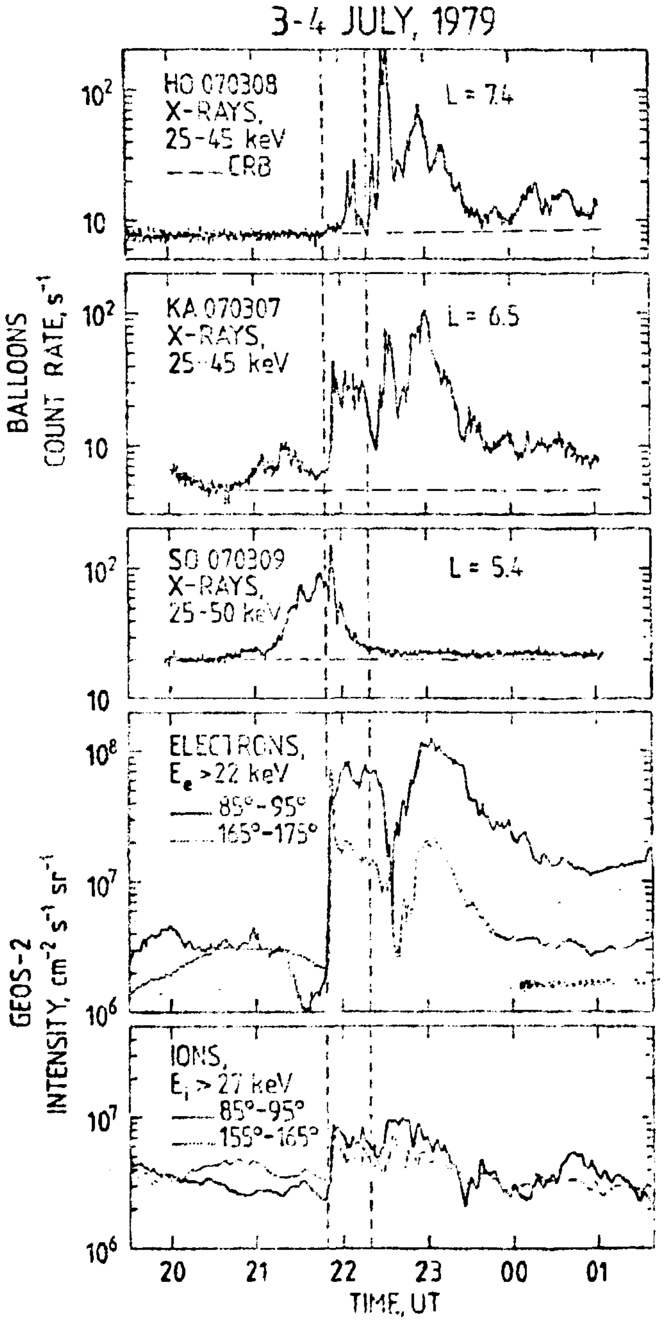

Fig. 3. Electron precipitation in the auroral zone near the conjugate point of the location of the geosynchronous satellite GEOS 2 on which an energetic particle spectrometer was operated. The substorm onset at 2149 UT and its intensification at 2220 UT are marked by dashed vertical lines. CRB is the cosmic ray background rate of the X-ray detectors. In the two lower-most panels the pitch angle ranges of the data are indicated /17/.

Some well-known phenomena observed on satellites can be associated with the movements of the X-ray emission pattern, such as the thinning and subsequent expansion of the plasma sheet /19/ and the inward and outward motion of the inner edge of the plasmasheet, which has been inferred from observations on geostationary satellites. An interesting case is reported by Kremser et al. /17/. Pedersen et al. /20/ have observed electric field signatures on two satellites (ISEE-1 and GEOS-1) situated at different L-shells in the nightside magnetosphere. The time delay between the two observations corresponded to the average E/B velocity (50 km/s) measured on the satellites in the signatures themselves. If projected down to the ionosphere this velocity is, however, an order of magnitude greater than what should be expected from the equatorward velocity (10 km/min) of the X-ray precipitation during growth phase. The relation between these two observations is therefore unclear.

A close correlation has, however, been found between the X-ray precipitation and phenomena observed from the ground. Riometers, magnetometers and allsky cameras reveal similar motions of CNA, the auroral electrojet and auroral arcs during all substorm phases /14,15,17,18/. The velocities agree very well, both in direction and magnitude.

Large-scale magnetospheric electric field

The number of satellites with electric field detectors simultaneously in orbit within the magnetosphere has always been fairly limited, and will remain so for the foreseeable future. Use of a large number of balloons, launched from several sites at different L-values, makes it possible to obtain a much more detailed instantaneous picture of the large-scale magnetospheric electric field, provided mapping of the potential distribution along the geomagnetic field lines is possible, i.e. magnetically field-aligned electric fields are negligible. A balloon campaign with altogether 24 balloons at L-values 3.9 - 22.6 was carried out in August 1969, by Mozer and Manka /21/. The results from this campaign was analyzed and a picture of the average magnetospheric electric field at different Kp-values was obtained. A special study by Mozer and Lucht /22/ of these data together with data from some other smaller campaigns (altogether 478 hours worth of data from 32 balloons) restricted to L-values between 5.4 and 8.2 gave an even more detailed picture of the average auroral zone electric field. Efforts of this kind, coordinated with future large satellite programs, e.g. the International Solar Terrestrial Program (ISTP), should contribute substantially to our understanding of magnetospheric physics. We strongly recommend such a large-scale balloon program, which should be feasible through concerted international collaboration.

Pulsations

As mentioned in the introduction the first MB-stage was devoted to studies of X-ray bursts. However, bursts and pulsations have of course been observed and studied also during the second and third MB-stages. Fig. 4 illustrates some types of X-ray pulsation and micro-structures, obtained during the 1979 winter SAMBO campaigns. Note how fast X-ray variations (second lowest left panel) are not seen in the photometer recording (lowest left panel) but a fairly good correlation is obtained for variations with time scales longer than a few seconds.

An interesting study of PC-5 pulsations by Iversen et al. /23/ has revealed very detailed correlations between X-rays and electric fields observed on balloons, and electrons, VLF emissions, and electric and magnetic field pulsations seen on the magnetically conjugate GEOS-2 satellite as illustrated in Fig. 5. The analysis resulted in the discovery of an earthward propagating magnetosonic wave, coupled to Alfvén waves along the geomagnetic field down to the ionosphere. This type of pulsation has not been observed before.

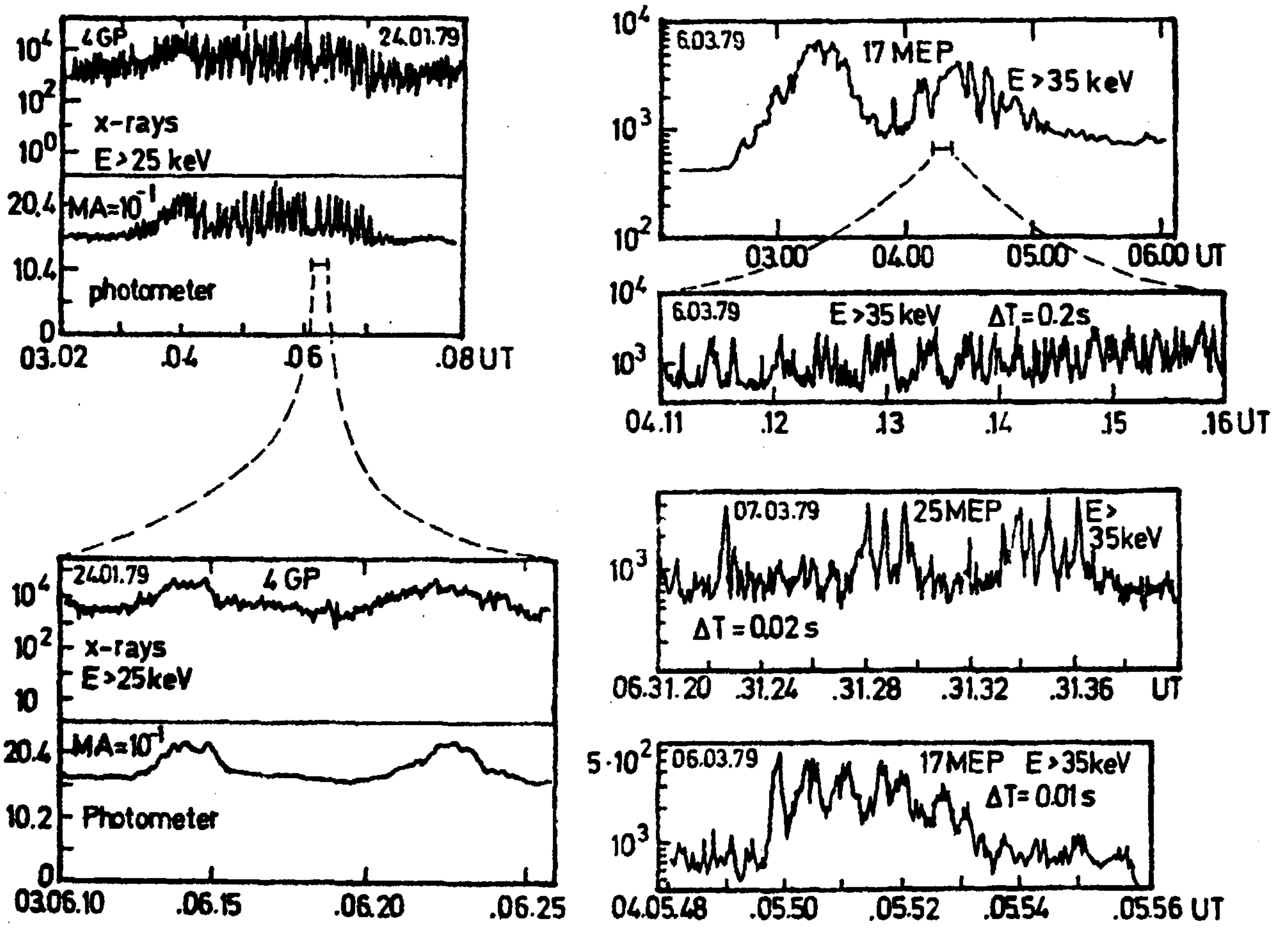

Fig. 4 Some types of X-ray pulsations with microstructures with time periods ranging from 0.01 second to several minutes (PC-5 pulsations, top right panel). These data were obtained during the SAMBO 1979 campaign.

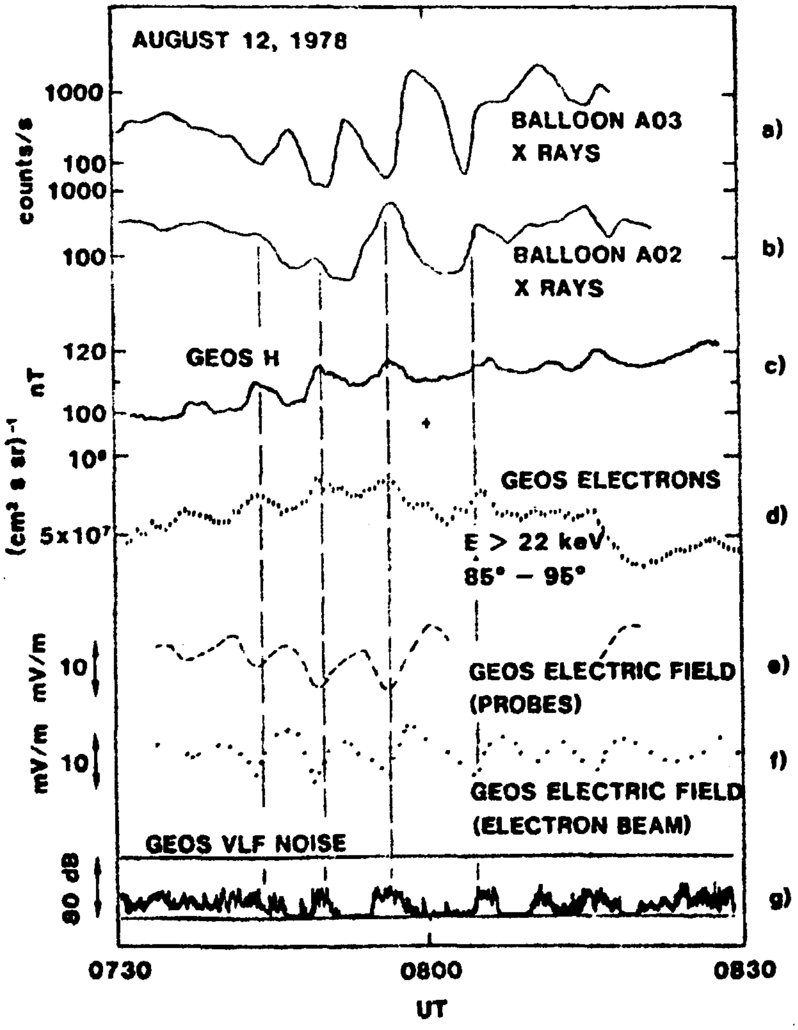

Fig. 5. Comparison of SBARMO balloon X-ray data and GEOS 2 electron, field and wave data during a PC-5 pulsation event /23/.

Small scale auroral structures

That the aurora has optical fine structure, the smallest being auroral rays, has been known as long as man has been present to observe it. The new auroral X-ray imager /9/ has now for the first time revealed fine structure on a spatial scale of the order of 10-20 km, as shown in Fig. 6.

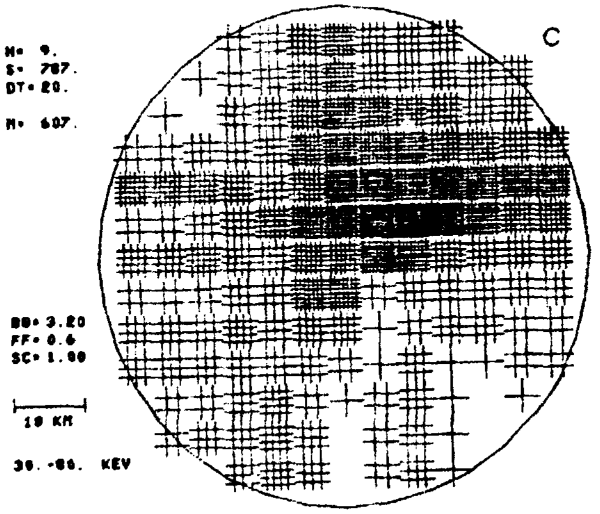

Fig. 6. An X-ray image obtained on August 31, 1978 from a balloon borne X-ray pinhole camera /9/. The number of horizontal or vertical lines within each 'square' of the image is linearly proportional to the number of photons that struck that square. The key to the left gives the start time for the image (H, S hour, second) the accumulation time in seconds (DT), the number of photons included in the image after background subtraction (N), the number of background counts subtracted from each square (BG), a factor which can be ignored (FF), a multiplication factor which determines how many lines on the image (M) correspond to how many photons (M n.SC), a unit length measure for determining scale lengths, and the energy range over which the image was constructed.

Since optical aurora is produced by less than 10 keV electrons and X-ray aurora by more energetic electrons, simultaneous studies of both kinds of structures can give new insights into the acceleration process, responsible for the different components. Measurements of precipitating as well as trapped electrons on rockets and satellites have indicated double or sometimes even multicomponent spectra, but the different sources of these components have not yet been identified. Both balloon-borne /9/ and satellite-borne imagers have indicated that the X-ray and optical auroral spatial structures only partly overlap. It seems hopeless to unravel the accelerator mechanisms without combined efforts of all kinds of experimental techniques available, on the ground and based on balloons, rockets and satellites.

CONCLUSIONS

The correlative studies of data from groundbased, balloon-borne and satellite-borne instruments, a few of them briefly described above, have shown that X-rays and electric fields measured on balloons are fairly good indicators of many magnetospheric processes. Remote sensing of phenomena in the close and distant magnetosphere is therefore possible by means of groundbased and balloon-borne instruments, due to the well-known propagation effects on waves and particles in the geomagnetic field. Uncertainties in the magnetic field geometry can also be partly resolved by studies of correlations between data from satellites and balloons. It has e.g. been established that at substorm breakup the equatorward boundary of the auroral zone is often conjugate to a point earthward of geosynchronous orbit /17/. During the PC-5 pulsation event illustrated in Fig. 5, the point conjugate to the GEOS-2 satellite could be located to be closer to one of two balloons 300 km apart from one another.

Balloons are particularly well suited for studies of phenomena with time scales of the order of minutes to hours, too long for sounding rockets and both too long and too short for satellites. The most important instruments are X-ray and electric field detectors. We wish to stress particularly the importance of electric field detectors, since their scientific merits have in the past been poorly exploited. The new X-ray imagers have also great scientific potential and should be used extensively in the future.

A few of the scientifically most important questions that may be addressed are:

1. How is the energetic electron precipitation, seen by X-ray imagers, related to low energy precipitation, observable by optical imagers?
2. Are small auroral optical and X-ray structures associated with similar structures in the distribution of field-aligned currents and electric fields, e.g.line currents (current ropes) and electrostatic shocks?
3. Is the large scale electric field and magnetospheric convection related to the small scale structure in the high and low energy precipitation? A threshold may e.g. exist above which structure appears, analogous to the threshold Reynolds number for onset of turbulence in a fluid.
4. What relations exist between wave emissions and emergence of small scale structures?
5. The distributions of electric fields and currents, and the precipitation spectra in the auroral breakup and westward traveling surge regions are of extreme importance for our understanding of the substorm mechanism /24/.

Active experiments in the magnetosphere and ionosphere may as well be an MB field of interest. Some attempts to locate artificial electron precipitation have been made, e.g. the Sovjet-French conjugate point experiment between Archangelsk and the Kerguelen Islands. In the future magnetic conjugacy in the ionosphere of artificial injections of waves and particles from the space shuttle may be located by means of balloons. Conjugacy between the two hemispheres at different disturbance levels is particularly interesting in the dawn and dusk sectors. Furthermore, ionospheric effects observable from balloons, of artificial particle injections from satellites in the magnetospheric tail would be invaluable for determining the shape of tail field lines.

Finally, it should be pointed out that, since balloon activities are relatively cheap, they offer good opportunities for developing countries to take part in the fascinating exploration of our magnetosphere, as well as in other areas of space research.

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Key words: Balloon, Electric field, Ionosphere, Magnetic pulsation, Magnetosphere, X-ray