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AN INSTRUMENT FOR RAPIDLY MEASURING PLASMA DISTRIBUTION FUNCTIONS WITH HIGH RESOLUTION

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ABSTRACT

A new instrument which can rapidly measure plasma particle distribution functions has been developed based upon recent innovations in electrostatic analyzer design and position sensitive particle detection. The new analyzer uses a quadrispherical geometry, but has a completely uniform 360° fan-shaped field of view. The polar angular distribution of entering particles is spatially imaged onto a position sensitive detector at the annular exit aperture after a deflection through 90°. Several methods of position sensitive detection have been successfully used in conjunction with this analyzer. The simplest is individual channel multipliers spaced around the annular exit. Microchannel plate electron multipliers permit greater position resolution to be obtained, and a detector using microchannel plates followed by a resistive anode image converter obtains angular resolution of about one degree -- i.e., 360 individual angle pixels. Instruments of this type were flown on a sounding rocket in early 1982 and will be included on the Giotto comet mission and the AMPTE ion release module (IRM).

INTRODUCTION

An important objective of space plasma particle investigations is to measure the three-dimensional ion and electron velocity distribution functions with the maximum resolution and speed allowed by instrument complexity and spacecraft constraints. For magnetospheric plasmas, the measurements should cover the entire 4Π sr solid angle with resolution down to a few degrees, and cover an energy range from a few eV to about 40 keV, with $\Delta E/E \simeq 0.1$-0.2. These measurements should be made, at least in some circumstances, with faster than one second time resolution. To fulfill these objectives, a formidable volume of data would be produced, which would overwhelm any reasonable telemetry capability. For example, a complete three-dimensional measurement with 3° resolution, $\Delta E/E = 0.1$ and four decades of energy range produces about 5×10^5 separate quantities. In the past, spacecraft limitations have required a compromise of most of these observational goals. In the future, however, microprocessors should radically increase the capabilities of plasma instruments by processing much of the raw data on-board, and thereby reducing the vast number of phase space measurements to a small number of quantities that retain most of the phase space "information." This approach is attractive because it is seldom necessary to use the full resolution of all three quantities -- energy, angle, and time -- simultaneously. The instrument processor can compute various quantities for transmission that are appropriate to the specific plasma conditions encountered. For example, in the magnetosheath and plasma sheet, moments of the distribution function such as density, bulk velocity, the momentum flux tensor, and heat flux could be computed every few seconds with almost negligible telemetry requirements. On the other hand, low altitude measurements of auroral beams and ion conics could be reduced to two-dimensional pitch angle distributions with maximum angle, energy, and time resolution. In all cases, the full distribution function would be transmitted with poorer time resolution for diagnostic use. To make such on-board processing practical, the plasma particle detector should have uniform and predictable response with the high energy, angle, and time resolution specified above. We have developed such an instrument, which combines an improved quadrispherical electrostatic analyzer with position sensitive particle detection.

THE SYMMETRIC QUADRISPHERE

The quadrisphere has been used for a number of space plasma instruments -- e.g., ISEE-1 and -2 [1], [2], and is well suited to fast plasma measurements. These instruments used the geometry of a "normal" quadrisphere shown in Figure 1, in which the polar angular distribution of entering particles is imaged spatially at the analyzer exit with some form of position sensing detector arrangement. This configuration exhibits good energy resolution, is mechanically and electrically simple, has a well-understood geometric factor and energy response, and has a polar angle field of view approaching 180°. The polar angle response, however, is not uniform, but decreases approximately proportionally to the cosine of the angle between the incident trajectory and the entrance normal. What is perhaps a more serious drawback is that the azimuthal response also changes with polar angle as Gosling et al. [3] have shown. This property exists because the analyzer lacks cylindrical symmetry owing to is planar entrance aperture.

A configuration that has complete cylindrical symmetry and yet retains the advantageous features of the quadrispherical geometry is illustrated in the right half of Figure 1. This analyzer has three concentric spherical section elements: an inner hemisphere with radius R_1 that is driven with the deflection voltage V, an outer hemisphere with radius $R_1 + \Delta_1$ which contains a circular hole subtending a half-angle Θ, and a small "top cap" section of radius $R_1 + \Delta_1 + \Delta_2$, which, in conjunction with the outer hemisphere, defines the cylindrical entrance aperture. Sample trajectories from three separate polar angle directions are illustrated. Although the analyzer uses hemispherical plates, it is classified a quadrisphere because of the nominal 90° particle deflection.

Neither the exact path of the particle trajectories in the entrance top cap region nor the optimum values of the geometric quantities Δ_2 and Θ are immediately obvious. The plate spacing in the top cap region is approximately $2\Delta_1$, so the electric field is about one-half that at the entrance to a normal quadrisphere. On the other hand, the total path length in this weaker field region is double that of the normal quadrisphere (i.e., through an angle 2Θ versus Θ for the normal quadrisphere) so that the total radial impulse is qualitatively equal. Numerical solutions to the Laplace equation and Hamiltonian equations of motion were computed to optimize the analyzer design and characterize its transmission properties. These solutions explicitly included fringing fields at the entrance aperture and in the top cap region so an optimum top cap geometry could be determined. A prototype analyzer based upon the resulting design was built and extensive laboratory measurements verify that it behaves as calculated. For these tests either a small Ni^{63} beta source or an ion accelerator was used to obtain measurements of response versus polar and azimuth angles and energy. The position sensitive detector used for these tests (shown in Figure 2) consisted of a microchannel plate (MCP) electron multiplier followed by a resistive anode and associated image processing electronics as described by Lampton and Carlson [4].

The measured contours of 0 and 50% transmission in the velocity-azimuth angle matrix is shown in Figure 3. The analyzer parameters listed in the upper left panel include a previously undefined quantity σ which is the truncation angle. It was found that polar angle focusing is improved by truncating the analyzer deflection angle to $(90° - \sigma)$ which was 83° in this example. The measured transmission contours are nearly identical to the values calculated from the equation in Gosling et al. [3] for a normal quadrisphere at 0° polar angle.

Calculations and tests were also performed to check the transmission dependence on dimensional tolerances. For example, the optimum ratio of the plate spacings Δ_2/Δ_1 is unity, but Figure 4 shows that the azimuth angle response only shifts by about 1.5° for a 50% change of this ratio. In general, the manufacturing tolerances required to assure uniform response in angle and energy are not unusually strict.

The polar angle response for five different truncation angles but fixed energy and azimuth angle is given in Figure 5. This test was made primarily to verify the agreement between the prototype analyzer response and the calculated values for a point source shown by dashed lines. The angular width of the sources was about 0.2°, so the measured and calculated values agree very well. This particular analyzer design (with optimum $\sigma = 7.2°$) achieved a polar angle FWHM resolution of 0.1°, which is at least an order of magnitude better than needed for our "ideal" instrument.

All design parameters can be expressed as functions of the analyzer Δ_1/R_1 ratio as summarized in Figure 6. In addition to the optimum values of Θ and σ, this graph gives the resulting normalized geometric factor G/R_1^2, the particle energy to analyzer voltage ratio T_∞/qV and the average velocity-azimuth angle product $<(\Delta v/v) \cdot \Delta\alpha>$. The geometric factor given here is defined for velocity distributions. In terms of the usual differential directional flux $\partial J/\partial E$, the detector count rate is given by: Count rate = $(G/R_1^2)(2ER_1^2)(\partial J/\partial E)$, where E is the particle energy.

Three types of position sensitive detection that have been used with this analyzer are illustrated in Figure 7. The first method, using individual channel multipliers, is suitable for applications where maximum angular resolution is not necessary. This approach also gives very high count rate capability since all detectors operate in parallel. This configuration is planned for the MPE/UCB plasma instrument on the AMPTE ion release module (IRM). The second approach, using a microchannel plate and discrete anodes, is very similar to the first, but gives more flexibility in designing angular bin sizes, and is also very compact. This configuration, using graduated width pitch angle bins, has been used on a polar cusp sounding rocket experiment. A similar system will be used for the plasma electron experiment on the Giotto Hally Comet mission. The continuous imaging resistive anode system allows the most flexibility because the angular binning can be arbitrarily selected electronically down to the limiting resolution of a few degrees. This approach was also tested on a sounding rocket, and is being studied for the NASA OPEN program.

ACKNOWLEDGEMENTS

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FIGURES

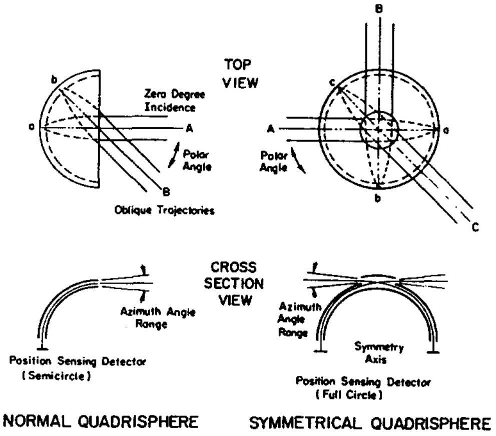

Fig.1 A comparison of normal and symmetrical quadrisphere geometries. With normal quadrisphere the response varies with polar angle. Symmetrical analyzer has cylindrical symmetry with complete 360° field of view. Typical trajectories illustrate focussing characteristics.

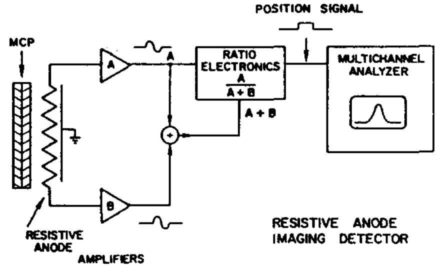

Fig.2 The resistive anode imaging system used for prototype tests. The analog position signal is proportional to the location of particles incident on the MCP.

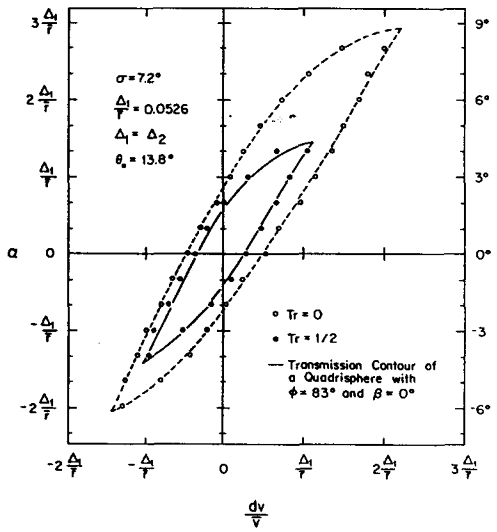

Fig.3 Velocity-azimuth transmission contours. Data points are measured response of prototype analyzer. Solid and dashed lines are computed response of a normal quadrisphere at zero incidence angle.

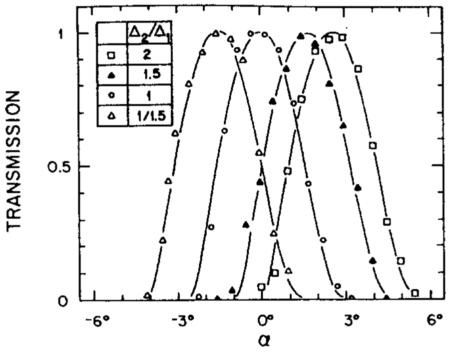

Fig.4 Shift of azimuth angle transmission peak with variation of Δ_1/Δ_2 ratio. Azimuth response is quite insensitive to gap dimensions. Optimum ratio is unity.

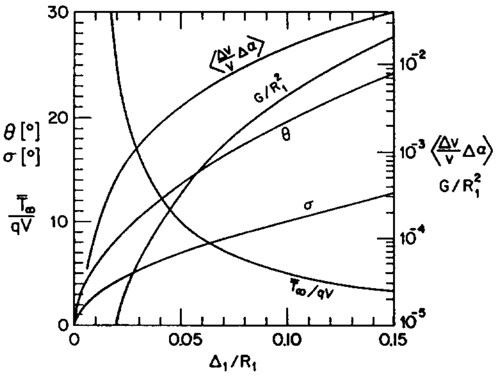

Fig.6 Summary of analyzer parameters vs. Δ_1/R_1. Curves for and are optimized design parameters. The resulting response properties are $G/R_1{}^2$, $\left\langle\frac{\Delta v}{v}\cdot\Delta\alpha\right\rangle$, and T_∞/qV.

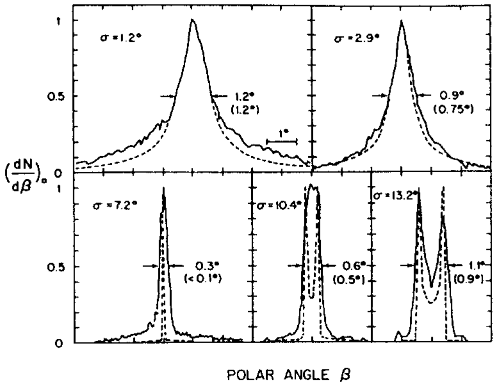

Fig.5 A comparison of measured and computed polar angle response for various values of truncation angle σ. Dashed lines are calculated response for a point source and solid lines are measured values using a source of ∿0.2° width. Using the optimum truncation angle of 7.2° gives an angular FWHM resolution of about 0.1°.

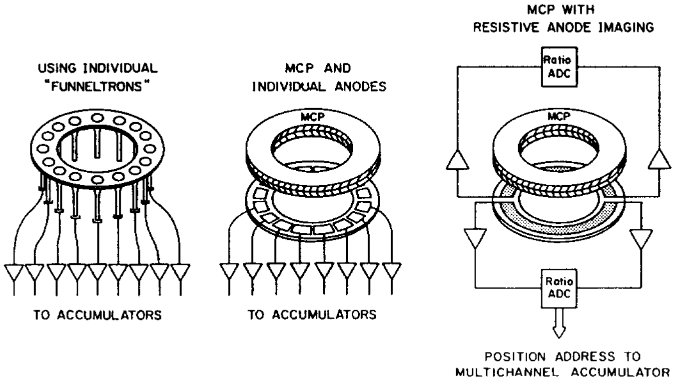

Fig.7 Three possibilities for position sensitive detection. The resistive anode imaging method allows the most versatile use of the analyzer in conjunction with a microprocessor system.