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76

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

SOLAR PLASMA MEASUREMENTS

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Group 63

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LEXINGTON MASSACHUSETTS

ABSTRACT

The existence of a corpuscular solar radiation which extends well into the solar system was proposed many years ago based on observations of geophysical phenomena. These early indirect observations of the solar plasma are reviewed here and are compared to recent direct plasma measurements from ionospheric sounding rockets and from both geocentric and heliocentric satellites. Some of the measurement techniques employed in these direct observations are discussed in detail.

Accepted for the Air Force
Franklin C. Hudson,
Chief, Lincoln Laboratory Office

SOLAR PLASMA MEASUREMENTS

I. BACKGROUND

The theory that a neutral but ionized gas of solar origin was the cause of magnetic disturbances on the earth was first postulated by Lindemann (1919). Atoms, if not ionized when they emerge from the solar corona, will be ionized by the sun's ultraviolet radiation on their way to earth. This gas or plasma will be mainly composed of ionized hydrogen but will contain a small proportion of helium, some of which may be unionized (neutral). These helium atoms, if present, would impinge exclusively on the sunlit hemisphere of the earth's atmosphere.

Based upon the observed time delay between sun spot activity and geomagnetic disturbances, Chapman and Bartels (1940) summarized a method of employing solar eclipses to distinguish between the ionized and neutral particle components of the solar plasma. The time delay implies that the solar corpuscular eclipse occurs at a different time and place from the optical eclipse. This was expected to lead to a decrease in atmospheric ionization which is caused by ultraviolet light plus the effects of neutral particle bombardment. After repeated failures to observe this decrease it was concluded that the neutral particle content of the solar gas is small.

The theory that the solar ejection of plasma is not only present during periods of solar activity, but also is a continuous process was advanced by Biermann (1953, 1957). His belief is based on the fact that the particles making up the tail of luminous comets show an acceleration outward from the sun independent of the comet's position. It had been previously assumed that this behavior was due to radiation pressure. Of significance is that most comets exhibit this radial acceleration even when far from the ecliptic plane. Therefore, if Biermann's contention is correct the solar plasma is more or less uniform about the sun.

Biermann theorized further that the ionization of the tail is also due to the momentum transfer from the solar plasma. To account for the observed effects, Biermann estimated a particle flux of about 10^{10} protons/cm^2 sec. This flux, together with an assumed velocity of 500 to 1000 km/sec based on the sun spot-geomagnetic storm delay of several days, implies a proton number density of 100 or 200 cm^{-3}.

This number density is low compared to the estimate of 500/cm^3 for electrons at the orbit of earth (Behr and Siedentopt, 1953) based upon observations of the polarized component of the zodiacal light. However, later estimates by Blackwell (1960) place an upper limit of about 50/cm^3 for the electron density near the earth.

In 1960, Biermann revised his flux estimate to 10^9/cm^2 sec. on the basis of new laboratory collisional cross-section data. The plasma velocity mentioned above (500-1000 km/sec) is that of plasma correlated with active sunspots and is therefore higher than the expected velocity of quiet-day solar plasma. Harrison (1961) suggested a quiet-day velocity of the order of 300 km/sec. In view of this, Biermann's flux estimate implies a particle density of less than 20/cm^3, which is consistent with the zodiacal light estimates.

Other investigators working from the hydrodynamic equations of motion have predicted theoretical number densities near the earth which vary from about 20 to 1000/cm^3 with velocities ranging up to 500 km/sec. Because the solar corpuscular radiation appears to many people to be a supersonic fluid of hydrodynamic character, it is often called the solar wind (Parker 1958).

In addition to geomagnetic zodiacal light and comet tail observations there are other observations which can be made from earth which yield information about the solar wind.

Storey (1954) concluded from the propagation characteristics of whistlers that the electron density was about 400/cm^3 at 2-3 earth radii. However, this estimate depends strongly on the electron density distribution near the earth and cannot be considered very accurate. More precise knowledge comes from the investigation of "nose whistlers" by Smith and Helliwell (1960) who deduced that at a distance of 5 earth radii the electron density is about 100/cm^3.

Another piece of evidence in support of the solar wind theory is the fact that weak aurora can be observed somewhere in the auroral zones on almost every clear night. There appears to be no direct correlation between these weak aurora and any specific solar events. It now seems probable that particles dumped into the earth's atmosphere from the outer Van Allen belt are at least partly responsible for the weak aurora, although the magnetic flux lines which pass through this belt do not normally fall in the auroral zones. The outer belt consists primarily of electrons whose origin is probably the solar wind (Electronics, 1960). Various mechanisms have been suggested to account for the much higher energies of the auroral and outer belt particles compared to those of the solar plasma.

In the presence of a continuous solar wind the geomagnetic field will be altered in shape. The field near the earth is roughly that of a simple dipole as determined long ago by spherical harmonic analysis of the components at the surface. Chapman and Ferrano (1931, 32, 33) showed mathematically that the solar wind would compress the geomagnetic field on the day side of the earth, and in addition would flow around the earth to form a hollow wake on the night side in which the magnetic field is relatively unaltered. This would place the earth within a long tear-drop shaped hollow, now called the magnetosphere, which is the shock boundary between the plasma and the geomagnetic field. Also considered was the possibility of a plasma-generated earth ring current which has since been used in attempts to explain auroral phenomena.

II. EARLY SOVIET ROCKETS AND SPACE PROBES

Neither the theories nor the observations discussed above provide much real information on the actual interplanetary conditions. With the advent of high altitude rocket and satellite technology, the direct measurement of solar plasma and its distant effects became possible. These direct measurements should, among other things, provide better insight into the physical processes occurring in the sun, determine the nature of some features of geomagnetic activity, and provide information concerning the modulation of cosmic rays which is correlated with solar activity. It will be necessary to determine the composition of the plasma, to measure the fluxes and energy spectra of all components of the plasma with their variations in time and position, and to correlate these measurements with solar and geomagnetic events. Also of importance is the plasma distribution function in velocity space, or some approximation to it, which could be called the plasma temperature.

The Russians seem to have made the pioneering efforts in both ionospheric and orbital ion measurements as well as being first to see indications of the now well-known Van Allen belts. In 1958 (Gringauz, 1961) the Russians launched a series of ionospheric probes which measured electron concentration and height distribution using rocket radio transmitters and ground-based receivers. Coherent unmodulated transmissions at 24, 48, and 144 Mc/s from vertically launched geophysical rockets provided Faraday rotation data and dispersion measurements by the phase method.

Results obtained by the two methods were in good agreement, but disclosed that local (near the rocket) ion concentrations cannot be measured by terrestrial observations. This is because the influence on the radio waves of temporal variations of ion concentrations occurring in the ionosphere will be greater than the effect made by the change in path length of the radio waves due to the interplanetary ionized gas near the rocket.

Following the lead of radio-astronomers, it should be noted that if a space vehicle were placed far enough away from the earth, the integrated ion concentration over the transmission path length could mask the ionospheric variations and thereby provide a value for the mean electron concentration in interplanetary space. Assuming a concentration of 100 electrons/cm^3 and frequencies of 100 and 400 Mc/s, the required earth-vehicle distance would be on the order of 10^8 km. This distance was, until recently, prohibitive because of transmitter power requirements. This technique will be used in the near future to measure electron concentrations in the solar corona during occultation of NASA's Sunblazer Spacecraft.

A spherical shielded Langmuir probe (Boyd, 1950) in which an ion retarding potential is applied to a grid was flown on Sputnik III in 1958 to study positive ion concentrations in the ionosphere. Later a second grid was added between the first grid and the ion collector plate in an attempt to suppress photo-electrons emitted from the collector. The photo-electrons are caused by solar ultraviolet light and severely limit the sensitivity of the instrument.

Such ion traps were flown on Luniks I and II in January and September of 1959 during relatively quiet solar periods (Shklovskii, Moroz, and Kurt, 1960). There were four hemispherical traps on each of the tumbling vehicles, and therefore no information on the direction of the plasma could be derived. Correcting for the inverse photoelectric current from the new suppressor grid (-200 volts), a residual constant flux of 0.2×10^9 singly charged ions/cm^2 sec. (corresponding roughly to 10^{-9} amperes) was found. Since proton velocities must have been at least as large as 60 km/sec to traverse the retarding potential of +15 volts on the first grid, the implied ion density was less than 30/cm^3. These observations, although crude, clearly show that the solar plasma is supersonic as proposed by Parker and others, and that it has a density consistent with the estimates based on comet observations, zodiacal light, etc.

The Soviet probes, which included at least one ion mass spectrometer, indicating that the transition from an oxygen ionosphere to ionized hydrogen takes place at an altitude of about 1000-2000 km with proton densities at that height of the order of 10^3/cm^3. The ion concentration decreases with altitude to about 10^2/cm^3 at 20000 km (Lunik II) and to even lower levels beyond 200000 km (Lunik III, October 1959). Both Lunik II and III detected periods of higher concentration of ions which were well correlated with the K-indexes which characterize geomagnetic activity.

The Soviets recognized the severe limitation on the sensitivity on their ion traps due to the photo-emission effects. Gringauz suggested that modulation of the incident charged particles at some frequency (presumably by application of a modulation voltage to the first grid) would permit the rejection of the unmodulated photo-electric currents in the instrument electronics. Also suggested was that the energy spectrum of the plasma could be investigated with charged particle traps (presumably by variation of the magnitude of the modulating voltage on the first grid).

III. EXPLORER X

On 15 March 1961, an American space probe, Explorer X, was launched. This probe was designed primarily to measure interplanetary magnetic fields and solar plasma. Correlation of the magnetic and plasma data can provide important insight into interplanetary dynamic processes.

The Explorer X plasma instrument was of the ion trap type and was designed by Bridge, Lazarus, et al. of M. I. T. with an attempt to provide a wide dynamic range of operation. It could measure particle fluxes between 5×10^6 and $5 \times 10^{10}/cm^2$ sec. With a collector area of 50 cm^2 this flux corresponds to a current range of 5×10^{-11} to 5×10^{-7} amperes. These current levels were easily measured using a miniature vacuum electrometer tube -- particularly since the modulated plasma scheme mentioned earlier was employed, thus making the measurement of DC currents unnecessary. The energy spectrum of the plasma was determined simply by modulating only selected energy increments of the incident plasma.

The instrument had six such energy increments, or levels, in overlapping regions from 6 ev. to 2300 ev. Measurements at each energy level were made in consecutive 5 second intervals with an off-time of 143 seconds between intervals. More than twenty minutes were required to complete the measurement of the entire energy spectrum which, unfortunately, was much longer than the expected time constant of the plasma variations.

Since the Faraday cup (ion trap) sensor has a wide angle of acceptance ($\pm 60^{\circ}$) it has rather poor directional resolution, although it assures a more complete spacial coverage. As the spacecraft rotates on its axis, the sensor, which is mounted normal to the spin axis, sweeps out the entire spacecraft equatorial plane. The probe was launched out of the ecliptic plane and along the direction of the anticipated magnetosphere.

The results of Explorer X are significant because they confirm the presence of the magnetosphere, beyond which plasma suddenly appeared at about 21 earth radii, and that the plasma came from the solar direction. The quiet-day solar wind had a bulk velocity of 250-400 km/sec (mean energy of about 500 ev. per proton) and a density of 7-20/cm^3. These results are consistent with the Russian values obtained almost a year earlier (although it appears to the author that the Russians did not recognize the existence of the magnetosphere -- possibly because of inappropriate probe trajectories).

Faraday cup experiments have been continued and made more sophisticated by Bridge, et al, and will be discussed more from a system viewpoint in Section V.

IV. RADIO FREQUENCY PROBE TECHNIQUES

In addition to the two radio wave probing techniques used in Russian ionospheric rockets which were discussed above, namely the dispersive Doppler and Faraday rotation effects, there are several other radio frequency techniques available to plasma investigators.

Bachynski, French, and Cloutier (1961) discussed from a theoretical standpoint the total noise power available at the receiving antenna of a hypersonic space vehicle embedded in a plasma environment. This subject is treated in exhaustive detail (including the effects of anisotropic plasma distributions) with the incidental conclusion that the noise power spectrum may be utilized as a diagnostic tool for the exploration of the hypersonic environment of space vehicles. This is particularly true at frequencies near the plasma frequency where the noise power from the plasma exhibits a sharp maximum. Unfortunately, since the plasma frequency is given by

$$f_o = \frac{1}{2\pi}\left[\frac{ne^2}{m\epsilon}\right]^{1/2} \approx 9(n)^{1/2}$$

where n = electron density per cubic meter

e = electronic charge in coulombs

m = electronic mass in kg

ϵ = permittivity of the local medium

it is clear that this method does not easily lend itself to the measurement of solar wind concentrations of the order of $100/cm^3 = 10^8/m^3$ because of unwieldy antenna dimensions.

A more recent technique has been developed by Haycock and Baker (1962) which directly measures the plasma frequency of the ionized medium. The plasma frequency equation above then yields the local electron density. The technique involves sweeping a frequency which is applied to a fairly long dipole, and searching for the parallel resonance formed between the free-space displacement current of the antenna and the electron drift current induced in the plasma. The resonance occurs because the electron conduction current lags the exitation electric field by 90^o whereas the capacitive displacement current leads the exitation by 90^o. Thus, when the two currents are equal in magnitude, the impedance seen at the antenna terminals passes through a maximum (the impedance will also be real if the electron collisional frequency is negligibly low). Note that this resonance will occur independently of the physical length of the antenna because the wavelength in the medium at the plasma frequency goes to infinity (by definition of the plasma frequency). Although the antenna appears electrically to be vanishingly small, it should be made physically long in order to minimize the effect of the space vehicle body and to reduce the off-frequency impedance to suitably low values.

A block diagram of the Haycock/Baker experiment is shown in Figure 1. The resonance is determined by detecting the phase quadrature between the antenna current and the current through a small fixed capacitor across which is impressed the antenna voltage. This, of course, represents the phase coincidence between the antenna current and voltage. The results of their ionospheric probes were in close agreement with the results of other types of probes, including ion traps.

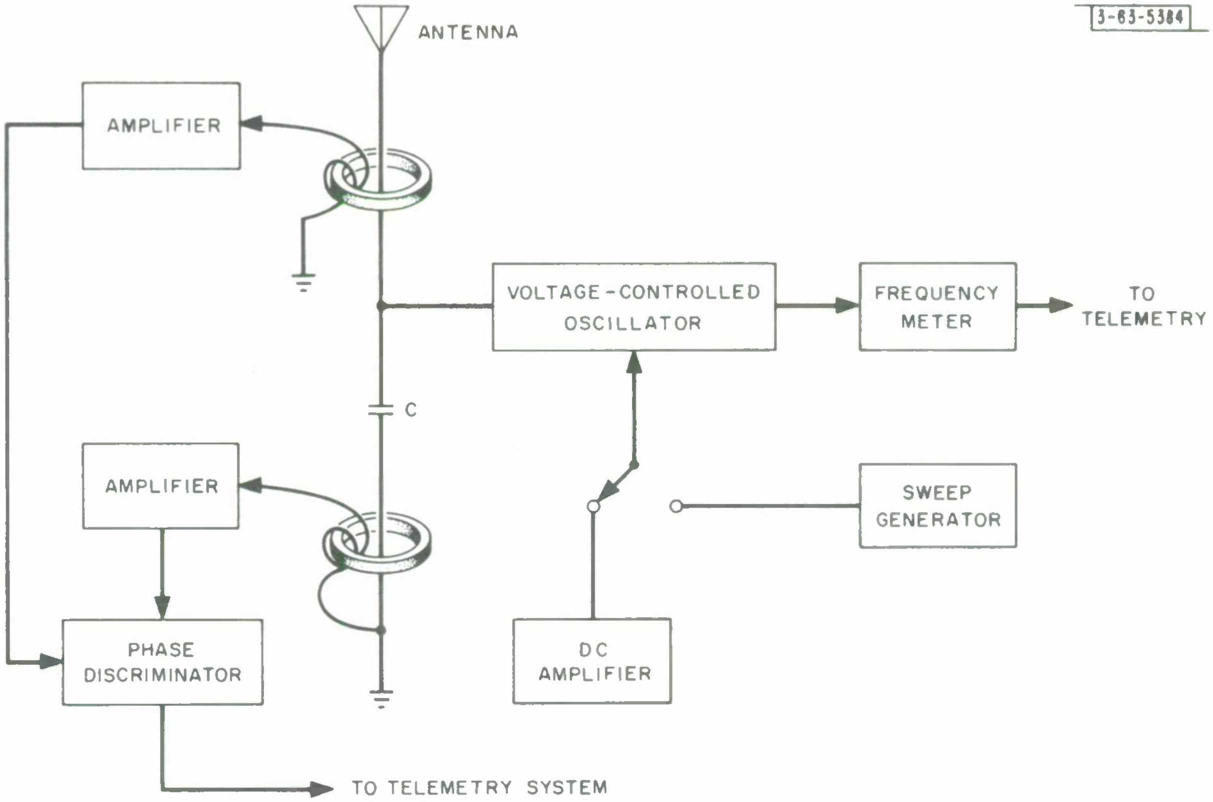

Fig. 1. Plasma frequency detection system (Haycock & Baker).

This plasma frequency detection method is not unlike the radio frequency impedance probe in which actual antenna impedance changes are painstakingly measured in an an ionized environment in order to infer the local electron densities.

One other radio frequency probing method deserves mention. It is the simple technique of measuring the capacity between two fixed plates of arbitrary configuration whose dielectric is the interplanetary medium. The frequency of resonance with some fixed inductor provides the measure of the capacitance value. Comparing this with the air-dielectric value determines the dielectric constant of the medium ($K = C/C_{air}$), from which the electron density can be calculated.

Although these radio frequency methods are relatively simple and accurate, they lack several very important properties: plasma composition and energy distribution cannot be investigated, the directional properties of the flow are completely ignored, and the sensitivity is poor. The next two sections deal with examples of the common types of plasma probes which are now flown almost exclusively in all solar plasma investigations. The first is an improvement over the early Soviet ion traps, and the second is the electrostatic plasma spectrometer.

V. THE FARADAY CUP ION-CURRENT PROBE

A series of design improvements on the retarding-potential ion probes of the Soviet and Explorer X satellites have been made by Bridge, et al, of M. I. T. The Soviet ion traps had a hemispherical outer grid and a planar collector surface, whereas the first American probes had all elements planar. The M. I. T. design introduced several additional grids and provided for their mechanical support by constructing the entire sensor in a cup-shaped container, to which the name Faraday cup is applied. Figure 2 shows the cup configuration and indicates the paths of several charged particles. The outer grid and the screen grid are maintained at the potential of the vehicle skin (local "ground"). The outer shell of the cup is sometimes biased at a slight negative voltage (with respect to the vehicle) to counteract the spacecraft potential produced by photo-emission from the vehicle surface. The modulator grid controls the flow of a certain range of energetic particles by means of a voltage square-wave. The negatively biased suppressor grid, which was originally added to earlier retarding-potential probes to inhibit the DC photoelectric current from the collector, is here included in addition to counter the effects of secondary emission from the collector by the modulated component of protons. The screen grid serves as an electrostatic shield between the modulator grid and the collector.

During the zero voltage portion of the modulating cycle most protons will reach the collector. Low energy electrons will be repelled by the negative potential of the suppressor grid. During the positive half cycle of the modulating voltage all protons having energy (in electron-volts) numerically less than the grid voltage will be repelled. The component of proton current below this energy level is thereby modulated. Electrons are at first accelerated by the positive grid voltage and then, after passing through the grid, are decelerated such that they pass through the screen grid unmodulated. An amplifier which is AC coupled to the collector plate will operate only upon the modulated portion of the collector current, i.e., the current produced by the protons within the modulated interval of the energy spectrum.

It should be clear that the energy interval is completely flexible and is determined solely by the upper and lower levels of the modulating voltage square-wave. So flexible is this modulation scheme that simply by making the voltage square-wave negative, electron measurements are feasible. This may require different voltages on the suppressor grid and collector element, but a compromise can be reached if a single cup is to be used for measurement of both electrons and protons.

Note that the modulation of plasma currents by a Faraday cup applies only to that component of the plasma velocity which is normal to the modulating grid. If the plasma is incident at an angle A to the cup normal, the voltage necessary to cut off the stream is less than the numerical plasma energy (in ev.) by a factor of $\cos^2 A$. As pointed out earlier the direction resolution of

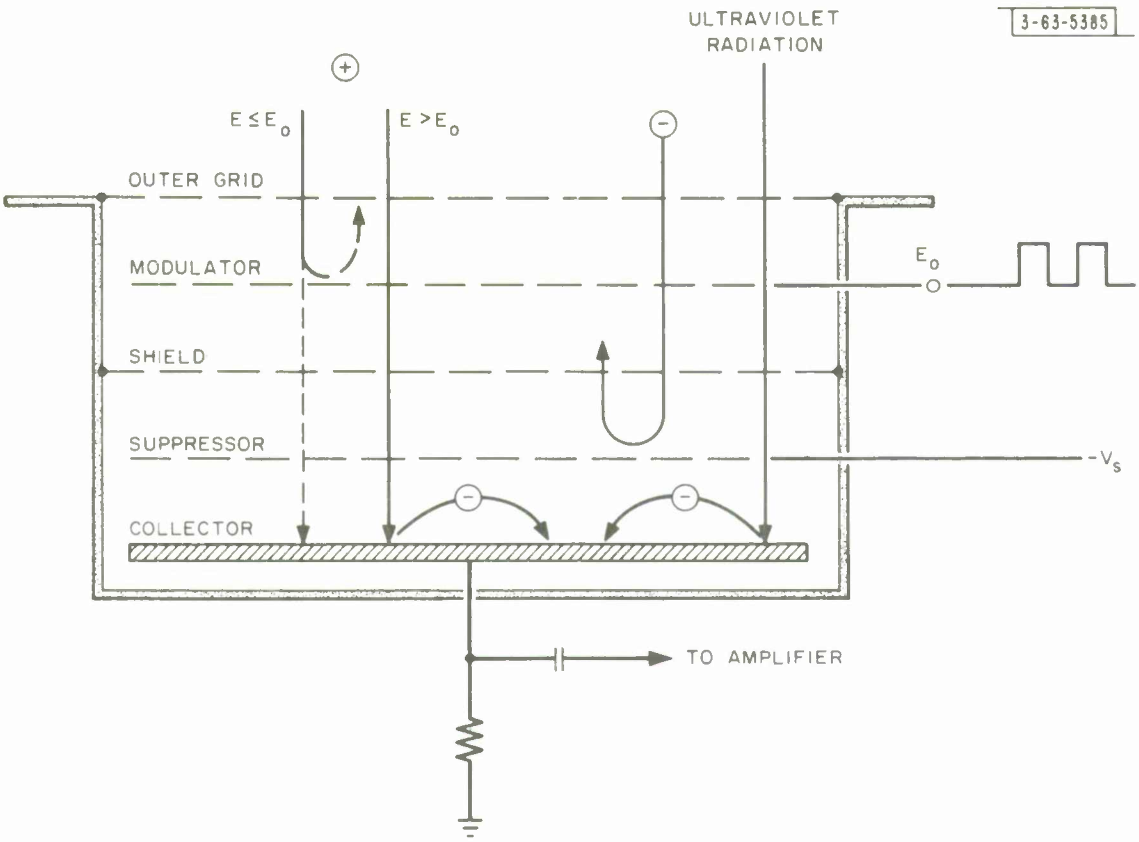

Fig. 2. Faraday cup diagram/MIT.

a Faraday cup is poor. This situation can be improved by several techniques. First, the collector plate can be split into two or more separate sections. Depending upon the "shadowing" by the cup sides, each of the collector sections will receive different levels of plasma current from which crude directionality may be inferred. Second, the plasma beam can be collimated before it reaches the sensor thereby reducing the viewing solid angle of the cup. Third, if the cup faces into the equatorial plane of a spin-stabilized satellite, the plasma direction in that plane is revealed by the temporal variations of the data. All three of these methods were used in the M. I. T. Plasma Probe aboard the recently launched (December 1965) Pioneer VI.

This Pioneer instrument investigates interplanetary positive ions with energies up to 10 kev and electrons with energies up to about 3 kev. The instrument is capable of measuring 5×10^4 to 5×10^9 singly charged particles/cm^2 sec corresponding to a current range of 5×10^{-13} to 5×10^{-8} amps. A simplified block diagram of the experiment is shown in Figure 3.

Measurements of currents down to levels on the order of 10^{-13} which are not only stable with temperature and time but also require wide dynamic range are not of a routine nature, even in the laboratory. The preamplifier flown in the M. I. T. instrument on Pioneer VI is the latest in a long line of space-qualified vacuum tube and solid state electrometer circuits. It is shown in Figure 4. Miniature vacuum electrometer tubes have been used in the past as the first stage of similar preamplifiers, but susceptibility to mechanical damage during rocket launching makes their use undesirable. The use of low-noise junction field-effect transistors has proven quite satisfactory. This preamplifier's voltage output is an approximately linear function of the input current from 10^{-12} to 5×10^{-8} amperes with a 2-volt output corresponding to maximum input. Its temperature stability is good, and little, if any, degradation has been seen with time.

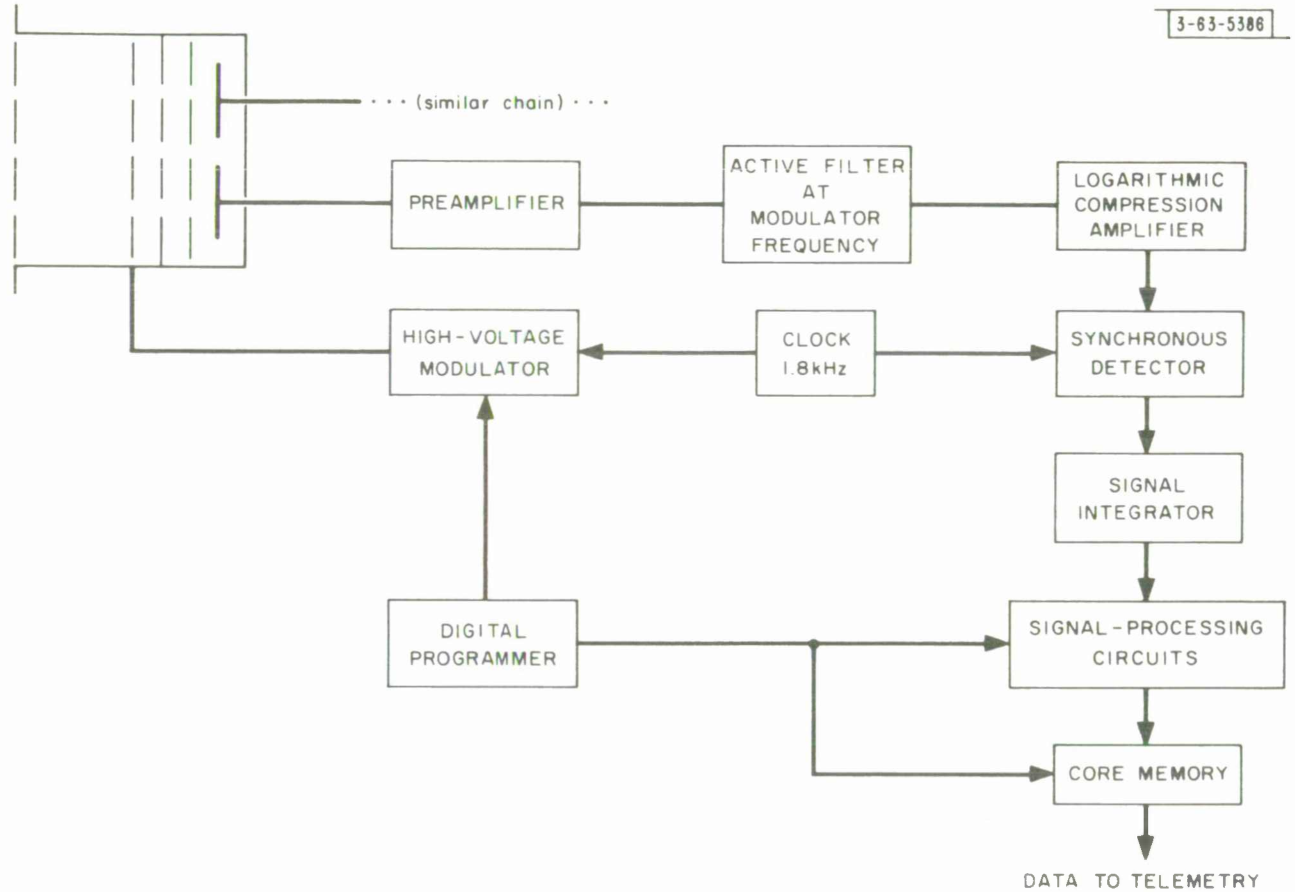

Fig. 3. Pioneer VI/MIT Faraday cup plasma probe.

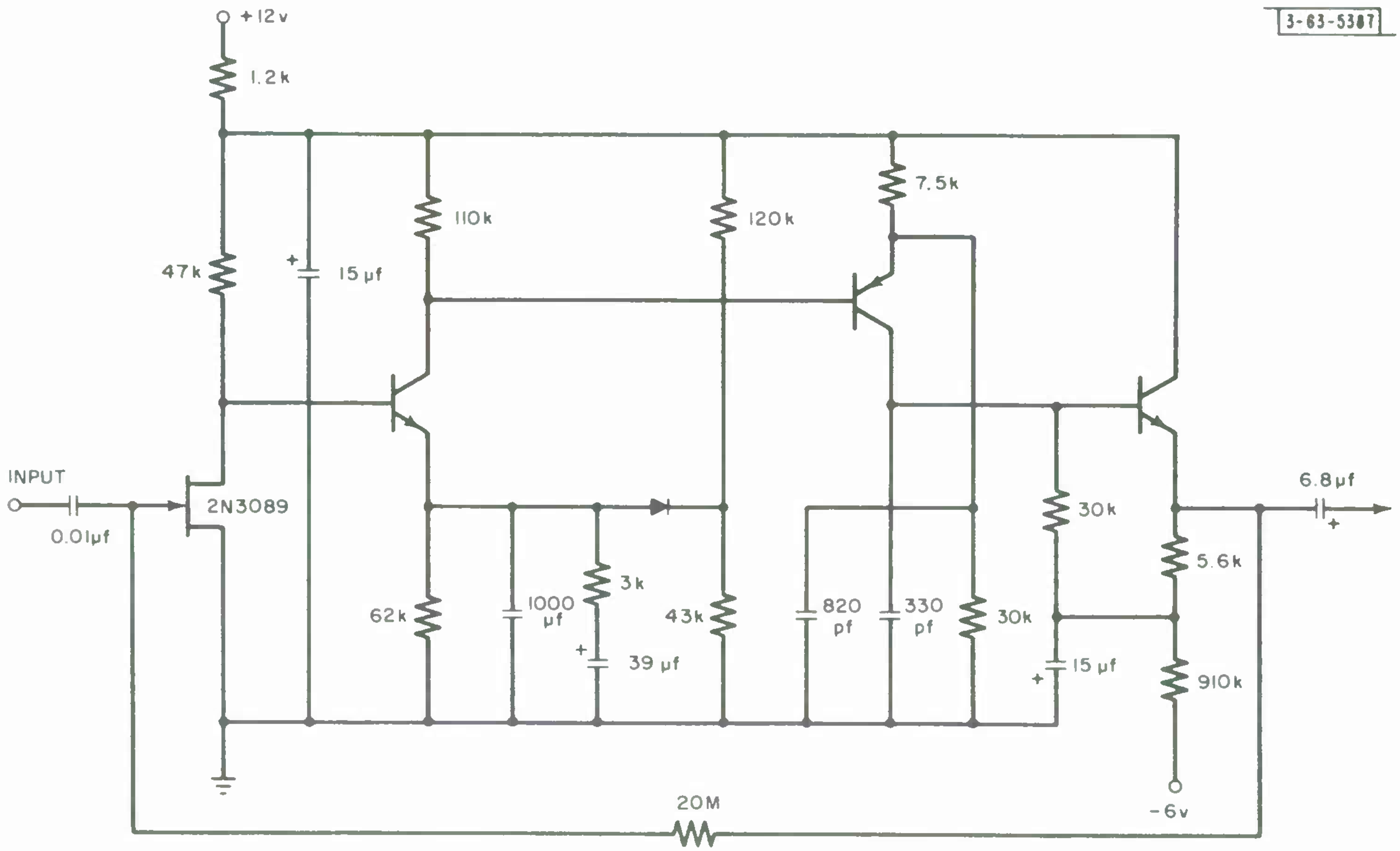

Fig. 4. MIT preamplifier schematic.

VI. THE ELECTROSTATIC PLASMA SPECTROMETER

Several models of the curved plate electrostatic plasma analyzer have been successfully flown on many recent earth satellites and interplanetary probes. The electrostatic analyzer bears a superficial resemblance to the better-known mass spectrometer. The latter splits, by means of a magnetic field, a monoenergetic beam of charged particles into several groups with differing charge/mass ratios. This method could be used for plasma analysis in space except that it generally involves heavy equipment. The electrostatic analyzer separates a flux of charged particles into groups with different energy/charge ratios by means of an electric field.

Figure 5 shows a cross-sectional view of the quadrispherical electrostatic plasma analyzer flown on Pioneer VI, and its measurement link. Several instruments of this type have been designed at NASA, Ames Research Center (Wolfe, et al, 1966). The particle beam enters the region between the plates and is accelerated downward towards the lower plate (assuming the charge and high voltage polarity are proper). Particles with an energy-to-charge ratio within a specific range, which depends upon the electric field between the plates, will follow a trajectory between the plates and strike the collector. Thus, if the plate voltage is kept fixed, the analyzer behaves as a narrow energy/charge ratio filter. Stepping the voltage permits analysis of the plasma energy spectrum.

In the case of a cylindrical-surface electrostatic analyzer, such as flown on the Mariner-2 mission to Venus (Snyder and Neugebauer, 1963), the particle acceptance cone was only about 10° half angle, and employed a single collector element. The spacecraft was stabilized and the acceptance cone was oriented towards the sun. The analyzer on Pioneer VI is quadrispherical in design and therefore has a solid angle of acceptance in the shape of a wide (nearly 180°) fan in the azimuthal plane. To regain angular resolution the collector consists of an array of eight separate detectors arranged around the bottom of the quadrispherical rim.

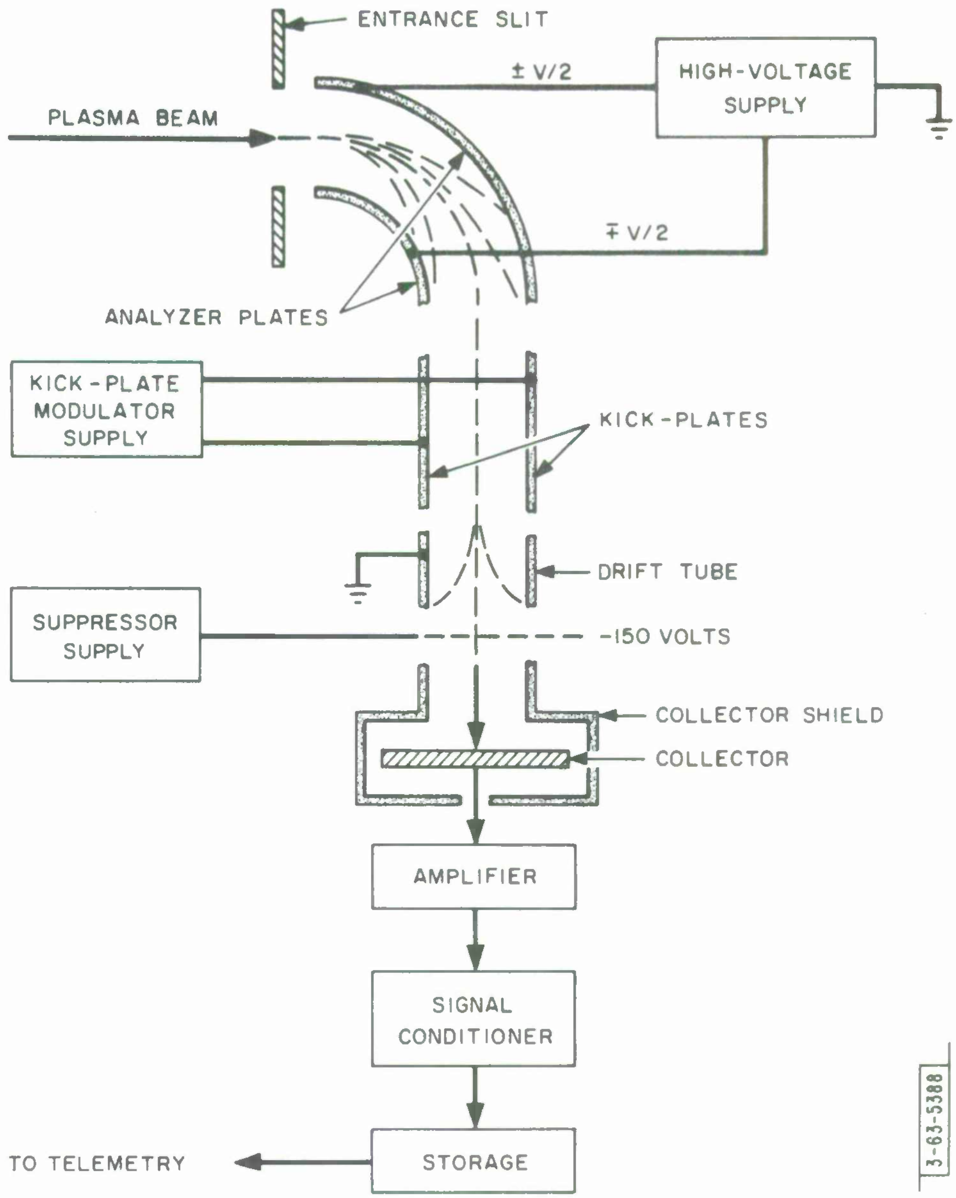

Fig. 5. Pioneer VI/NASA-ARC electrostatic plasma analyzer.

Due to the usual difficulties in measuring very low DC currents, the "filtered" beam of particles is modulated at 1 kHz by the so-called "kick-plates" shown in Figure 5. The resulting AC current is measured down to 10^{-14} amperes by straight forward electrometer techniques. On the Mariner-2 analyzer, the DC current output of the single collector was measured down to 10^{-13} amperes by a vibrating reed capacitance electrometer. The NASA electrostatic analyzers flown on the OGO and IMP 1 and 2 spacecraft measured DC currents down to 10^{-13} amperes by utilizing an electrometer tube (Victoreen VX55) at the input. Long term drift was minimized here by applying a compensation voltage in series with the input. This voltage was obtained by periodically sampling the electrometer output with a large capacitor while holding the input current at zero, and then transferring this capacitor to the electrometer input. There was some concern about tube breakage during launch, but to date all have remained intact.

VII. CONCLUSIONS

The direct measurement of the interplanetary ionized gas which is partly responsible for a multitude of geophysical phenomena has only recently been possible. Since that time a wide variety of solar plasma measurement techniques has rapidly evolved. These methods depend upon (1) the direct amplification of current produced by selected plasma components, or (2) the electromagnetic characteristics of the plasma-filled medium. To date, all plasma data seems to indicate an unexpected complexity of the interplanetary medium even outside the magnetosphere. It seems clear that even with the increasing sophistication of space instrumentation much more effort will be required to shed light on the true nature of interplanetary processes.

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13. ABSTRACT

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14. KEY WORDS

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