quently, it is likely that the internal energy in the first part of the shock is entirely carried in large-amplitude oscillations.[10] The majority of heavy ions may then be brought to relative rest by virtue of their phase with respect to these oscillations with very little destruction of the nuclear species. As mentioned above, these oscillations also provide a mechanism for the transmission of the shock to much lower densities. The damping of such oscillations by wave and by particle interactions and behavior of the material after the oscillations break up are subjects currently under study.

A final problem under investigation is the disposition of the blown-off material with energies below a few Bev. The amount of such material is at least one order of magnitude too large to be contained as cosmic radiation by the estimated galactic magnetic fields. We are examining mechanisms whereby such material is confined by local magnetic fields to the neighborhood of the explosion long enough to lose its energy by synchrotron radiation, as appears to be the present situation in the Crab nebula.

It is a pleasure to acknowledge discussions with and suggestions from many of our colleagues. We are particularly indebted in this regard to Dr. Edward Teller.

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†Consultant to the Lawrence Radiation Laboratory.

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PLASMA RESONANCE IN A RADIO-FREQUENCY PROBE

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As the frequency of a low-voltage rf signal superposed on a probe is swept within an adequate frequency range, the dc component[1] of the electron current due to the nonlinearity of the sheath impedance is measured. It has been found that a resonant increase appears in the current at the electron plasma frequency,

$$\omega_P = (4\pi N_0 e^2/m)^{1/2}, \qquad (1)$$

where N_0 is the electron density.

The schematic diagram of the apparatus used is shown in Fig. 1(a). The rf probe does not necessarily have to be a cathode-probe system, where the rf voltage is applied between the cathode and the probe. The experimental results are qualitatively unaffected by the shape or dimensions of the probe. In this experiment a plane probe consisting of a nickel disk 2 cm in diameter is

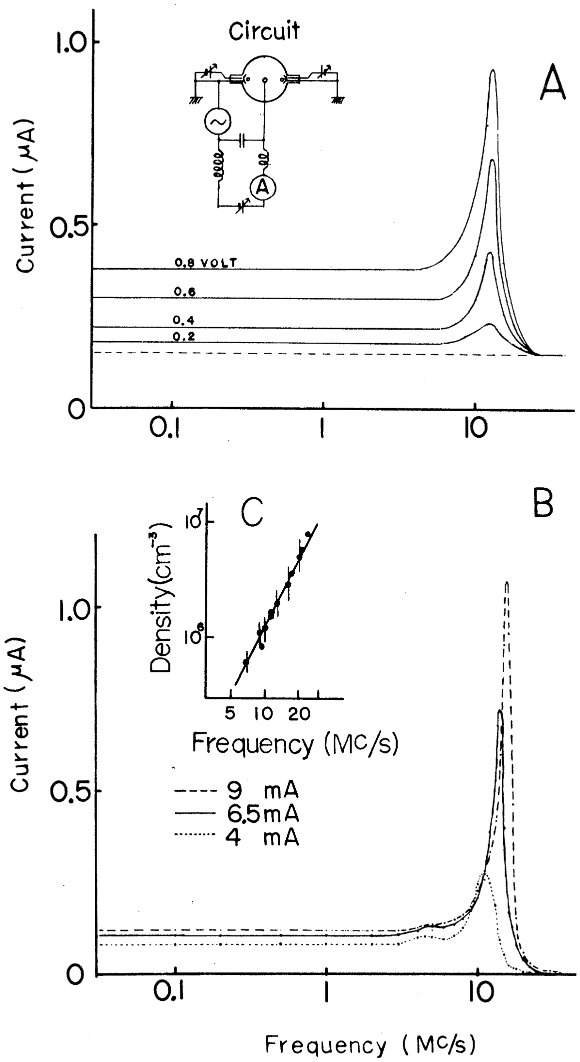

FIG. 1. (A) Characteristic curves of the rf probe with a constant discharge current of 5 ma, corresponding to 5.6×10^6 electrons per cc, for various rf voltages ranging from 0.2 to 0.8 volt. The electron temperature is 1800°K. (B) Characteristic curves for various discharge currents corresponding to 1.2×10^6, 6.6×10^6, and 7.9×10^6 electrons per cc. (C) Resonance frequency versus electron density determined by the Langmuir probe method. The solid line denotes Eq. (1).

used. It is biased relative to the cathode so as to be always negative with respect to the plasma potential, even when the rf voltage is superposed on the probe.

The discharge tube[2] is a Pyrex glass sphere 30 cm in diameter filled with mercury vapor at a pressure of 10^{-4} mm Hg. Two anode-hot cathode systems are arranged in such a way as to produce a very low density and homogeneous plasma, and the discharge currents can control the electron density. The plasma in the tube being of a diffusive type, there is no beam present.

The relation between the frequency of the rf voltage and the corresponding dc component of electron current to the probe is shown in Fig. 1(a) for various amplitudes of rf voltage with a constant discharge current of 5 ma, and with the probe set 0.5 volt below the plasma potential. In Fig. 1(b), however, the probe is set at the wall potential. The curves in this case are for various discharge currents with a constant rf potential difference of 0.4 volt.

Every characteristic curve in Fig. 1 consists of the following three frequency ranges: the first range where the electron current maintains a constant value independent of frequency, the second range where a resonance peak appears, and the third range where the superposed rf field has no effect on the dc current to the probe.

In the first frequency range, the electron current density at the probe surface for a superposed rf voltage $V\cos\omega t$ is given by

$$j = j_0\langle \exp(-eV\cos\omega t/kT)\rangle_{\rm av} = j_0 J_0(ieV/kT), \qquad (2)$$

where the average is taken over a long time. $J_0(iz)$ is the zeroth order Bessel function for a pure imaginary argument, and

$$j_0 = N_0 e(kT/2\pi m)^{1/2}\exp(-eV_0/kT).$$

T is the electron temperature, and V_0 is the potential difference between the plasma and the probe.

j_0 corresponds to the constant current in the third frequency range, since the Boltzmann distribution of electron density for the oscillating electric field in Eq. (2) is no longer valid when the frequency is higher than the electron plasma frequency. Accordingly Eq. (2) holds when the field changes slowly in a time interval of the order of ω_p^{-1}. The ratio of j to j_0 gives the electron temperature through the argument of the Bessel function.

In the second frequency range, it will be noted from Fig. 1(a) that the positions of the peaks along the frequency axis coincide with each other whenever the discharge current is the same. In Fig. 1(c) the values of resonance frequency are plotted against the electron density determined by the well-known Langmuir probe method. The solid line was calculated from Eq. (1). It is seen from the figure that the resonance occurs at the electron plasma frequency.

The height of a resonance peak depends not only on the magnitude of the rf voltage, but on the collision frequency of electrons with atoms. Thus this height decreases as the pressure is increased.

The mechanism of the resonance is interpreted in terms of the interaction between the electron beam and the plasma medium.[3-5]

In the experiment, the oscillating electric field applied between the plasma and the probe drives off some electrons from the positive ion sheath around the probe into the plasma during one half-cycle, and during the next half-cycle, because of the shielding effect of the plasma, the field cannot restore these electrons which were driven off. These electrons which are driven off can be regarded as an electron beam with its density modulated by the frequency of the oscillating field.

An electron beam of this kind is known to excite growing plasma waves[4] when the kinetic energy of the beam exceeds the thermal energy of the electrons of the medium.

This interpretation, in terms of a beam-plasma interaction, seems to be supported by the experiments shown in Fig. 2, where the resonance peak nearly vanishes when the energy supplied by the field to the electron beam becomes comparable to the thermal energy of the electrons.

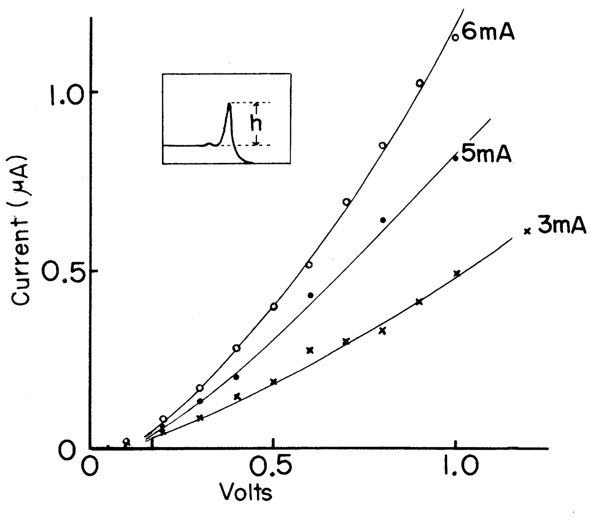

FIG. 2. The height of resonance peaks in μa versus rf potential difference in volts, for several discharge currents. The electron thermal energy is 0.17 ev which is shown by a short line on the abscissa.

The growing wave gives a density fluctuation $\tilde{N}_0$ of the following form:

$$\tilde{N}_0 = A \exp(\gamma d + i\varphi - i\omega t) = \tilde{N} \exp(-i\omega t), \tag{3}$$

where d is a suitable distance; φ is a phase difference, expected to be π, given, in terms of the beam velocity u, by

$$\varphi \approx \omega d/u \approx \pi,$$

and γ is a growth rate which is a function of ω having a sharp maximum at $\omega = \omega_p$ and rapidly decreasing to zero for ω different from ω_p.[4,5]

The dc electron current in this case is given by

$$j = j_0 J_0(is)[1 - i\tilde{N} J_1(is)/N_0 J_0(is)], \tag{4}$$

where $s = eV/kT$, and J_1 is the first order Bessel function. In the first frequency range, $\tilde{N}$ is small enough that (4) reduces to (2).

At a frequency nearly equal to the electron plasma frequency, γ in (3) gives a maximum value of $\tilde{N}$, and j shows a resonant increase. Hence the resonance can be fully explained by the behavior of $\tilde{N}$.

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