HEAVY IONS IN THE MAGNETOSPHERE

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Abstract. For purposes of this review heavy ions include all species of ions having a mass per unit charge of 2 AMU or greater. The discussion is limited primarily to ions in the energy range between 100 eV and 100 keV. Prior to the discovery in 1972 of large fluxes of energetic O+ ions precipitating into the auroral zone during geomagnetic storms, the only reported magnetosphere ion species observed in this energy range were helium and hydrogen. More recently O+ and He+ have been identified as significant components of the storm time ring current, suggesting that an ionosphere source may be involved in the generation of the fluxes responsible for this current. Mass spectrometer measurements on board the S3-3 satellite have shown that ionospheric ions in the auroral zone are frequently accelerated upward along geomagnetic field lines to several keV energy in the altitude region from 5000 km to greater than 8000 km. These observations also show evidence for acceleration perpendicular to the magnetic field and thus cannot be explained by a parallel electric field alone. This auroral acceleration region is most likely the source for the magnetospheric heavy ions of ionospheric origin, but further acceleration would probably be required to bring them to characteristic ring current energies. Recent observations from the GEOS-1 spacecraft combined with earlier results suggest comparable contributions to the hot magnetospheric plasma from the solar wind and the ionosphere.

1. Introduction

As the field of space plasma physics has matured we have come to recognize the need to study all aspects of the hot plasma, both theoretically and experimentally. As a result, ever increasing emphasis is being placed on the investigation of the mass and charge composition of the hot plasma in the magnetosphere. A detailed knowledge of the ionic composition of the plasma over a wide range in mass and energy not only provides us with the best available indication of the origins of these plasmas, but the detailed distribution functions for multiple ion species also provide us with important new information on the transport, energization and loss processes acting on these plasmas between their source regions and the point of observation.

The most probable sources for the hot magnetospheric plasmas are the solar wind (Meinel, 1951; Axford, 1970) and the ionosphere (Van Allen, 1962; Axford, 1970). Axford (1969, 1970) suggested that the origin of the energetic plasma within the magnetosphere could be determined from a measurement of the 3He/4He abundance ratio or from the charge state of the energetic helium. The 3He/4He abundance ratio in the ionosphere is only about 10^{-8} (Axford, 1969) whereas the solar wind ratio is in the range of 10^{-3} to 10^{-4} (Bame et al., 1968; Geiss et al., 1970, 1972a, b). Furthermore, the helium in the solar wind is primarily doubly charged while that in the ionosphere is singly charged. Bühler et al. (1972, 1976) and Axford et al. (1972) measured helium isotopes and derived the 3He/4He ratio in aurora by exposing foils to particle fluxes on two rocket flights. The foils were recovered and were subsequently analyzed by heating them in the source of a laboratory mass spectrometer. Similar experiments were also carried out at lower latitudes (Geiss et


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The conclusion of these experiments was that the helium ions were of solar wind origin. Measurements of the helium charge states in auroral precipitation have also suggested a solar wind origin (Reasoner et al., 1968; Whalen et al., 1971; Whalen and McDiarmid, 1972; Sharp et al., 1974a; see also review by Reasoner, 1973). On the other hand measurements of significant fluxes of O+ precipitating in the auroral zone (Shelley et al., 1972, 1974; Sharp et al., 1974b, 1976a, b) suggested an ionospheric origin for at least a portion of the energetic plasma.

More recently the high altitude region of the ionosphere (the outer plasmasphere) has been suggested as a potential ion source, acting as an intermediate reservoir between the lower ionosphere and the hot plasma of the magnetosphere (Freeman et al., 1977). Young et al. (1977a) have shown that the charge composition of the outer plasmasphere can differ greatly from that of the lower ionosphere.

The earliest hot plasma mass composition experiments in the magnetosphere were limited to the measurement of the charge states of helium (Reasoner et al., 1968; Whalen et al., 1971; Whalen and McDiarmid, 1972). As the mass range and mass resolution of the instrumentation was improved, not only were ions of ionospheric origin (4He+ and 16O+) observed (e.g. Shelley et al., 1972; Johnson et al., 1974), but it was not uncommon to find 4He++ and 16O+ ions (presumably of solar wind and ionospheric origin respectively) coexisting in the same plasma (Sharp et al., 1974a; Shelley et al., 1976a; Lynch et al., 1976). Measurements of mass composition at higher energies have also been used to infer the origin of the ions (Krimigis et al., 1970; Margo-Compero, 1972; Blake, 1973; Krimigis, 1973; Fritz and Wilken, 1976; Spjeldvik and Fritz, 1978a, b; Fritz and Williams, 1973; Fritz, 1976; Fritz and Spjeldvik, 1979).

We now recognize the fact that the problems to be addressed by energetic ion mass composition experiments are far more complex than simply establishing the source or sources of the hot magnetospheric plasma. These experiments represent a valuable new tool for the study of plasma dynamics. By investigating the spatial, temporal, and phase space distributions of two or more ion species one can establish limits on the types of interactions which have acted on the ions as a function of location and geophysical conditions or compare the results with the predictions of various models. If resonant wave particle interactions are involved, one species may show effects of significant interaction such as a filled loss cone while a companion species which does not resonate may show a stable, unperturbed distribution. On the other hand, if forces acting on the plasma are predominantly adiabatic, the relative distributions of all species will be altered in a very predictable manner. For example, if only adiabatic forces were to act on solar wind plasma during its entry into and transport through the magnetosphere one would expect the energy per nucleon distributions of the hydrogen and helium ions in the magnetosphere to be approximately equal since they are known to have approximately equal velocity distributions in the solar wind. If a charge dependent force were involved there would be a shift in the energy per nucleon distribution for the two species due to their different charge