Plasma Fireballs

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***Abstract*—Fireballs is a generic name for the many forms of anode glow phenomena in low-pressure gas discharges. The glow indicates energetic electrons impacting with neutrals. A sharp boundary of the glow suggests a localized electric field such as a sheath or double layer. Fireballs mostly appear as spheres and cylinders, but new forms have been observed in dipole magnetic fields. The dynamics of pulsed and unstable fireballs has been investigated.**

***Index Terms*—Anode double layers, discharges, instabilities, plasma waves.**

WHEN a positively biased electrode is immersed in a low-pressure dc discharge (few milliTorr), a glow around the electrode is frequently visible. It is due to the acceleration of electrons to energies sufficient for electron–neutral excitations (on the order of 10–20 eV). This can occur in the sheath around the electrode, but the luminous boundary often expands to much larger distances from the electrode than the Debye length. In this case, a double layer is formed in the plasma, and the fireball becomes a highly nonlinear structure, involving the physics of ionization, double layers, beams, and associated instabilities. Although much work has been done [1], there are many open questions as regards the time–space evolution, stability, and properties in magnetic fields. Some of these will be addressed later.

Fireballs are studied in a simple dc discharge device [1] consisting of a filamentary cathode, biased negatively with respect to the grounded chamber wall, producing plasma densities of 10^8-10^9 cm^{-3} in Ar, Ne, and H_2 at pressures of $1-5$ mTorr. A spherical electrode of 1-cm diameter is inserted into the unmagnetized plasma and biased positively with a dc or pulsed voltage on the order of 100 V. The visible structure of the fireballs is recorded with a digital camera. A movable coax-fed Langmuir probe is used to study density, waves, and beams. A movable photodiode provides space-and-time-resolved light measurements. A strong permanent magnet (0.2 T and 2.5-cm diameter) is used to produce fireballs in a dipole magnetic field.

We start by showing in Fig. 1 some of the different shapes of fireballs observed. A fireball in Ne with diffuse boundary is shown in Fig. 1(a). The visible image is time integrated and does not reveal that the current is unstable and that the fireball undergoes rapid relaxation oscillations. Thus, time-resolved measurements are often imperative. Fig. 1(b) shows a stable fireball in Ar with a sharp boundary. Many previous experiments have shown the existence of a double layer at this boundary [2]. The spherical shape forms self-consistently irrespective of the shape of the electrode. The radius decreases with increasing electron density (cathode temperature and electrode voltage) and gas pressure. The size and location are sensitive to probe perturbations, which upset the balance between plasma production and losses in the fireball. Fig. 1(c) shows a luminous sheath at voltages below the threshold for fireball creation. It is concentric with the spherical electrode and reveals a radial electric field. Fig. 1(d) shows an argon firerod, which is frequently seen in magnetized plasmas. In the present case, there is no magnetic field, and the rod can form in different directions. Surface conditions of the electrode do not determine its direction because the rod is invariant upon rotation of the sphere. Finally, Fig. 1(e) and (f) shows fireballs in hydrogen in the dipole field of a strong SmCo magnet. When the entire magnet is biased positively, a localized fireball forms on part of the surface, usually off-axis, whereas other regions show a luminous sheath. The fireball follows the diverging field lines. An axially symmetric fireball is formed with a 1-cm-diameter disc electrode centered in the middle of the magnet. It forms a pear-shaped fireball. It is less sensitive to probe perturbations than the unmagnetized fireballs. Because the electrons are magnetized, they can only be energized along the magnetic field near the spherical boundary.

The time evolution of fireballs has been studied with a pulsed electrode voltage. The rise time for current and light is a few microseconds. The light decay is much slower than the current decay since the energetic electrons are no longer collected by the electrode but must thermalize in the plasma. Pulsing the fireball also produces transient responses in the electron saturation current of probes. Axial and radial time-of-flight measurements have shown ballistic ions and ion acoustic waves emitted from the fireball. The latter may be due to ion-beam–plasma instabilities. By using a high-frequency receiver (10–500 MHz), the excitation of plasma waves inside a fireball has been detected. These indicate the presence of electron beams produced at the double layer. When plasma production and losses get out of balance, the fireball can undergo relaxation oscillations, which have earlier been analyzed within the framework of chaos [1]. These produce similar transient effects as pulsing the electrode voltage. Thus, unstable fireballs produce bursts of particles and waves, a few of which have been studied in magnetic fields.

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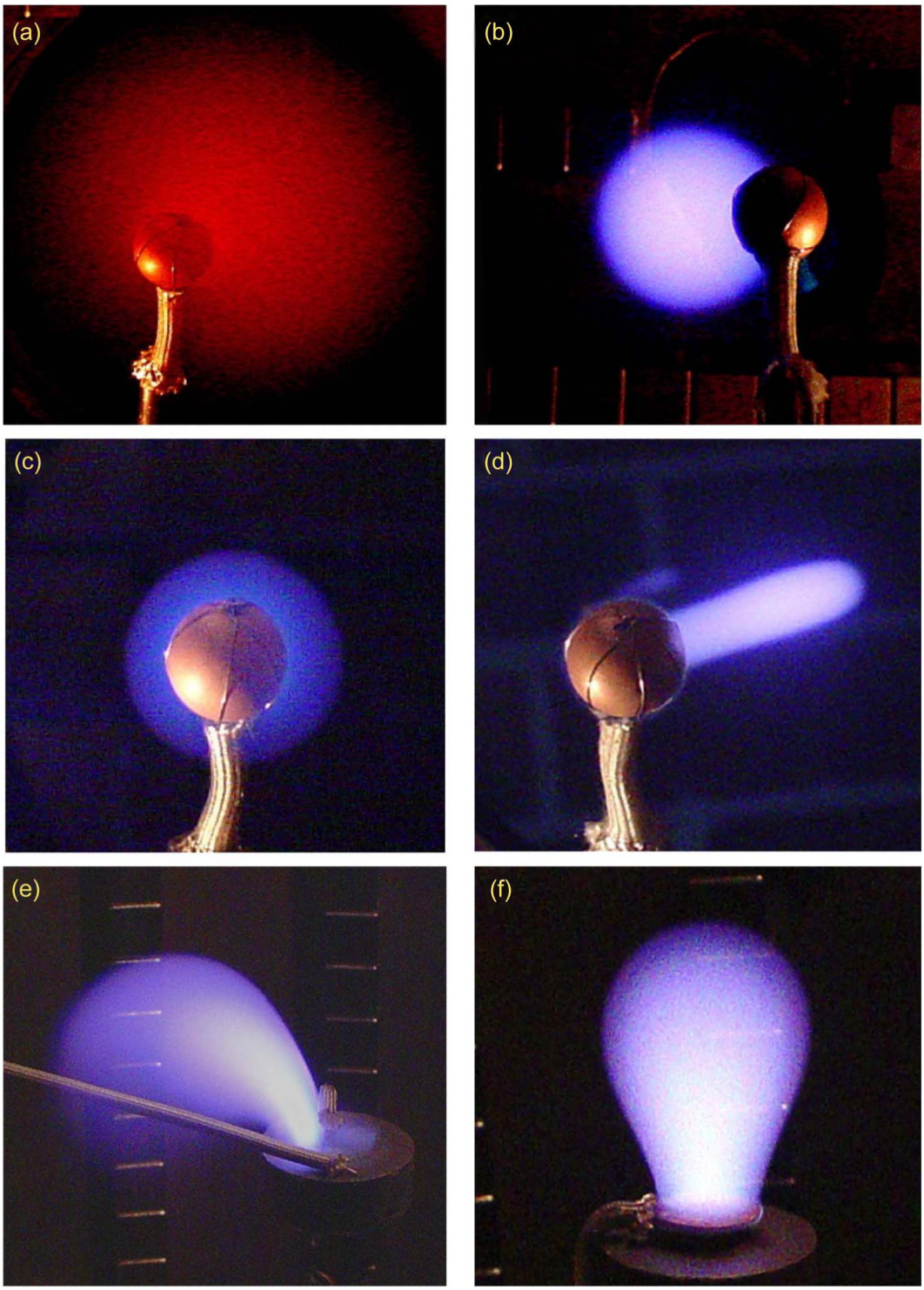

Fig. 1. Images of different plasma fireball formations. (a) Unstable fireball in Ne, which appears diffuse due to fluctuations. (b) Stable spherical fireball in Ar whose sharp boundary indicates the presence of a double layer. The fireball forms at the side of the electrode which is a 1-cm-diameter sphere. (c) Luminous sheath at voltages below the threshold for fireball formation. (d) Firerod in an unmagnetized Ar plasma. (e) Fireballs in hydrogen in a dipole magnetic field (e) off-axis and (f) on-axis.

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