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Interacting spots in a quasi two-dimensional dc-driven gas discharge system

九州工業大学工学部　　那須野悟 (Satoru Nasuno)
Department of Electrical Engineering
Kyushu Institute of Technology

The gas discharge [1] shows a rich variety of spatio-temporal pattern formations, such as lightning (random branching, which is often fractal [2]), auroras (chaotically waving curtains [3]), and spatially periodic structures (strips and hexagons) developed along and/or lateral to the current flow in glow discharge devices [4, 5, 6, 7]. Here we report a qualitatively different type of structure, which is highly localized particle-like excitation in d.c.-driven gas discharge system with large plane parallel electrodes. These localized excitations wander irregularly with keeping their shape unchanged, and exhibit a transition from isolated to aggregated state as the discharge current increases. The centre of aggregated cluster also wanders quite irregularly and its internal structure changes intermittently among some symmetrical molecule-like structures by rearranging the mutual position of elements according to chaotic changes in the direction of motion. These localized excitations can show synchronous dynamics even in distant places, and provides us a new class of nonlinear dynamics which has both local and global interactions, as well as a mimic of interacting motile elements such as biological organisms.

Our gas discharge device consists of two large plane parallel electrodes: a cathode consists of nickel plate and an anode consists of a thin transparent conducting film of indium-tin-oxide (ITO) on the glass substrate, as shown in Fig.1. The lateral dimensions of active discharge channel is typically 3cm $\times$ 3cm, and the distance between the electrodes is d =100μm. The electrodes are immersed in the low pressure air and are connected to a d.c. power source, which can supply either a constant voltage of up to 2kV or a constant current of up to 150mA, via a series resistor R of 35.2kΩ. The spatial distribution of the light intensity emitted by the discharge can be observed through the transparent anode and measured with CCD camera which has high speed shutter.

When a sufficiently high voltage greater than a critical value is applied across the electrodes, the air between electrodes breakdown electrically,

forming charged ions and free electrons and permitting current to flow. The behavior of resulting discharge largely depends on the total current I and the pressure p of the air. We therefore studied the discharge as a function of a constant current I supplied by a power source and the pressure p. The stable, self-sustaining, luminous discharge occurs for currents larger than a critical value I_c (~0.1mA), below which the discharge is no longer self-maintained and repeatedly starts and stop.

Even though the spatially uniform electric field is applied to the electrodes to excite discharge, the resulting discharge is not homogenous but always localized in small portions of the electrodes.

For relatively small currents, the discharge excitation concentrates in small circular areas, which can be directly seen by the light emitted by the discharge. Fig.2a shows a typical example of such luminous discharge spot and Fig.2b shows its light-intensity profile. The intensity profile is radially symmetric, bell shaped and remains unchanged upon collision with other spots, like 'solitons' [8]. The typical color of the discharge spots is pale-purple in the bulk and bluish-purple near the boundary of a spot. The discharge spots are not stationary but usually wander irregularly, excepting for a narrow range of currents immediately above I_c, typically $I_c \leq I < 0.3$mA. The mean speed increases almost linearly from zero as increasing I beyond the onset of wandering at a fixed pressure.

The total number of discharge spots in the system and their interactions depends on I and p. The results for $33 < p < 45$Torr are summarized in Fig.3. This diagram is obtained upon increasing I, while almost the same one is observed upon decreasing I and there is no appreciable hysteresis, excepting the lower boundary for self-sustaining discharge.

For small currents, the discharge spots prefer to be isolated each other. On the other hand, they tend to stick together to form a single cluster above a critical current, which depends on p as represented by the middle solid line in Fig.3. In each regime, the total number of spots are fixed for a given I and p, and increases with increasing I. The diameter of the spots slightly depends on I and p, but typically 3mm (about 7% of the transverse size of electrodes). The intensity at the centre of the spots increases with increasing I and shows discontinuous large drop when the number of spots increases. Because the luminous density emitted by discharge increases with the current density, this implies that the maximum current density varies discontinuously when the number of spots changes. The voltage

drop between the electrodes, however, does not show any detectable change when the number of spots changes.

Now let us discuss the dynamic aspects of discharge spots in isolated regime. Although the motion of each spots are quite irregular, there exists some interaction between them: it is repulsive at very short distances and attractive at some longer distances. When two spots collide, they never merge into a single spot but retain their shape to form a diatomic-molecule-like structure and after a while dissociate each other. In order to characterize this motion more quantitatively, we measured the distance between each centre of two spots as a function of time. As seen from Fig.4, the distance changes quite irregularly for most of the time, but it intermittently goes down to a small value, which is slightly smaller than one diameter and corresponds to the bound state, and stay for some duration. Even in the bound state, the centre of this 'diatomic molecule' wander irregularly, with irregular rotation of the molecule around it.

When there exist more than two spots, it often occurs that one spot disappear suddenly and at the same time another new spot appear in a distant place. It looks as if the spot moved by the 'teleportation' which is familiar in SF movies. Of course, this is not teleportation because these particle-like spots are not distinguishable. The disappearance usually occurs for one of bounded spots and the creation takes place, irrespective of distance, from an isolated spot.

The synchronous disappearance and creation of discharge spots at distant places indicates that the local discharge dynamics is affected not only by neighboring dynamics but also by all dynamics within the system. Owning to this globally coupled dynamics, the total number of spots within the system is kept constant in time when control parameters are fixed. The physical origin of this global coupling will come from the global constraint of constant current. The similar synchronous phenomenon was also observed by supplying a constant voltage V_s to the electrodes and the sires resistor R, instead of supplying a constant current. In this case, the global coupling is also established by the feedback of local current change to the applied voltage V across the whole electrodes through the relation $V = V_s - IR$.

Next we would like to discuss about the spots in aggregated regime, where they form a single cluster with divers molecule-like structures as shown in Fig.2e-2m. These macroscopic 'molecules' are not stationary but

quite active: their centres of mass wander very irregularly , and further-more, when the number of spots is more than three, they change their internal structures intermittently by rearranging the mutual position of elements according to chaotic changes in the direction of motion. For example, when the number of spots is four, the 'molecule' switches inter-mittently between chain-etramer state (Fig.2g) and square-tetramer state (Fig.2h). When there exist six spots, the spatio-temporal behavior of spots exhibits more rich variety. We observed five different configurations, as shown in Fig.2i-2m, and the configuration of the 'molecule' switches be-tween them randomly in time. It seems that there is a preferred direction of propagation for each configurations, i.e. the 'molecule' tends to move in the direction of the mirror axis of each configurations, and when the 'molecule' is taking the configurations with rotational symmetry like Fig.2h and Fig.2j, the mobility appears to go down comparing with other config-urations. The molecules consisted of five spots can observed only near the transition boundary from four to six spots. For the pressures larger than about 45Torr, the aggregated states are no longer stable and only tempo-rally bounded pairs can exist. In this pressure regime, we observed up to nine isolated spots.

As seen from Fig.2f and 2g, the spots of two slightly different sizes can coexists in the aggregated regime, in contrast to the isolated regime where all spots have the same size. For instance, in case of a triatomic-molecule-like state (Fig.2f), a middle spot is always larger than the other two just like molecule of water, H_2O, and tends to propagate at the head.

At a higher current, localized circular excitations give way to another type of localized structure, i.e. a single snaking luminous string, whose width is almost same with the diameter of the discharge spots and whose length is much larger than its width and varies in time. The string snakes and folds irregularly in time, and intermittently disappears and replaced by a completely new one. At rather higher currents, a string become a closed loop (Fig.2n). The shape of the loop is rather simple ring when it is nucleated, but as time goes the length of the loop increases with developing folds. When the complexity of the fold reaches to some extent, the loop disappears and replaced by a more simple one. The system repeat this process intermittently.

Besides the discharge spots reported above, few examples of two-dimensional localized excitations are known in disspative systems so far [9, 10, 11, 12],

including those in d.c.-driven gas discharge system with photosensitive-semiconductor electrodes [13] and those in a.c-driven gas discharge systems [14, 15]. Those localized excitations are, however, motionless or less brisk in their movements and show rather simpler spatio-temporal behaviors, comparing with the present case, where their active motion reminds us of a problem of interacting motile elements such as biological organisms [16]. Finally, it would be interesting to point out that most theoretical model which can show interacting localized excitations takes into account only local couplings [17, 18], and the role of global coupling remains unclear [19], whereas many systems in nature, including biological systems, has more or less global coupling as well as local one, like the present system.

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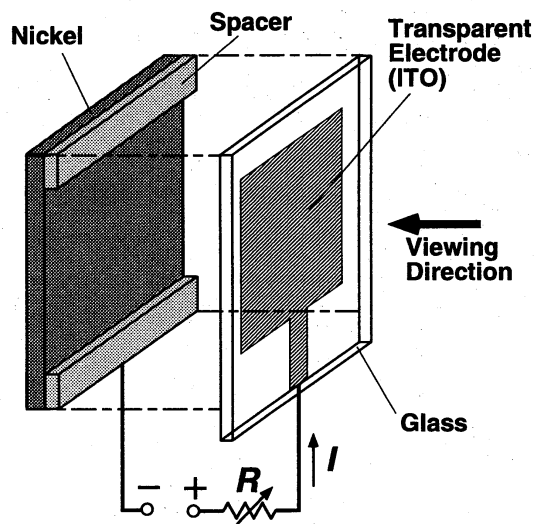

Figure 1: Schematic diagram of the discharge devise. A cathode consists of nickel plate of 50mm×50mm×3mm and an anode consists of a thin transparent conducting film of indium-tin-oxide (ITO) on the glass plate (effective area used for discharge is typically 30mm×30mm). These electrodes are separated by the spacer of 100μm thick and immersed in the low pressure air.
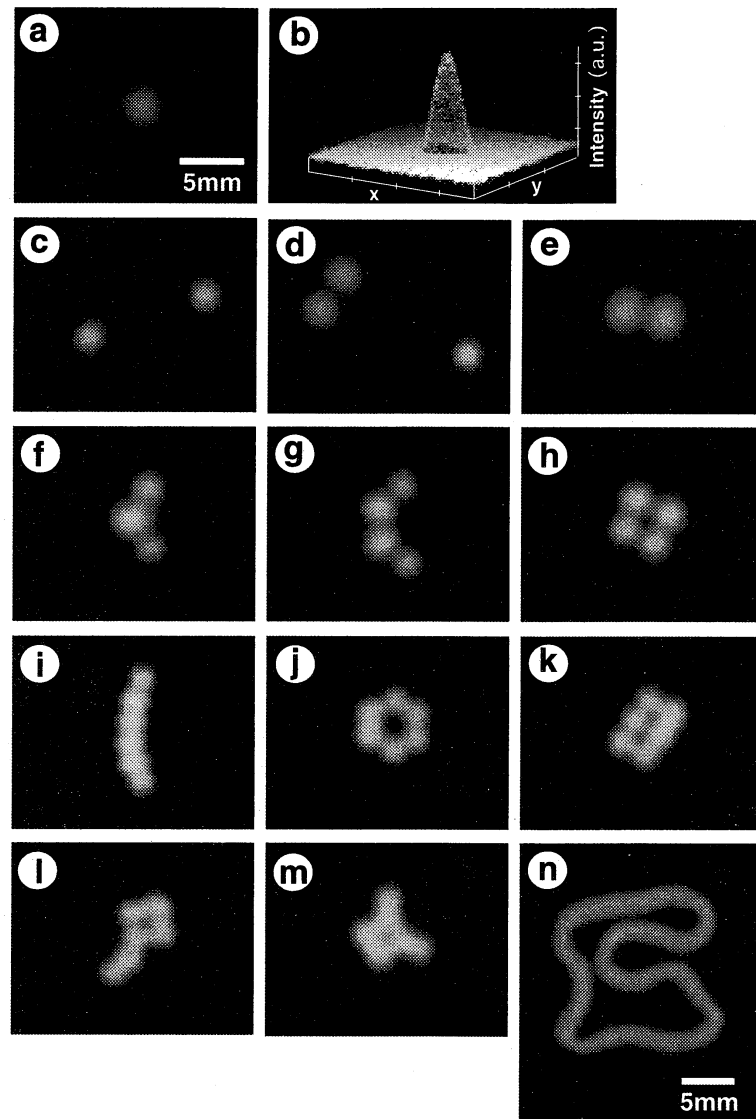
Figure 2: Typical snapshots of localized discharge patterns. (a) A single discharge spot. (b) Intensity profile of a single discharge spot. (c) A pair of isolated spots. (d) Three discharge spots, among which two are temporally bounded. (e) Diatomic 'molecule' consists of discharge spots. (f) Triatomic 'molecule' with H_2O-like configuration. Note that the middle spot is larger than the rest two. (g)-(h) 'Molecules' consists of four discharge spots. (i)-(m) 'Molecules' consists of six discharge spots. In essence, the centers of all these patterns move very irregularly. At a given set of control parameter values, the number of spots consisting in a single cluster is constant in time, while the configuration of the spots can switch intermittently among those consisted of the same number of spots according to the chaotic changes in the direction of motion. (n) Waving loop. The maginification of (n) is differnet from the others.
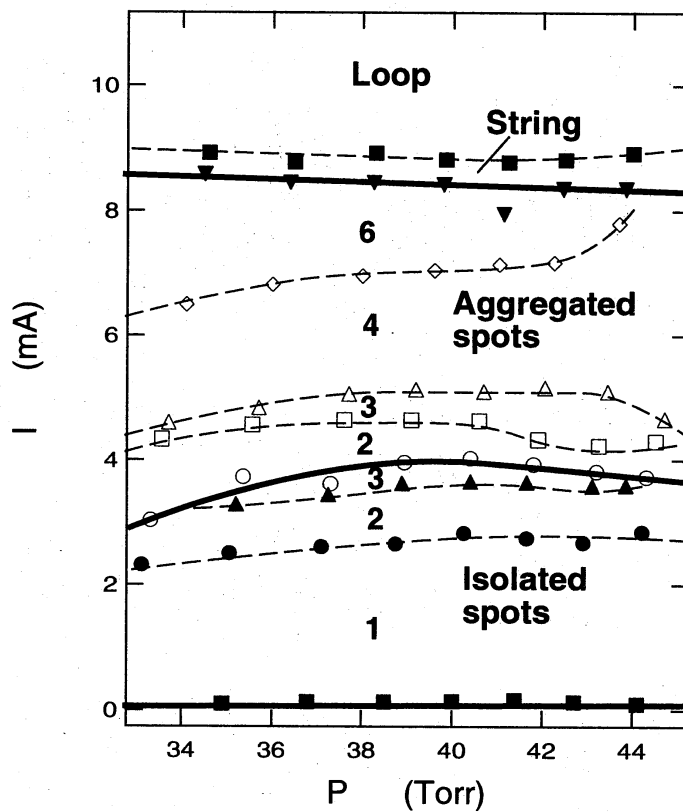
Figure 3: Diagram showing the stable regions for different states, as a function of p and I. The bottom solid line denotes the boundary above which self-sustaining, luminous discharge occurs. The discharge current flow exhibits small circular spots below the top solid line and waving strings above it. The middle solid line represents the transition from isolated to aggregated spots. The numbers denote the total number of spots within the system in each corresponding regions.
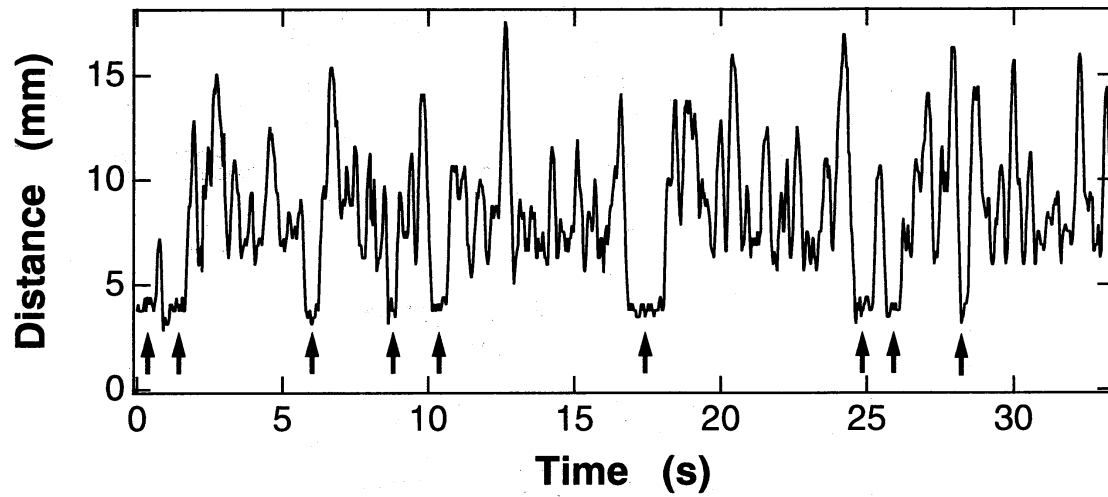
Figure 4: Temporal variation of the distance between the centers of two wandering spots for I =2.37mA and p =35Torr. The periods with a minimum value in distance, which are indicated by arrows, correspond to the bounded state.