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Dissipation of Plasma Cloud generated by Stage Separation of Rockets: Dispersion & Decay Analyses

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Abstract:

In the launch of a multi-stage rocket, the spent lower stage is separated from the upper stage(s) by exploding the nuts/bolts which attached the two parts using high explosives. This generates a plasma cloud which temporarily disrupts radar signals tracking the vehicle and the burnt-up rocket. In this study, we study the dissipation of this plasma cloud in space and time by dispersion of the cloud and loss through chemical recombination, respectively. Dispersion is determined by solving the diffusion equation whereas decay is analyzed by solving the continuity equation with an altitude-dependent recombination rate. The two processes are studied independently from one another from which the decay of the maximum ion density is determined. This analysis is carried out for a stage separation at an altitude of 60 km using Hexanitrostilbene as the high *explosive. It is assumed that* 10^{24} *positive ions are produced in this event which translates to a peak ion density of* 7.9×10^{9} cm^{-3} *in the 1s aftermath of the event. The radar signals are normally restored when the peak ion density falls to the level of* 10^{7} cm^{-3} *in the matter of a short 7 seconds of time.*

Introduction:

In a multi-stage rocket propulsion, the burnt-up lower stage is normally separated from the rest of the upper stages by exploding the nuts/bolts which attach the rockets by means of pyrotechnics. In this process, the lower stage is discarded and the upper stages gain velocity boosts due to weight reduction in addition to that generated by impulsive reaction. The stage separation generates a plasma cloud which temporarily disrupts radar signals tracking the vehicle and the burnt-up rocket. This effect is particularly more intense in the separation of the spent first/booster stage separation from the upper stages because of the larger number of bolts and its proximity to the radar system. In this study, we study the dissipation of this plasma cloud in space and time by dispersion and loss. Specially, we analyze the dispersion and decay of this plasma cloud as functions of altitude and time. The two processes are studied independently from one another: Dispersion is determined from solving the diffusion equation whereas decay is analyzed by solving the continuity equation with an altitude-dependent loss rate.

Trajectory Parameters and Coordinate System:

The lower state of a multi-stage rocket is typically separated from the upper stages at an altitude of 60 km or higher [1]. The ***trajectory parameters*** of the space vehicle can be determined from the universal trajectory curve (cf. [1]). For a stage separation at an altitude of 60 km, the velocity V and flight path angle θ at stage separation are 7 km/s and 25° respectively, the former being 88.5% of the ***minimum circular orbit velocity*** [1]. In 10 seconds following the stage separation, the upper stages travel about 70 km, which translates to a ***horizontal traverse*** of $V\cos\theta = 63.44$ km; and ***vertical ascent*** of $V\sin\theta = 19.58$ km. For such distances, the ***flight path*** and the ***arc along the Earth's surface*** can be closely approximated by straight lines. The flight path trajectory up to 10 seconds after the stage separation is shown in Fig. 1. An ***orthonormal coordinate system*** is used in this study with; x along the flight path; y in the horizontal plane; and z in the vertical plane such that x, y and z form a ***right-handed system***.

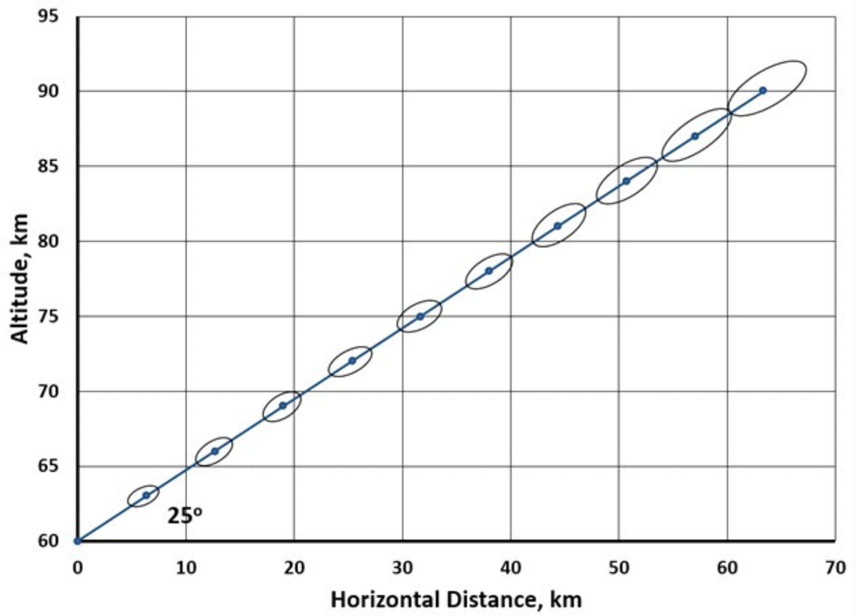

Fig. 1

Explosives used in Stage Separation and Ion Cloud Generated:

In a multi-stage rocket, the stages are held together by one to two dozen equi-spaced ***nuts/bolts***. In a stage separation, these bolts are severed by ***high explosives*** which are stable and resistant to pre-mature detonation from shock, fire or electrical discharge. The common explosives used include ***Triaminobenzene TATB*** (chemical formula $\mathbf{C_6H_6N_6O_6}$; molecular weight 258.150 amu), ***Hexanitrostilbene HNS*** ($\mathbf{C_{14}H_6N_6O_{12}}$; 450.238 amu) and ***Hexanitrodiphenyl DIPAM*** ($\mathbf{C_{12}H_6N_8O_{12}}$; 454.228 amu) [2].

It is estimated that 1 to 2 lb of explosives are required to effect a stage separation of rockets. The amount of ***ion-electron plasma cloud*** generated in a typical stage separation, using HNS, for an example, can be estimated as follows: By ***Avogadro's law***, 1 gram-molecular weight of HNS (= 450.238 gm) contains 6.02214×10^{23} (***Avogadro's number***) molecules of HNS. Hence 1 lb (= 453.6 gm) of HNS would contain (by ***rule-of-three***) 6.0671×10^{23} molecules of HNS. It is further known that the main ionic products of HNS explosion consist largely of NO_x^+ ions (NO_2^+ and NO^+). Since one molecule of HNS contains 6 NO_2 groups, the maximum number of NO_x^+ ions in the explosion of 1 lb of HNS explosives is

6.0671×10^{24} positive ions. By the ***charge-neutrality condition***, an equal number of free electrons are produced in the process, which readily attach themselves to the principal neutral species N_2 to form N_2^+ and are removed by ion-neutral reactions. In this study, we assume that 10^{24} ions are produced in this stage separation.

Dispersion of Ions by Diffusion:

Once produced, the ions would rapidly disperse outwards. For now, they are treated as indestructible particles, i.e., their loss processes are disregarded. Prior to the stage separation, the explosives travel with the multi-stage rocket system. After the stage separation, the ion cloud generated is assumed to travel behind the upper stages. Any additional velocity boost to the upper stage will be passed on the ion cloud by vacuum action.

The dispersion of the ion cloud in the moving coordinate system is governed by the ***diffusion equation*** (cf. [3]):

$$\frac{DN}{Dt} = k_x \frac{\partial^2 N}{\partial x^2} + k_y \frac{\partial^2 N}{\partial y^2} + k_z \frac{\partial^2 N}{\partial z^2} \tag{1}$$

where k_x, k_y and k_z are the ***eddy diffusion coefficients*** along x, y and z respectively.

Although molecular and thermal diffusion coefficients can be estimated from the kinetic theory, the eddy diffusion coefficient in the lower atmosphere of the Earth is a much more speculative matter. It has been reported that values of the order of 10^8 cm^2/s are possible in the lower atmospheres of Jupiter, Venus and Mars [4]. In our case, higher values of the coefficient are appropriate, since besides the ***shock waves*** created by the motion of the vehicle, additional ***blast waves*** are generated by the explosive charges. Further, since more ***turbulence*** is created in the direction of motion, we have assigned values of $k_x = 2\times10^9$ cm^2/s; and $k_y = k_z = 2\times10^8$ cm^2/s.

The solution of Eq. (1) is found to be (cf. [5]):

$$N(x, y, z, t) = \frac{Q}{(2\pi)^{3/2}\,\sigma_x \sigma_y \sigma_z} e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}} \tag{2}$$

where $\sigma_x = \sqrt{2k_x t}$ etc. are the respective standard deviations along x, y, z directions, respectively. In Fig. 1, the outlines of the clouds containing 2 ***standard deviations*** or 95.45% of the ions are shown at intervals of 1s up to 10 secs. Apart from the expanding outlines, a prime feature of the outlines is the elongation of the cloud along the x-direction or direction of motion by a factor of $\sigma_x/\sigma_z = (k_x/k_z)^{1/2}$.

The ion distribution in the y-z plane after time $t = 1$s, 2s and 4s after the explosion, are shown in Fig. 2. It should be noted that the ion density at $t = 0$s is technically a ***singularity*** and therefore ***undefined***. The ***peak ion densities*** after 1s, 2s and 4s are 7.9×10^9 cm^{-3}, 2.8×10^9 cm^{-3} and 9.5×10^8 cm^{-3}, respectively. Since the peak ion density spans several orders of magnitude which cannot be accommodated in this figure up to $t = 10$s, it is more appropriate to plot the ion density in a ***logarithmic scale***. This is done in Fig. 3 for $t = 1$s, 5s and 10s.

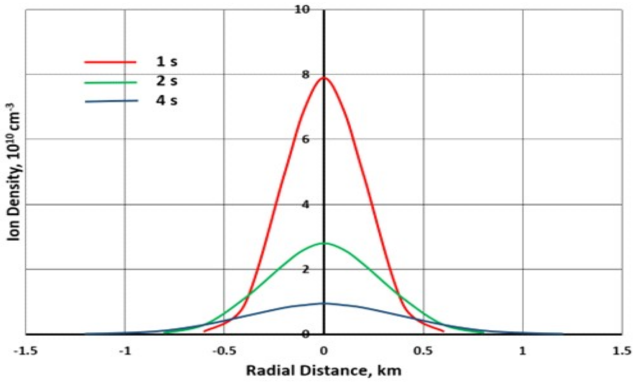

Fig. 2

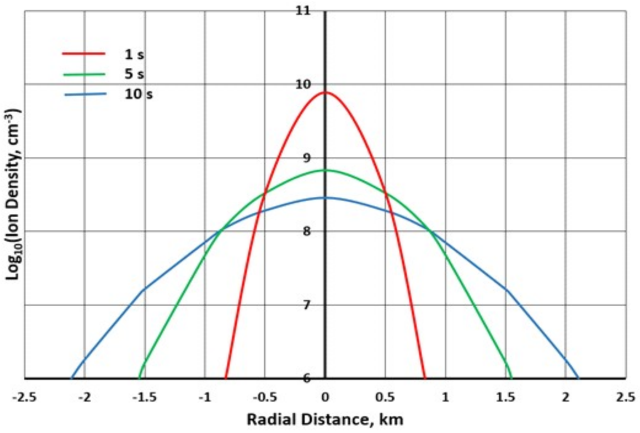

Fig. 3

Decay of Ion Cloud by Chemical Loss:

Besides the dispersion of the ions by diffusion, the positive ions undergo decay by the ion-neutral charge transfer reactions. For the HNS explosive, NO_2^+ and NO^+, collectively written as NO_x^+ are the major ion species produced. They are lost by chemical reactions with the dominant neutral species in the atmosphere at the altitudes under consideration N_2:

$$NO_x^+ + N_2 \rightarrow NO_x + N_2^+ \tag{3}$$

The reaction rates are not well-known but believed to be about $k = 1.2\times10^{-15}$ cm^3 s^{-1} [6]. The ***number density*** of N_2 at 60 km altitude is $n(N_2) = 6.86\times10^{15}$ cm^{-3} [7] and ***atmospheric scale height*** is $H = 6.527$ km [7]. The ***loss coefficient*** of ions is thus $\beta = k \times n(N_2) = 8.232\text{s}^{-1}$. Since the neutral density decreases with height, we replace β by $\beta\exp(h/H)$, where h is the ***vertical height***. For the moving ion cloud, we convert h by t from the relation $h/t = V\sin\theta$ whence we get $\beta\exp(-\gamma t)$ with $\gamma = V\sin\theta/H = 0.3\text{s}^{-1}$. The ***continuity equation*** with ***altitude-dependable loss rate*** in the ***moving frame of reference*** for the ion cloud is then:

$$\frac{DN}{Dt} = -\beta e^{-\gamma t} N \tag{4}$$

One can separate the variables and integrate from time $t = 1$s as follows:

$$\int_{N_1}^{N} \frac{DN}{N} = -\int_{t_1}^{t} \beta e^{-\gamma t} Dt \tag{5}$$

Upon carrying out the integrations and simplifying, we obtain the peak ion density as a function of time:

$$N = N_1 e^{\frac{\beta}{\gamma}(e^{-\gamma t} - e^{-\gamma t_1})} \tag{6}$$

The decay of the peak ion density at the center of the cloud was calculated from Eq. (6) as an ***initial value problem*** with ***initial condition*** of $N_1 = 7.937\times10^9$ cm^{-3} at $t = 1$s. The ion densities are plotted in Fig. 4 (marked N_l) and compared with the values from the dispersion model (marked N_d). The two curves are quite close to one another, signifying that the dispersion and chemical loss effects on the peak ion density are comparable. Initially, the dispersion effect was marginally greater, but after about 4s, the loss effect slightly surpassed the former. Without any plausible physical reason, this similarity is thought to be accidental.

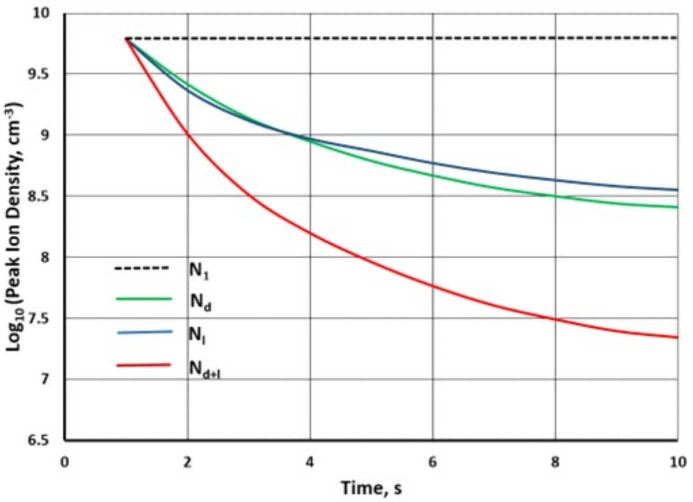

Fig. 4

Dissipation of Ion Cloud by Combined Effects of Dispersion and Chemical Loss:

The prescription for including the loss effect in the diffusion equation is to solve the following differential equation:

$$\frac{DN}{Dt} = k_x \frac{\partial^2 N}{\partial x^2} + k_y \frac{\partial^2 N}{\partial y^2} + k_z \frac{\partial^2 N}{\partial z^2} - \beta e^{-\gamma t} N \tag{7}$$

That will be a daunting task by all means. Here we follow a simpler alternative approach. In Fig. 4, N_1 is the peak ion density at 1s. If N_1 could remain constant in time, it would follow a ***trajectory*** shown by the dashed line in that figure. N_d and N_l are the peak ion densities at any time due to dispersion alone and loss alone, respectively. Then, the ***fraction*** of peak ion density due to dispersion only is $r_d = N_d / N_1$; and that due to loss alone is $r_l = N_l / N_1$. Considering the fractions to be ***multiplicative***, $r_{d+l} = N_d N_l / N_1^2$, whence:

$$N_{d+l} = \frac{N_d N_l}{N_1} \tag{8}$$

This peak ion density under the combined actions of dispersion and loss is calculated using Eq. (8) and plotted in Fig. 4. The ion densities decay fairly rapidly in time, decaying two orders of magnitude to the order of 10^7 cm^{-3} in under 6 seconds, to the level where the radar signals are restored. Consequently, the radar signals disrupted during a first-stage rocket separation do recover in about a short 7 seconds of time.

Remarks:

It would be instructive to repeat this analysis using other types of explosives such as TATB and DIPAM both of which, unlike HNS, contain the NH_2 groups in addition to the NO_2 groups. The ionic products of explosion are expected to be more complex in these cases. The recovery times of the radar echoes would also be different in consequence.

References:

[1] R.P. Haviland & C.M. House : *Handbook of Satellites and Space Vehicles*, Van Nostrand, Princeton (1965).

[2] T. Urbanski : *Chemistry and Technology of Explosives*, **4**, Pergamon Press, Oxford (1984).

[3] F. Pasquill : *Atmospheric Diffusion*, Ellis Harwood, New York (1974).

[4] D.M. Hunten in *Jupiter*, University of Arizona Press (1976).

[5] A.C. Giere : *NASA Tech. Memo. 78128* (1977).

[6] S. Matsuoka, H. Nakamura & T. Tamura : Ion-molecula reactions of N_3^+, N_4^+, O_2^+ and NO_2^+ in nitrogen containing trace of oxigen gas, *J. Chem. Phys.* **75(2)**, 681-689 (1981).

[7] *U.S. Standard Atmosphere*, Washington (1976).