THE SPACE DUST PARAMETERS REGISTRATION SYSTEM

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ABSTRACT

The mathematical model of a space debris particles detector on the basis of pumped metal-dielectric-metal (MDM) film structure is designed. The efficiency of its usage for registration of space debris particles at different altitudes is estimated, and also the information possibilities of the detector are considered. The analysis of influencing of noise characteristics on observed data is done.

The detector of micrometeoroids and space debris proposed in [1] is the most perspective one. Its technical characteristics meet requirements for such instruments.
In this paper the mathematical model of the combined ionization and capacitor detector is considered. This instrument schematically shown in Fig.1 has a spherical design and large sensitive surface. There is a spherical coordinate system as for ion scattering used in Fig.1.

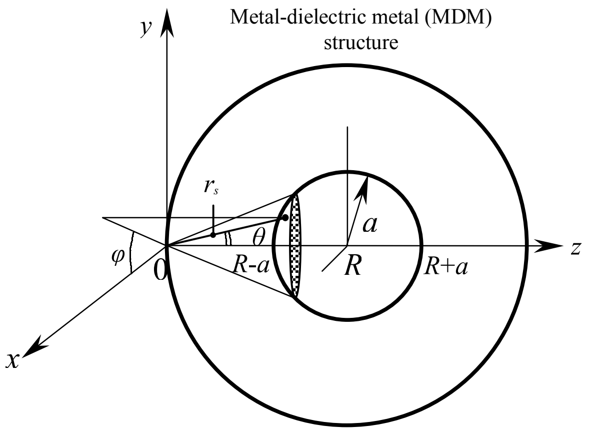

Fig.1. Schematic illustration of the detector

Distribution of ions in room on speeds is

$$\frac{dN}{d\overline{V}} = \frac{N_0}{\pi^{3/2} \cdot V_p^3} \cdot \exp\left[-\frac{\left(\overline{V} - \overline{V}_i\right)^2}{V_p^2}\right], \qquad (1)$$

where N_0 is an amount of ions emitted after the high-velocity impact of the space particle and the target (the metal-dielectric-metal (MDM) structure); $\vec{V}$ is a velocity of an ion; $\vec{V}_i$ is a velocity of the ion having the same direction as impact; V_p is the most probable velocity of ions.
The values N_0, V_i, V_p depend on the space particle speed V_0, its density ρ_s and mass m [2,3]

$$V_p = \frac{V_0}{1 + \sqrt{\frac{\rho_s}{\rho_t}}}; \qquad (2)$$

$$V_i = \sqrt{\frac{\rho_s}{\rho_t}} \cdot V_p; \qquad (3)$$

$$N_0 = \frac{Q_0}{e}; \qquad (4)$$

$$Q_0 = c \cdot m \cdot V_0^3. \qquad (5)$$

Q_0 is the total ion charge generated by the high-velocity impact; m is the micrometeorite particle mass (for a round fragment $m = \pi \cdot \rho_s \cdot d_s^3 / 6$; d_s is a diameter of the fragment); c is a constant depending on properties of a material of the particle and the target; V_0 is a speed of the particle; e is an elementary charge; ρ_s, ρ_t are the densities of the particle and target.
Let's convert the function of ion distribution on speeds to the same one of time, i.e. to dependence $I(t)$.

$$\frac{dN}{dV} \rightarrow \frac{dN}{dt} = I(t). \qquad (6)$$

Since $\frac{dN}{dV} = F_1(V_0, P, m)$, therefore,

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$I(t) = F_2(V_0, P, m)$, where $P = \sqrt{\frac{\rho_s}{\rho_t}}$.

While performing the transformation of Eq.6 a spherical coordinate system is used, this system has its center at a point where the space particle encounters the exterior sphere (Fig. 1)

$\frac{dN}{dV}$ is equivalent to $\frac{d^3N}{dVd\theta d\varphi}$.

$$\int_0^{2\pi} d^3N d\varphi = 2\pi \frac{N_0}{\pi^{3/2}V_p^3} \exp\left[-\left(\frac{V^2 + V_i^2 - 2VV_i\cos\theta}{V_p^2}\right)\right] \times \\ \times V^2 \sin\theta dV d\theta \quad (7)$$

Equation describing the internal sphere can be written as

$$r_s = \omega R - \sqrt{(\omega R)^2 - R^2 + a^2} = A(\omega), \quad (8)$$

where a, R are radii of the internal and exterior spheres respectively; r_s is a distance from the impact point of the particle up to an impact point of the ion on the receiver, $\omega = Cos\theta$.

Time of flight of the ion in a gap between two spheres is

$$t = \frac{r_s}{V}. \quad (9)$$

We can see from the expression (9), that

$$dV = -\frac{r_s}{t^2} \cdot dt. \quad (10)$$

Taking into consideration that $\omega = Cos\theta$ and $d\omega = -Sin\theta \cdot d\theta$ and using the Eqs.7-10 we get the distribution function of concentration on time.

$$\frac{dN}{dt} = \frac{2 \cdot N_0}{\pi^{1/2} \cdot V_p^3} \cdot \int_\omega^1 \exp\left(\frac{\frac{2 \cdot A \cdot V_i \cdot \omega}{t} - V_i^2 - \frac{A^2}{t^2}}{V_p^2}\right) \cdot \frac{A^3}{t^4} \cdot d\omega \quad (11)$$

In case the ions move on a tangent to the internal sphere a magnitude ω can be derived from the following formula

$$\omega_m = \cos\theta_m = r_{sm} / R = \sqrt{R^2 - a^2} / R, \quad (12)$$

Thus, the Eqs.5,13 describe dependence of a current pulse of the ion receiver on arguments V_0, m, P.

Time of flight of ions from the impact point on exterior sphere to ion receiver equals

$$t = \int_a^R \frac{dr}{\sqrt{\frac{2}{m_i} \cdot \left(-\frac{\delta_1}{r} + \frac{\delta_2}{R - r}\right) + V_0^2}}, \quad (13)$$

where $\delta_1 = -e \cdot U \cdot \frac{a \cdot R}{a - R}$; $\delta_2 = -\frac{e^2}{16\pi\varepsilon_0}$.

The solution of the integral in Eq.13 has a rather complicated form. It can be essentially simplified considering the physical processes during the charged particle's flight in a drift room of the detector. The field of interaction of the charge carrier with a charge induced by it on a conducting plate of the exterior sphere is decelerating. The external field of the detector, vice-versa, is accelerating for the given particle. Electric intensity of interaction of the charge carrier with the induced charge is very great nearby the conducting plate and exceeds an electric intensity of the detector. When the particle moves to the detector's internal sphere there is an attenuation of interaction with the induced charge and increasing of the detector's field action.

The charged particle is decelerated by the field of the induced charge, and then it is accelerated by the detector's field. Thus, the Eq.14 for time of ion arrival to the internal sphere can be rewritten as

$$t = \int_a^{r_0} \frac{dr}{\sqrt{\frac{2 \cdot e \cdot U}{r \cdot m_i} \cdot \frac{a \cdot R}{R - a} + V_0^2}} + \int_{r_0}^R \frac{dr}{\sqrt{V_0^2 - \frac{1}{m_i} \cdot \frac{e^2}{8\pi\varepsilon_0 (R - r)}}}, \quad (14)$$

where coordinate r_0 is determined from a condition of balance between energies of decelerating and accelerating fields

$$\left\{\frac{e\cdot U}{r_0}\cdot\frac{a\cdot R}{R-a}=\frac{e^2}{16\varepsilon_0(R-r_0)};\ a\le r_0\le R.\right. \quad (15)$$

The substitution of Eq.14 for Eq.13 contributes to an inaccuracy of measuring of ion arrival time, but it considerably simplifies a solution. After series of transformations we have the time of ion flight in the detector's drift room

$$t=t_1+t_2, \quad (16)$$

$$t_1=\frac{\sqrt{V_0^2(r_0-a)^2+\frac{2\cdot e\cdot U\cdot a\cdot R}{m_i\cdot(R-a)}\cdot(r_0-a)}}{V_0^2}-\frac{\frac{2\cdot e\cdot U}{m_i}\cdot\frac{a\cdot R}{R-a}}{V_0^3}\times$$
$$\times\ln\left[\frac{2\cdot V_0\cdot\sqrt{r_0}+2\sqrt{\frac{2\cdot e\cdot U}{m_i}\cdot\frac{a\cdot R}{R-a}+V_0^2\cdot r_0}}{2\cdot V_0\cdot\sqrt{a}+2\sqrt{\frac{2\cdot e\cdot U}{m_i}\cdot\frac{a\cdot R}{R-a}+V_0^2\cdot a}}\right]; \quad (17)$$

$$t_2=\frac{\sqrt{V_0^2(R-r_0)^2+\frac{e^2\cdot(R-r_0)}{8\pi\varepsilon_0 m_i}}}{V_0^2}-\frac{\frac{e^2}{8\varepsilon\varepsilon_0 m_i}}{V_0^3}\times$$
$$\times\ln\left[\frac{\sqrt{\frac{e^2}{8\pi\varepsilon_0 m_i}}}{V_0\cdot\sqrt{R-r_0}+\sqrt{\frac{e^2}{8\pi\varepsilon_0 m_i}+V_0^2\cdot(R-r_0)}}\right]. \quad (18)$$

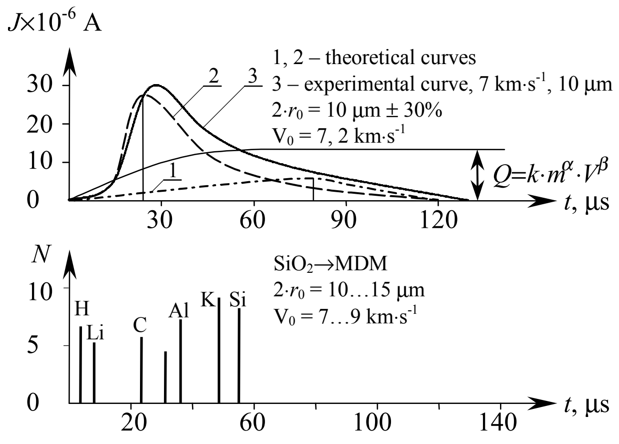

Fig.2. Spectral and integral dependencies of current pulse

The results obtained indicate that if there is no electric field applied between spheres of the detector the recorded current pulse has no separation on masses.

The leading-edge time of the current pulse measured from the impact up to the maximum of impulse is inversely proportional to the space particle's speed, and integral of a current is proportional to product $m\cdot V_0^3$. If the voltage applied to the ion receiver is greater than 300…400 V the spectrum of ionic currents is registered on its output. This spectrum can be calculated using the Eqs.16-18. With the voltage U=1000 V and R=3 m ionic impulses can be separated for a range of mild masses (1…20 atomic mass unit). Increasing of ion mass leads to the resolution capability drop just as it takes place in ordinary time-of-flight mass spectrometers. The spectrum of ions having different masses is shown in Fig.2.

To improve the resolution capability of the considered detector design we offer to use decelerating electric field applied between two spheres. Secondary electron multipliers mounted on the internal surface of the exterior sphere of the detector are used as ion receivers. In this case charged particle (ion) motion can be described by an expression

$$\left\{\begin{array}{l} W=\frac{m_i\left(\frac{dr}{dt}\right)^2}{2}+\frac{L^2}{2m_i r^2}+\frac{|\delta|}{r}=const \\ L=m_i V r\sin\gamma=const \end{array}\right. \quad (19)$$

where W is a total energy of a particle; L is a moment of a particle relatively the center of the sphere; γ is an angle between vectors $\vec{r}$ and $\vec{V}$; m_i is the mass of an ion, $\delta=e\cdot U\cdot\frac{a\cdot R}{a-R}+\frac{r\cdot e^2}{16\pi\varepsilon_0(R-r)}$.

The Eq.19 is converted to the following one

$$\left\{\begin{array}{l} t=\int\frac{dr}{\sqrt{\frac{2}{m_i}\cdot\left[W-W_p(r)\right]-\frac{L}{m_i r^2}}}+c_1 \\ \varphi=\int\frac{\frac{L}{r^2}dr}{\sqrt{2\cdot m_i\cdot\left[W-W_p(r)\right]-\frac{L}{r^2}}}+c_2 \end{array}\right. \quad (20)$$

where $W_p(r) = \frac{-\delta}{r}$ is a potential energy of the particle in the electric field; c_1, c_2 are the integration constants. The first expression in Eq.20 is a law of motion of the particle along a trajectory, the second one is the particle's trajectory equation. The shape of particle's trajectory is a hyperbola.

The time of particle's flight is derived from integration of the Eq.20. As well as in case when ions fly from the exterior sphere to the internal one to obtain a rather simple solution it is required to simplify the first expression of the Eq.20. When the particle (ion) is near the conducting surface of the exterior sphere the total energy components $\frac{\delta_1}{r} = \frac{e \cdot U \cdot a \cdot R}{r \cdot (R-a)}$ and $\frac{L^2}{m_i r^2}$ are much less than $\frac{\delta_2}{R-r} = \frac{e^2}{8\pi\varepsilon_0 (R-r)}$. When the particle moves to the detector's internal sphere the first two components of total energy increase, and the last one reduces. Therefore the particle's motion in the drift room can be considered as two different stages.

1. Deceleration of the ion in the field of the charge induced by it on the surface of the exterior sphere.
2. Deceleration of the ion in the field of the detector.

Using such method the first equation of the Eq.20 can be converted to

$$t = t_1 + t_2 = \int_{r_{\min}}^{r_0} \frac{dr}{\sqrt{\frac{2}{m_i}\left(W - \frac{\delta_1}{r}\right) - \frac{L^2}{m_i r^2}}} + \int_{r_0}^{R} \frac{dr}{\sqrt{\frac{2}{m_i}\left(W - \frac{\delta_2}{r}\right)}}, \quad (21)$$

where the magnitudes δ_1, δ_2 are determined as the similar magnitudes in Eq.13; coordinate r_{min} is a minimum distance the particle comes towards the center of the inner shell, and it can be derived from the following equation

$$\frac{m_i \cdot V_0^2}{2} - \frac{\delta_1}{r_{\min}} - \frac{\delta_2}{R - r_{\min}} - \frac{L^2}{m_i r_{\min}^2} = 0, \quad (22)$$

Coordinate r_0 is the maximal value $r_0 = \max\{r_0', r_0''\}$ for a system

$$\begin{cases} \frac{\delta_1}{r_0'} = \frac{\delta_2}{R - r_0'}; r_{\min} \le r_0 \le R \\ \frac{L^2}{m_i (r'')^2} = \frac{\delta_2}{R - r_0''}; \end{cases} \quad (23)$$

The solution of Eq.21 has less accuracy of measurement of flight time but it has more simple form than strict solution derived from Eq.20. After a series of transforms we have

$$t = t_1 + t_2,$$

$$t_1 = \frac{\sqrt{2m_i W \cdot (r_0 - r_{\min})^2 - 2\delta_1 m_i (r_0 - r_{\min}) - L^2}}{2W} + \frac{\delta_1}{2} \cdot \sqrt{\frac{m_i}{2W^3}} \times$$

$$\times \ln\left[\frac{\sqrt{\frac{2}{m_i W}} \cdot (2m_i r_0 W - m_i \delta_1) + 2\sqrt{2m_i W \cdot r_0^2 - 2\delta_1 m_i r_0 - L^2}}{\sqrt{\frac{2}{m_i W}} \cdot (2m_i r_{\min} W - m_i \delta_1) + 2\sqrt{2m_i W \cdot r_{\min}^2 - 2\delta_1 m_i r_{\min} - L^2}}\right];$$

$$t_2 = \frac{\sqrt{2m_i W \cdot (R - r_0)^2 - 2\delta_2 m_i (R - r_0)}}{2W} - \frac{\delta_2}{2} \sqrt{\frac{m_i^3}{2W^3}} \times$$

$$\times \ln\left[\frac{\sqrt{|m\delta_2|}}{\sqrt{2W(R - r_0)} + \sqrt{2W(R - r_0) - m\delta_2}}\right] \quad (24)$$

The Eq.24 allows to study detector's resolution capability in a mode of space particle element composition measurement. Variation of the voltage U applied between spheres enables to transfer a maxima of a curve $R_C = f(m_i)$ in broad enough range of element masses the natural or artificial space particle contains of.

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