Dusty plasmas at the Moon: Effects of magnetic fields

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Abstract. Processes associated with the presence of magnetic fields, which can be important in dusty plasmas on the Moon, are considered. Lower-hybrid wave processes under interaction of the magnetotail of the Earth with dusty plasma near the surface of the Moon are described. Lower-hybrid waves are excited due to the relative motion of magnetospheric ions and charged dust grains, which leads to the establishment of a well developed lower hybrid plasma turbulence. The effective collision frequency characterizing the anomalous loss of ion momentum due to ion-wave interaction, as well as the electric fields arising in the system are found. It is shown that the electric fields excited due to the development of lower-hybrid turbulence are somewhat weaker than those arising due to the charging of the lunar surface under the action of solar radiation. Nevertheless, they are quite significant to affect the electric field pattern above the Moon. The obtained effective collision frequencies should be taken into account when deriving hydrodynamic equations for dusty plasma ions with allowance for their turbulent heating. Problems related to the consideration of magnetic fields, which can be important for detailed study of the dusty plasmas at the Moon, are stated. The possibility of generation of wave motions in the near-surface lunar plasma should be taken into consideration when interpreting the observational data.

1. Introduction

Investigation of the properties and manifestations of dusty plasmas near the lunar surface and in the lunar exosphere is currently playing an important role in space exploration [1]. The Luna-25, Luna-26, and Luna-27 missions are being prepared in Russia. It is planned to mount an apparatus on the landing modules of the Luna-25 and Luna-27 space stations that would directly detect dust grains above the lunar surface and conduct optical measurements. The orbiter, Luna-26, is also supposed to be equipped with devices for detection of dust particles in the lunar exosphere. During the recent mission LADEE (Lunar Atmosphere and Dust Environment Explorer) [2], the lunar dust was studied by means of observation from the orbit.

Therefore, at present, there is great interest in the description of a dusty plasma system near the surface of the Moon [1,3–27]. It is assumed that the surface of the Moon gets charged under the action of solar electromagnetic radiation, solar wind plasma, and plasma of the magnetotail of the Earth. As a result of interaction with solar radiation, the lunar surface emits electrons due to the photoelectric effect, which leads to the formation of a layer of photoelectrons above the
surface. Photoelectrons are also emitted by the dust grains levitating above the lunar surface as a result of their interaction with solar electromagnetic radiation. The dust grains on the lunar surface or in the near-surface layer absorb photoelectrons, photons of solar radiation, electrons and ions of the solar wind, and electrons and ions of the magnetospheric plasma when the Moon crosses the magnetotail of the Earth. All these processes lead to the charging of dust grains, their interaction with the charged lunar surface, and motion and elevation of dust.

The dusty plasma on the Moon has been studied without taking into account magnetic fields that might actually exist. Indeed, about one-fourth of the orbit of the Moon lies within the magnetotail of the Earth. The tail contains very rarefied plasma in the wings of the geomagnetic tail, along with denser and hotter plasma in the plasma sheath. The typical magnetic fields in the magnetotail are from $\sim 10^{-5}$ to $\sim 10^{-4}$ G [28, 29].

In addition, the Moon contains areas of crustal magnetic fields known as magnetic anomaly areas. The surface fields measured by Apollo 12, 14, 15, and 16 magnetometers were $3.8 \times 10^{-4}$, $1.03 \times 10^{-3}$, $3 \times 10^{-5}$, and $3.27 \times 10^{-3}$ G, respectively [30]. While the Apollo landing sites were all on the lunar near side, satellite observations showed that the largest and strongest magnetic fields, responsible for most of the solar wind limb disturbances were located on the lunar far side (e.g., [31]).

The characteristic size and number density of charged dust grains above the lunar surface are about 100 nm and $10^3$ cm$^{-3}$, respectively. For such dusty plasma parameters the values of the dust plasma frequency $\omega_{pd}$ and of the ion gyrofrequency $\omega_{Bi}$ are of the same order of magnitude ($\sim 1$ s$^{-1}$ for the magnetic field $B \sim 10^{-4}$ G). Thus some dusty plasma processes at the Moon are determined by the influence of the magnetic fields. Here, we discuss processes related to the presence of the magnetic fields which can be important in dusty plasmas at the Moon.

2. Lunar dusty plasma parameters

The near-Moon dusty plasma in the region where the lunar surface interacts with the magnetotail plasma was recently discussed in detail in [32]. The Moon and the near-Moon plasma move relative to the magnetotail plasma with a velocity of about 1 km s$^{-1}$. Moreover, during geomagnetic storms and substorms, particles with energies of about 10 keV trapped in the radiation belts can penetrate the magnetotail [33, 34], thereby forming charged particle fluxes in the latter. All this indicates the possibility of the development of plasma instabilities in the regions where the lunar surface interacts with the magnetotail plasma, which underscores the importance of investigation of the wave processes in these regions.

The plasma under study is composed of magnetospheric electrons and ions, electrons and ions of the solar wind, charged dust grains, and photoelectrons formed as a result of photoelectric effect from the lunar surface and the dust grains levitating above the latter. Let us describe characteristic parameters of the dusty plasma that will be used in the subsequent calculations.

To determine the density and temperature of plasma in the solar wind and magnetosphere near the Moon, we will use the data collected by ARTEMIS P2 spacecraft (orbiting the Moon since 2011) between January 22 and January 31, 2013, when the Moon was passing through the magnetotail [17, 20]. It can be seen that the electron ($n_e$) and ion ($n_i$) number densities measured during this passage drop by two to three orders of magnitude in the magnetotail relative to those in the solar wind ($n_{eS} \approx n_{iS} \sim 10$ cm$^{-3}$), while the ion temperature $T_i$ increases from several tens of eV to about 1000 eV and the electron temperature $T_e$ increases from about 10 eV to several hundred eV. Here, index $S$ refers to the solar wind plasma. Higher values of the electron temperature (up to 2 keV) can be observed in the plasma sheath, while lower ion temperatures down to $T_{iS} \approx 6$ eV were detected in the solar wind. In the situation in which the velocity $\mathbf{u}$ of the dusty plasma flow near the surface of the Moon relative to the magnetotail plasma is determined by the velocity of the Moon relative to the magnetotail, the absolute value of this velocity $u = |\mathbf{u}|$ is about 1 km s$^{-1}$. However, it should be taken into consideration that,
Table 1. Parameters of photoelectrons in the near-surface layer of the illuminated part of the Moon for different levels of the solar activity and different values of the quantum yield.

|     | A                        | B                        | C                        |
|-----|--------------------------|--------------------------|--------------------------|
| $n_{e(ph)Y1}$, cm$^{-3}$ | $2.2 \times 10^5$        | $2.1 \times 10^5$        | $1.9 \times 10^5$        |
| $T_{e(ph)Y1}$, eV     | 0.2                      | 0.1                      | 0.1                      |
| $n_{e(ph)Y2}$, cm$^{-3}$ | $8.6 \times 10^2$        | $2.9 \times 10^2$        | $1.3 \times 10^2$        |
| $T_{e(ph)Y2}$, eV     | 2.1                      | 1.9                      | 1.3                      |

As to the parameters of the charged dust, according to the results of [7], the characteristic size $a$ and characteristic number density $n_d$ of charged dust grains in the near-surface layer of the illuminated part of the Moon are about 100 nm and $10^3$ cm$^{-3}$, respectively. The high value of the dust density is related to the high density of photoelectrons above the Moon (including the photoelectrons produced by solar radiation photons from the surface of the levitating dust grains). There are no photoelectrons above the dark part of the Moon. The number density of the charged dust can be estimated from the relation

$$n_d \sim n_{eS}/|Z_d|,$$

where $n_{eS}$ is the density of the photoelectrons generated by the solar wind, $Z_d$ is the charge number of a dust grain (here, $q_d = -|Z_d|e$ is the dust grain charge and $-e$ is the electron charge). The number density $n_d$ of dust grains with a size of about 100 nm above the dark part of the Moon is estimated to be from $\sim 10^{-2}$ to $\sim 10^{-1}$ cm$^{-3}$ [16].

The situation in which the quantum yield of the Moon regolith is determined by the data of [35] (i.e., the parameters of photoelectrons are characterized by the values shown in the upper part of table 1) was analyzed in [7]. When the quantum yield of the Moon regolith is determined by the data of [36], the following expression similar to equation (1) can be used to estimate the dust density:

$$n_d \sim n_{e(ph)}/|Z_d|.$$
3. Lower-hybrid turbulence

When considering wave processes, the influence of the magnetic fields is important if at least one species of dusty plasma particles is magnetized. For not very slow processes with characteristic time scales \( \tau \ll \omega_{\text{pd}}^{-1} \), this can be realized only for electrons (because \( \omega_{\text{Bi}} \sim \omega_{\text{pd}} \)). Thus we study the situation when electrons are magnetized while ions and dust particles are not magnetized, and assume that the following inequalities are valid \( \omega_{\text{Bd}} \ll \omega_{\text{Bi}} \ll \omega \ll \omega_{\text{Be}} \); \( |k|vT_i \gg \omega_{\text{Bi}}; |k|vTe \ll \omega_{\text{Be}} \). Here, \( \omega_{\text{Bd}} \) and \( \omega_{\text{Be}} \) are dust and electron gyrofrequencies, \( k \) is the wave vector, \( v_{\text{T}a} \) is the thermal velocity of the particles of the kind \( a \). The subscripts \( e, i, d \) stand for electrons, ions, and dust particles, respectively. Furthermore, in most of the regions where magnetic fields at the Moon are present, for plasma parameters described in the previous section the following relationships are fulfilled \( \omega_{\text{pd}} \sim \omega_{\text{Bi}} \ll \omega_{\text{ph}} \sim \omega_{\text{Be}} \ll \omega_{\text{peM}} \sim \omega_{\text{peS}} \ll \omega_{\text{pe(ph)}} \), where index \( M \) corresponds to the magnetospheric plasma, \( \omega_{\text{peM(S)}} \) is the plasma frequency of magnetosphere (solar wind) electrons while \( \omega_{\text{pe(ph)}} \) is the plasma frequency of photoelectrons; \( \omega_{\text{phM(S)}} \) is the plasma frequency of magnetosphere (solar wind) ions. Below in this section we suppose that the relationships presented in this paragraph are satisfied.

3.1. Hydrodynamic instability

For electrostatic perturbations, the case of \( \omega_{\text{Bi}} \ll \omega \ll \omega_{\text{Be}} \) corresponds to the so-called lower-hybrid waves [37]. Let us study a possibility of excitation of lower-hybrid turbulence in dusty plasmas at the Moon.

The simplest instability resulting in excitation of the lower-hybrid waves is hydrodynamic instability of the Buneman type [38] described by the linear dispersion equation (in the frame of reference related to the magnetospheric plasma) which has the form

\[
1 + \frac{\omega_{\text{ph}}^2 + \omega_{\text{pe(ph)}}^2}{\omega_{\text{Be}}^2} \sin^2 \Theta - \frac{\omega_{\text{phM}}^2 + \omega_{\text{peM}}^2 \cos^2 \Theta}{\omega^2} - \frac{\omega_{\text{pd}}^2}{(\omega - k \cdot u)^2} - \frac{\omega_{\text{pe(ph)}}^2 \cos^2 \Theta}{(\omega - k || u ||)^2} = 0, \tag{3}
\]

where \( k || \) is the wave vector component parallel to the external magnetic field, \( \cos \Theta = k || / |k| \).

Let us consider the situation inherent for the lower-hybrid waves [37], when \( \cos \Theta \ll 1 \) and \( |k || u || | \ll |k \cdot u| \). In this situation, as it will be shown below, the solution of equation (3) is \( \omega \approx k \cdot u \). Thus for typical dusty plasma parameters dispersion relation (3) can be written in the form

\[
1 + \frac{\omega_{\text{ph}}^2}{\omega_{\text{Be}}^2} - \frac{\omega_{\text{phM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta}{\omega^2} - \frac{\omega_{\text{pd}}^2}{(\omega - k \cdot u)^2} = 0. \tag{4}
\]

Dispersion relation (4) has unstable solutions. Instability results in the excitation of longitudinal electrostatic plasma oscillations with the growth rate on the order of the dust plasma frequency. Indeed, let us recast dispersion relation (4) in the form

\[
1 - \frac{\omega_{\text{ph}}^2}{\left(1 + \frac{\omega_{\text{ph}}^2}{\omega_{\text{Be}}^2}\right)} \omega^2 - \frac{\omega_{\text{phM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta}{\omega^2} - \frac{\omega_{\text{pd}}^2}{(\omega - k \cdot u)^2} = 0. \tag{5}
\]

We have

\[
\omega_{\text{pd}}^2 \left( \omega_{\text{phM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta \right) \leq \frac{\omega_{\text{pd}}^2}{\omega_{\text{phM}}^2} \leq \frac{nM}{mM} m_i = 0, \tag{6}
\]

where \( m_i(d) \) is the ion (dust grain) mass. Since \( n_d Z_d^2 m_i / nM nM d \ll 1 \), the contribution of the third term on the left-hand side of equation (5) is significant only at values \( k \cdot u \) sufficiently close to \( \omega \). The maximum value of the instability growth rate can be found by using the method
described in [39], according to which
\[ \omega = \sqrt{\omega_{\text{piM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta} + \delta \omega \equiv \omega_{\text{LH}}(\cos \Theta) + \delta \omega \quad \text{if} \quad \delta \omega \ll \omega_{\text{LH}}(\cos \Theta), \quad (7) \]
\[ \omega = k \cdot u + \delta \omega \quad \text{if} \quad \delta \omega \ll |k \cdot u|. \quad (8) \]

Thus, assuming that
\[ \omega_{\text{LH}}(\cos \Theta) \approx k \cdot u, \quad (9) \]
we obtain the cubic equation
\[ \frac{2\delta \omega}{\omega_{\text{LH}}(\cos \Theta)} - \frac{\omega_{\text{LH}}^2(\cos \Theta)}{(\delta \omega)^2} \frac{\omega_{\text{pd}}^2}{\omega_{\text{piM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta} = 0, \quad (10) \]
which has an unstable solution with the growth rate
\[ \gamma_{\text{Hydro}}^{\text{max}} = \frac{3}{24/3} \frac{\omega_{\text{LH}}(\cos \Theta)}{\left( \frac{\omega_{\text{pd}}^2}{\omega_{\text{piM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta} \right)^{1/3}} \]
\[ = \frac{\sqrt{3}}{24/3} \frac{\omega_{\text{pd}}}{\sqrt{1 + \omega_{\text{pe(ph)}}^2 / \omega_{\text{Be}}^2}} \left( \frac{\omega_{\text{piM}}^2 + \omega_{\text{pe(ph)}}^2 \cos^2 \Theta}{\omega_{\text{pd}}^2} \right)^{1/6}. \quad (11) \]

Dispersion relation (7) is typical of the lower-hybrid waves. Because of the presence of the exponent 1/6 in the last multiplier on the right-hand side of equation (11), we can assume that, typical dusty plasma parameters, the growth rate of the discussed waves in the region of Moon interaction with the magnetosphere of the Earth is determined by the dust plasma frequency \( \omega_{\text{pd}} \).

Let us estimate the typical instability growth time
\[ \tau = 1/\gamma_{\text{Hydro}}^{\text{max}} \quad (12) \]
in the transition or boundary layers of the magnetosphere for \( u \sim 1 \text{ km s}^{-1} \) and the parameters of photoelectrons corresponding to the lower part of table 1, i.e., for the quantum yield of the Moon regolith adapted from [36]. In this case, we have \( |B| \sim 10^{-4} \text{ G}, a \sim 100 \text{ nm}, |Z_a| \sim 10, n_q \sim 10 \text{ cm}^{-3}, n_{\text{iM}} \sim 10 \text{ cm}^{-3}, m_d \sim 10^{-14} \text{ g}, \cos \Theta \sim \omega_{\text{piM}} / \omega_{\text{pe(ph)}}, \) and \( n_{\text{e(ph)}} \sim 10^2 \text{ m}^{-3} \), while the typical instability growth time \( \tau \) is about 30 s. Thus, the time \( t_{\text{II}} \sim 10 \text{ h} \) during which the dusty plasma interacts with the regions of the magnetic transition or boundary layers of the magnetosphere is sufficient for the generation of the lower-hybrid waves due to hydrodynamic instability. Moreover, since \( t_{\text{II}} \gg \tau \), efficient nonlinear processes can be expected.

### 3.2. Nonlinear processes

Dispersion relation (5) shows that the development of the hydrodynamic instability is caused by the relative motion of magnetospheric ions and charged dust grains (this is especially noticeable for the case when \( \cos \Theta \lesssim \omega_{\text{piM}} / \omega_{\text{pe(ph)}} \) when the significance of the magnetosphere ions is more important than that of photoelectrons). Thus, the following scheme of the development of plasma turbulence is suggested. The magnetospheric plasma ions excite the lower-hybrid waves due to the hydrodynamic instability. As a result, similar to the problem on the anomalous plasma resistance [40], an anomalous loss of the ion momentum takes place. In the saturated state achieved when the growth of the instability becomes limited by nonlinear processes, plasma experiences turbulent heating the nature of which is determined by the turbulence caused by the instability. Turbulent heating is different for the ion and dust components.
To find the effective collision frequency $\nu_{eff}$, which characterizes the anomalous loss of the ion momentum, we use the momentum conservation law in the “magnetospheric ions + lower-hybrid waves” system with taking into account that the ions are not magnetized. The average loss of momentum by ions per unit time is

$$\nu_{eff} m_i n_i M_u \approx -F. \quad (13)$$

Here, $F$ is the drag force acting on the ions due to their interaction with the lower-hybrid waves. If momentum (13) is transferred to the waves characterized by the energy density $W$, the change in the wave momentum is given by

$$\int \gamma_k W_k \frac{k}{\omega_k} dk, \quad (14)$$

Equating expressions (13) and (14), we have

$$\nu_{eff} m_i n_i M_u \approx \int \gamma_k W_k \frac{k}{\omega_k} dk. \quad (16)$$

Thus, we find that

$$\nu_{eff} \approx \frac{1}{m_i n_i M_u} \left| \int \gamma_k W_k \frac{k}{\omega_k} dk \right|. \quad (17)$$

Thus, knowing $\gamma_k$ and $\omega_k$, we need to determine $\nu_{eff}$ to find $W_k$. To this end, we need to analyze the nonlinear processes.

Knowing the value $\nu_{eff}$ allows us to determine the plasma conductivity and the characteristic electric fields arising upon wave propagation, as well as to write the hydrodynamic equations for ions with allowance for turbulent plasma heating. The condition under which the dissipative effects caused by turbulent plasma heating dominate over those caused by the interaction of electrons and ions with dust grains has the form

$$\nu_{eff} \gg \tilde{\nu}, \quad (18)$$

where $\tilde{\nu}$ characterizes the dissipative processes caused by the interaction of plasma particles with the charged dust grains in the hydrodynamic equation for ions describing the transfer of momentum. In the case of negatively charged dust grains, the expression for $\tilde{\nu}$ takes the form [41]

$$\tilde{\nu} = \nu_q \frac{Z_d n_d/n_e}{(1 + Z_d n_d/n_e) z [1 + (T_i/T_e) + z]} \left( z + \frac{4 T_i/T_e}{3} + \frac{2 z^2}{3 T_i/T_e} \Lambda \right), \quad (19)$$

where $\nu_q$ is the frequency of the dust grain charging given by

$$\nu_q = \frac{\omega_p^2 a [1 + (T_i/T_e) + z]}{\sqrt{2\pi v_{Ti}}}, \quad (20)$$

$z = Z_d e^2/a T_e$, $\Lambda = \ln (\lambda_D i/\max \{a, b\})$ is the Coulomb logarithm, $\lambda_D i$ is the ion Debye length, and $b \approx Z_d e^2/T_i$. When dust grains are charged positively, the dissipative processes caused by the interaction of positively charged ions with charged grains are substantially weaker than in the case of negatively charged dust grains [42], i.e., the value of $\tilde{\nu}$ in this situation is much smaller than that determined by formula (19).

The case in which the lower-hybrid waves are excited due to hydrodynamic instability should be analyzed in terms of strong turbulence. The existing theories of strong turbulence can be
used only for estimates. For the hydrodynamic instability under consideration, such an estimate can be obtained as follows.

From expressions (17) and (11), we find that

$$\nu_{\text{eff}} \sim \frac{1}{m_i m_i M_u} \frac{\omega_{pd}^{2/3} \omega_{\text{LH}}^{1/3} (\cos \Theta)}{\left(1 + \omega_{\text{pe(ph)}}^2 / \omega_{\text{Be}}^2\right)^{1/3} [\omega_{\text{LH}}(\cos \Theta) / k]_c h},$$

(21)

where $[\omega_{\text{LH}}(\cos \Theta) / k]_c h$ is the characteristic value of $\omega_{\text{LH}}(\cos \Theta) / k$ in the wave spectrum. The energy density of the oscillations satisfies the relation $W \lesssim \varepsilon_d$, where $\varepsilon_d$ is the kinetic energy density of dust grains.

In the course of turbulent heating, the ion temperature grows faster than the temperature of dust grains. Using the momentum and energy conservation laws, let us find the relation between the work of the drag force $F$ and the ion energy density $\varepsilon_i$ upon interaction of ions and dust grains with oscillations. The work of the drag force $F \approx -\nu_{\text{eff}} m_i m_i M_u$ is spent on the heating of plasma ions,

$$\frac{d\varepsilon_i}{dt} \sim \nu_{\text{eff}} m_i m_i M_u u^2 \approx \int \gamma_k W_k \frac{(k \cdot u)}{\omega_k} dk.$$

(22)

In a state of saturation, which is reached when the nonlinear effects limit the growth of instability, the momentum and energy of oscillations are transferred to charged dust grains. Thus, in the saturation state, the dust grains absorb the oscillation energy at the rate

$$\frac{d\varepsilon_d}{dt} \sim \int \gamma_k W_k dk.$$

(23)

Relations (22) and (23) yield

$$\frac{d\varepsilon_i}{d\varepsilon_d} \sim \int \gamma_k W_k \frac{(k \cdot u)}{\omega_k} dk \int \gamma_k W_k dk \sim \frac{u}{\omega_{\text{LH}}(\cos \Theta) / k}.$$

(24)

Using relation (24), we obtain the following estimate for $\varepsilon_d$:

$$\varepsilon_d \sim \frac{\varepsilon_i}{u} \left[\frac{\omega_{\text{LH}}(\cos \Theta)}{k}\right]_c h.$$

(25)

Substituting $\varepsilon_d$ for $W$ into (21) and using $\varepsilon_i \sim m_i m_i M_u^2 / 2$, where $v_{\text{IM}}$ is the magnetosphere ion thermal velocity, we find

$$\nu_{\text{eff}} \sim \frac{\omega_{pd}^{2/3} \omega_{\text{LH}}^{1/3} (\cos \Theta)}{\left(1 + \omega_{\text{pe(ph)}}^2 / \omega_{\text{Be}}^2\right)^{1/3} u^2}.$$

(26)

Under conditions typical for the magnetic transition or boundary layers of the magnetosphere ($|B| \sim 10^{-4}$ G, $a \sim 100$ nm, $u \sim 1$ km/s, $|Z_d| \sim 10$, $n_d \sim 10$ cm$^{-3}$, $n_i \sim 10$ cm$^{-3}$, $m_d \sim 10^{-14}$ g, $T_{\text{IM}} \sim 100$ eV, $\cos \Theta \sim \omega_{\text{plIM}} / \omega_{\text{pe(ph)}}$, and $n_{\text{e(ph)}} \sim 10^2$ cm$^{-3}$), where lower-hybrid turbulence can develop due to hydrodynamic instability, condition (18) can easily be satisfied. Thus, in the situation under study, the effects caused by plasma heating prevail over those caused by the interaction of plasma ions with dust grains and the dissipative properties of the system in the equation for the ion momentum transfer are mainly determined by the frequency $\nu_{\text{eff}}$.

Using the condition $eE \sim \nu_{\text{eff}} m_i u$, we find that the characteristic electric field strength $E$ arising in the dusty plasma due to the development of lower-hybrid turbulence is

$$E \sim \frac{\omega_{pd}^{2/3} \omega_{\text{LH}}^{1/3} (\cos \Theta)}{\left(1 + \omega_{\text{pe(ph)}}^2 / \omega_{\text{Be}}^2\right)^{1/3} e u}.$$

(27)
Calculations by (27) for $|\mathbf{B}| \sim 10^{-4}$ G, $a \sim 100$ nm, $u \sim 1$ km s$^{-1}$, $|Z_d| \sim 10$, $n_d \sim 10$ cm$^{-3}$, $n_{iM} \sim 10$ cm$^{-3}$, $m_d \sim 10^{-14}$ g, $T_{iM} \sim 100$ eV, $\cos \Theta \sim \omega_{piM}/\omega_{pe(ph)}$, and $n_{e(ph)} \sim 10^2$ cm$^{-3}$ show that electric fields with an amplitude of $E \sim 0.1$ V m$^{-1}$ can be induced in the dusty plasma system near the Moon in the presence of lower-hybrid turbulence. This value is somewhat lower than the field $E \sim 1$ V m$^{-1}$ [7], excited near the lunar surface due to its charging in the interaction with solar radiation. Nevertheless, the electric fields excited due to the development of lower-hybrid turbulence can affect the electric field pattern above the lunar surface, because the electric field arising due to the interaction of solar radiation with the lunar surface decreases with increasing altitude.

4. Unsolved problems

So, from the above description, some features of dusty plasma on the Moon in the presence of magnetic fields are clarified. However, the problems associated with exposure to magnetic fields remain unresolved. Here we outline some of such problems which can be important for detailed study of the dusty plasmas at the Moon.

4.1. Magnetic reconnection

Reconnection of interplanetary and terrestrial magnetic field lines is an important element in the magnetosphere of the Earth, both on the dayside magnetopause and in the magnetotail. One of the expected signatures of the merging process is the acceleration of plasma away from the reconnection site on recently merged field lines [43, 44]. Reconnection in the magnetosphere of the Earth extends from regions situated at most a few Earth radii ($R_E$) to many tens or hundreds of $R_E$ [45]. Thus the Moon is situated in the region, where magnetic reconnection can occur, and plasma turbulence existing in the region of interaction of the magnetotail of the Earth with the Moon can influence the character of magnetic reconnection.

When two magnetic field lines with opposite directions come close together in a dissipative medium reconnection is possible [39]. The fact that the magnetic field depends on position means the presence of a current, its field changes the magnetic field from a value $\mathbf{B}$ on one side of the layer, where the reconnection takes place to $-\mathbf{B}$ on the other side. The rate of magnetic reconnection depends strongly on the presence of anomalous dissipative processes related to $\nu_{\text{eff}}$, in particular, to the anomalous resistivity. If the resistivity is anomalous, then the rate of magnetic reconnection increases by several orders of magnitude in comparison with the classical collision-dominated electrical conductivity. The reconnection may occur not only for field lines which are exactly directed in opposite directions, but also in the case when only some of the components of the magnetic field are directed in opposite directions.

The typical model for describing the reconnection is Parker–Sweet diffusion model [46, 47] modified to allow for the anomalous dissipation. In this model, the reconnection is considered as a result of mutual diffusion of magnetic fields in the magnetosphere of the Earth, which are assumed to be opposite directed. The width of the transient layer of the reconnection zone is determined by the following expression:

$$
 d \approx \frac{c}{\omega_{pe}} \sqrt{\frac{L \nu_{\text{eff}}}{v_A}},
$$

(28)

where $L$ is the characteristic inhomogeneity scale along the direction of the transient layer and $v_A$ is the Alfvén velocity. The magnitude of $L$ is typically from 5$R_E$ to 10$R_E$. For the ion-acoustic turbulence [23] developed over the night side lunar surface in the magnetotail lobes ($u \sim 10$ km s$^{-1}$, $a \sim 100$ nm, $|Z_d| \sim 10$, $n_d \sim 10^{-3}$ cm$^{-3}$, $n_{eM} \sim n_{IM} \sim 0.01$ cm$^{-3}$, $m_d \sim 10^{-14}$ g, and $T_{iM} \sim T_{iM} \sim 100$ eV) assuming that $L = 5R_E$ and geomagnetic field $|\mathbf{B}| \approx (4-5) \times 10^{-4}$ G, we find $d \sim 1$ km.
The above estimates relate to the influence of the lunar dusty plasma on the reconnection of the geomagnetic field lines. A model should be developed which will allow us to describe the reconnection of geomagnetic field lines, to determine its mechanism and the structure of the reconnection zone. Furthermore, an interesting problem, which should be studied in the future, is to consider the effects on reconnection of the geomagnetic field with the lunar crustal magnetic field. Since the crustal magnetic fields are widely and non-uniformly distributed over the lunar surface [30, 48], the anti-parallel magnetic field geometry would be present at many locations near the magnetized lunar surface for a given background magnetic field.

4.2. Electromagnetic ion cyclotron waves and other kinds of nonpotential waves

Here we investigated electrostatic waves associated with magnetic fields in dusty plasmas on the Moon. However, on the Moon, narrowband electromagnetic ion cyclotron waves with frequencies ranging from 0.04 to 0.17 Hz were found [49] in the magnetic field data obtained by the Apollo 15 and 16 Lunar Surface Magnetometers in 1972, only when the Moon was in the magnetotail of the Earth. The frequency was slightly lower than the proton gyrofrequency of the ambient plasma, and the polarization was left handed with respect to the background magnetic field. ARTEMIS P1 probe also detected similar waves at a lunar flyby in the magnetosphere of the Earth [50]. The problem is to study whether the electromagnetic ion cyclotron waves can be generated in lunar dusty plasmas. Moreover the problem of interest is to investigate other kinds of nonpotential or electrodynamic waves which can be excited in dusty plasmas at the Moon.

5. Conclusions

In this work, we have discussed some processes related to the presence of magnetic fields which can be important in dusty plasmas at the Moon. One-fourth of the orbit of the Moon lies within the magnetotail of the Earth. The typical magnetic fields in the magnetotail are from $\sim 10^{-5}$ to $10^{-4}$ G. The Moon possesses also regions of crustal magnetic fields, known as magnetic anomaly regions. We have described the lower-hybrid wave processes under interaction of the magnetotail of the Earth with dusty plasma near the surface of the Moon. The lower-hybrid waves can be excited in the regions of the transient or boundary magnetospheric layers. The instability develops due to the relative motion of magnetospheric ions and charged dust grains. Due to the relatively long growth time of the instability, well-developed lower-hybrid plasma turbulence has time to be established. We have found the effective collision frequency characterizing the anomalous loss of ion momentum due to ion-wave interaction, as well as the electric fields arising in the system. It is shown that the electric fields excited due to the development of lower-hybrid turbulence are somewhat weaker than those arising due to the charging of the lunar surface under the action of solar radiation. Nevertheless, they are quite significant to affect the electric field pattern above the Moon. The obtained effective collision frequencies should be taken into account when deriving hydrodynamic equations for dusty plasma ions with allowance for their turbulent heating.

Furthermore, in spite of rather long history of investigations of the lunar dusty plasma, there are unsolved problems concerning effects of magnetic fields. Here, we have outlined some of the problems, where the consideration of magnetic fields is of interest, which can be important for detailed study of the dusty plasmas at the Moon.

The wave motions (or any their manifestations) in the region of interaction of the magnetotail of the Earth with the dusty plasma near the lunar surface can be detected by means of apparatuses that are planned to be installed on the Luna-25, Luna-26, and Luna-27 lunar modules. For instance, among the remote sensors installed on these spacecrafts, there will be a Langmuir probe capable of measuring local fluctuations of the plasma density and potential. On the other hand, the possibility of generation of wave motions in the near-surface lunar plasma
should be taken into consideration when processing the current-voltage characteristic of the Langmuir probe and interpreting the observational data.

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