OBSERVATIONAL CONSEQUENCES OF BARYONIC GASEOUS DARK MATTER

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Abstract. Possible observational consequences of dark matter in the Galaxy in the form of dense molecular gas clouds – clumpuscules of masses $M_c \sim 10^{-3} \, M_\odot$ and radii $R_c \sim 3 \times 10^{13}$ cm – are considered. Recent models of the extreme scattering events – refraction of radio-waves from quasars in dense plasma clumps in the Galactic halo – definitely show on such clouds as possible dark matter candidate. We argue that collisions of such clumpuscules are quite frequent: around $1-10 \, M_\odot$ a year can be ejected in the interstellar medium due to collisions. Optical continuum and 21 cm emissions from post-collisional gas are found to be observable. We show that clumpuscules can form around O stars HII regions of sizes $R \sim 30$ pc and emission measure $EM \simeq 20$ cm$^{-6}$ pc, and can also be observable in $H\alpha$ emission. Evaporation of clumpuscules by external ionizing radiation can be a substantial mass source. From requirement that the total mass input on the Hubble time cannot exceed the luminous mass in the Galaxy, typical radius of clouds is constrained as $R_c < 3.5 \times 10^{12}$ cm, and their contribution to surface mass density as $50 \, M_\odot$ pc$^{-2}$. It is argued that dissipation of kinetic energy of the gas ejected by such clouds can be an efficient energy source for the Galactic halo.
1. Introduction

Baryon dark matter has been supported observationally when microlensing events by massive compact halo objects (MACHOs) were detected [1–3]. The nature of MACHOs remains still unclear, although from general point of view stars of small masses, $M \sim 10^{-3} M_\odot$ (brown dwarfs, called often “jupiters”) can provide gravitational lensing with observed characteristics, and on the other hand, being below the limit of hydrogen burning, they have too low luminosity to be seen. It is quite possible that microlensing events with observed frequency can be connected also with red dwarfs ($M \gtrsim 0.08 M_\odot$) with total mass exceeding the mass of luminous matter in the Galaxy [4].

Recently dense atomic and molecular clouds, confined by external pressure or self-gravity, are discussed as an alternative possible reservoir of dark matter [5–14]. Contrary to brown dwarfs these clouds are assumingly cold (from 3 K [6] to 10 K [14]) and have negligible proper luminosity and are unseen even in infrared, their column densities are predicted to reach $\sim 3 \times 10^{23}$ [11, 12] to $10^{25}$ cm$^{-2}$ [13], and they are optically thick in 21 cm. From this point of view dark matter gas clouds are notoriously hard to detect.

In [7] $\gamma$-radiation from interaction of cosmic rays with nuclei of dark matter molecular clouds has been estimated and suggested to test the presence of such clouds in the galactic halo. Very recently statistical evidences for a large scale anisotropic excess in $\gamma$-rays were presented [15], with the flux above 1 GeV close to the one predicted in [7]. This can be considered in support of dark mass in the form of dense cold gas.

Additional evidences for the existence of dark matter gas clouds are connected with optical (non-gravitational) lensing of radio emission from quasars passing through atmospheres of ionized gas surrounding such clouds. Ten years ago dramatic short variations of fluxes (of several weeks to months duration) from compact radio quasars were discovered at wavelengths 3.7 and 11 cm – the so-called extreme scattering events [16]. The origin of these variations was attributed to refraction by dense plasma clouds moving perpendicularly to the line of sight [16, 17]. From variations of radio fluxes lensing clouds are inferred to have characteristic sizes of a few AU and electron densities of $n_e \simeq 10^3$ cm$^{-3}$. The internal gas pressure $n_e T_e \gtrsim 10^7$ K cm$^{-3}$ exceeds pressure in the surrounding gas by 3-4 orders of magnitude, and therefore refracting plasma clouds must be transient structures of several months life time, which is far from being enough to explain observed frequency of the extreme scattering events [16, 17]. Only
recently this difficulty has found a solution [18] with the assumption that lensing plasma can be connected with extended HII atmospheres around cool dense self-gravitating molecular clouds as was suggested in [9]. In the framework of this model high interior pressure provides steady outflow of ionized gas from the HII cloud atmosphere, and thus the density distribution in lensing plasma regions is kept time-independent. The individual cloud masses are high enough to support photoionization mass outflow on galactic time scales. In [18] these clouds were identified with the dense molecular clumpuscules described in [5, 6]. This allowed the authors to reproduce with good accuracy the dual-wavelength (3.7 and 11 cm) light-curve of the quasar 0954+658, while all the previous models had difficulties with reproducing this. Quite recently, the idea that such dense molecular clouds contribute significantly to dark matter has obtained further support: it was shown that they act as gaseous (non-gravitational) lenses for stellar light, which in turn can result in the observed excess of microlensing events, compared to the expected from stars and stellar remnants toward the LMC [19]. In this paper we consider possible dynamical and observational consequences of the existence of dark matter in the form of dense molecular clouds. (Through the paper we will refer these clouds to as DM-clouds, or following [13], clumpuscules).

In §2 we will discuss general properties of the population of DM-clouds in the Galaxy which can be inferred from the results of [18]; in §3 we describe qualitatively dynamics of collisions of DM-clouds; in §4 we estimate optical emission from colliding clumpuscules; in §5 we estimate 21 cm emission from clumpuscules and their debris after collisions; in §6 we consider $H_\alpha$ emission from ionized atmospheres of DM-clouds; in §7 possible implications for the Galactic halo gas is discussed; §8 contains discussions of the results and conclusions.

2. General properties of molecular DM-clouds.

In [5, 6] molecular DM-clouds were assumed to have high enough total mass (about one order of magnitude in excess of the mass of visible matter), quite low proper luminosity, and life time comparable with the Hubble time. It follows then that individual masses of these objects must be close to the Jovian mass, $M_c \sim 10^{-3} M_\odot$, and densities, temperatures and sizes such to make them marginally gravitationally stable: $n_c \sim 10^{11} \text{ cm}^{-3}$, $T_c \sim 3 \text{ K}$, $R_c \sim 10^{14} \text{ cm}$. The interpretation of the extreme scattering events suggested in [18] leads to very close value for the radius of a DM-cloud: the duration of these events around 2 months suggests that $R_c \lesssim 3 \times 10^{14} \text{ cm}$ for the transverse velocity of DM-clouds restricted from above by the escape velocity for the
Galaxy 500 km s$^{-1}$. The covering factor of the clouds is estimated from the flux monitoring data [16] as $f \sim 5 \times 10^{-3}$. It allows, in turn, to estimate the contribution of DM-clouds to the total surface density of the Galaxy as [18]: $\Sigma \sim f M_c / \pi R_c^2$, where $M_c$ is found from hydrostatic equilibrium $M_c \sim k T_c R_c / G m_p$. It gives for $T_c \gtrsim 3$ K the surface density $\Sigma \gtrsim 10^2 M_\odot$ pc$^{-2}$ [18], which is close to the value estimated from dynamical arguments [20].

The characteristic free-path length of DM-clouds with respect to cloud-cloud collisions is of $r_0/f$, where $r_0$ is the characteristic size of the region occupied by clouds. For $r_0 \sim 10$ kpc, one gets for characteristic time between collisions $\gtrsim 10^{10}$ yr. Cloud destruction by the external UV radiation is slow enough with similar characteristic time, due to their high masses and densities. Moreover, contact interactions of DM-clouds with interstellar clouds are inefficient because of high differences in densities, and thus one can conclude (see [18]) that the population of DM-clouds does not change significantly over the Hubble time. At the same time, even so inefficient destruction of DM-clouds can result in dynamically important consequences because their total mass in the Galaxy is large.

We will assume for specificity the distribution of DM-clouds in the form

$$N = \frac{N_0}{1 + (r/r_0)^2},$$

(1)

which fits the singular isothermal sphere at $r > r_0$ (through the paper $r_0$ is regarded as a free parameter); here $N_0$ is the number of clouds per unit volume in the galactic center, $r$ is the galactocentric radius. The collision rate per unit volume is then

$$\nu = \pi R_c^2 N^2 v_c,$$

(2)

where all clouds are assumed to have equal characteristic velocity $v_c$ independent of their position in the Galaxy. In what follows we accept in numerical estimates $R_c = 3 \times 10^{13}$ cm and $v_c = 250$ km s$^{-1}$ – two times less than the escape velocity – unless other values specified. The total rate of collisions in the Galaxy is

$$\nu_G = 4\pi \int_0^\infty \nu(r)r^2 dr = \pi^3 R_c^2 r_0^3 N_0^2 v_c,$$

(3)
which is connected with the characteristic covering factor of DM-clouds $f \sim \pi N_0 R_c^2 r_0$ by equation
\[
\nu_G \sim \frac{4 r_0 v_c}{\pi R_c^2} f^2.
\]

For adopted values of $R_c$, $v_c$ and $f$ this gives $\nu_G \sim 10^{-26} r_0 \text{ s}^{-1}$, or $\nu_G \sim (10^3 - 10^4) \text{ yr}^{-1}$ for $r_0 = 1 \text{ kpc}$ and $r_0 = 10 \text{ kpc}$, respectively; the total number of clumpuscules in the Galaxy can reach $N \sim 10^{13} - 10^{15}$. (Note, that for given characteristic length of clouds distribution $r_0$ and fixed total number of clouds in the Galaxy $N$, the surface density from clumpuscules is proportional to their radius $\Sigma \sim kT_c NR_c/\pi G m_p r_0^2$, however, for fixed current covering factor it is inversely proportional to $R_c$: $\Sigma \propto f R_c^{-1}$.) Therefore, the amount of material of molecular clumpuscules processed by collisional shocks is $\sim \nu_G M_c \sim 1 - 10 \ M_\odot \text{ yr}^{-1}$. This value is comparable or exceeds typical rates of matter processing in such galactic events as star formation, heating of the interstellar gas by supernovae shocks, accretion of galactic halo gas to the plane. One can expect thus that collisions of DM-clouds have important consequences for the interstellar gas and might be observed.

### 3. Collisional dynamics of molecular DM-clouds.

In this Section we describe qualitatively dynamics of collisions of DM-clouds. Detailed description of numerical results will be given elsewhere. Let us consider a head-on collision of two equal clouds, and neglect self-gravity effects. In the center-of-mass frame a contact discontinuity forms in the symmetry plane, from which two shocks propagate outward. Characteristic duration of the collision, \textit{i.e.} time needed for the shock to reach outside boundary of the cloud, is $\tau_s \sim R_c/v_c \sim 0.4 \text{ yr}$ for adopted parameters. Due to high density behind the shock, $n_s = 4n_c \sim 4 \times 10^{12} \text{ cm}^{-3}$, radiation cooling time in bremsstrahlung processes is only $\tau_R \sim 3 \text{ s}$. However, hard radiation emitted by shocked gas is absorbed on scales $\sim 10^6 \text{ cm}$, and after time interval $\sim 10^5 \text{ s}$, when the shock wave covers around 1 - 2 % of the cloud mass, it becomes ionized $x \sim 1$ and Thomson optical depth increases to $\tau_T \sim 20$. This circumstance allows us to neglect radiative cooling.

Due to high postshock pressure, $P_s \sim \rho_c v_c^2 \sim 10^3 \text{ erg cm}^{-3}$ ($\sim 10^{19} \text{ K cm}^{-3}$), a strong axial gas outflow along the symmetry plane forms immediately after collision, which decreases pressure and temperature behind the shock, and moreover it scatters a substantial mass fraction
of clouds during the collision $t \sim \tau_s$. In [21] this effect was described first and then confirmed in a sequence of papers [22-26]. The fraction of scattered mass for diffuse interstellar clouds dominated by radiative cooling was estimated in [21] as 25%. In radiationless case this fraction can be somewhat larger due to higher pressure. (One should stress, however, an approximate character of these estimates – recent simulations with high precision [26] have demonstrated that at late stages after collision, $t > 10 - 15$ dynamical times, Rayleigh-Taylor instability develops to form multiple clumps and filaments, and violates strongly the integrity of post-collisional clouds. Thus, the fraction of escaped gas can be higher.)

After the shock wave reaches external boundary of the cloud, a rarefaction wave starts to propagate inward resulting in expansion of the cloud with velocity equal to the local sound speed (see [21]). At $t \gtrsim \tau_s$ the rarefaction wave reaches the symmetry plane and reflects. When the reflected wave reaches external boundary of the cloud, gas pressure in outer regions relaxes already to external pressure, and thus the secondary reflected wave is a compression wave. These wave motions result in separation of clouds with final pressure relaxed to the external value. Since viscosity behind shock waves works to increase entropy, cloud collisions are dissipative even in radiationless case. This means that after separation of clouds pressure equilibrium establishes at gas density less than the initial one: the new equilibrium corresponds to the Poisson adiabat with entropy larger than the initial value.

Self-gravity effects on collisional dynamics are weak, and are only important for unperturbed clouds (i.e. before collision), as they are assumed to be marginally stable [5, 6]. After collision thermal energy of clouds becomes larger than their gravitational energy due to dissipative increase of entropy at the shock, and separated clouds expand freely up to pressure equilibrium with ambient medium. At late stages clouds can get transparent to external heating sources, and their subsequent expansion settles in an isothermal regime, and finally they mix with surrounding gas.

An important qualitative difference of shocked gas in colliding clumpuscules from that described in [21 – 26] is connected with the fact that due to high relative velocity of clumpuscules the postshock gas is dominated by radiation pressure. As mentioned above, Thomson optical depth of the shocked gas reaches unity quickly, and thus gas and radiation behind the shock set in equilibrium. The postshock pressure is then
\[ P = \frac{\mathcal{R}}{\mu} \rho T + \frac{4}{3} \sigma_{SB} T^4, \]  
(4)

where $\mathcal{R}$ is the gas constant, $\sigma_{SB}$ [erg cm$^{-3}$ K$^{-4}$], the Stefan-Boltzmann constant. On the other hand, $P = \rho_0 D^2 (1 - \eta)$, where $\eta^{-1} = \rho/\rho_0$ is the compression factor, $D$, the shock velocity in the center-of-mass frame. It can be readily shown that the solution of eq. (4) at $v_c = 250$ km s$^{-1}$ is $T \simeq 2.8 \times 10^4$ K, and the contribution of gas pressure [first term in eq. (4)] is $\sim 0.01$ for $n_c = 10^{12}$ cm$^{-3}$. Fractional ionization (determined by Saha equation) is $x = 1$ (more precisely $1 - x \simeq 6 \times 10^{-7}$). Due to radiation diffusion the shock front is smoothed (see [27]) over scales of several free-path lengths of photons, in our case $\sim 10^{-2} R_c$. From this point of view, qualitative dynamics of shocks and subsequent separations of clouds after collision is similar to that described in [21]. The sound speed behind the shock is

\[ c_s = \frac{2}{3} \frac{\sigma_{SB}^{1/2} T^2}{\rho^{1/2}}, \]  
(5)

and for adopted parameters $c_s \simeq 0.7 \times 10^7$ cm s$^{-1}$.

4. Optical emission.

The postshock temperature is

\[ T_s \simeq 2.8 \times 10^4 \left( \frac{v_c}{250 \text{ km s}^{-1}} \right)^{1/2} \text{ K}, \]

for $v_c \gtrsim 15$ km s$^{-1}$ (for $n_c \sim 10^{12}$ cm$^{-3}$), at lower velocities the contribution of radiation to pressure behind shock is smaller than gas pressure, and temperature is determined by

\[ T_s \simeq 2.5 \times 10^6 \left( \frac{v_c}{250 \text{ km s}^{-1}} \right)^2 \text{ K}. \]

Thomson optical depth after ionization of the preshock gas reaches $\tau_T \sim \sigma_T R_c n_c \sim 20$. The luminosity of the colliding DM-clouds is determined by diffusion of photons from the hot interior and is equal to

\[ L_h \simeq \sigma_{SB} \tau_T^{-1} c T^4 S, \]

where $S \sim 2\pi R_c^2$ is the emitting area. For adopted parameters it gives $L_h \sim 10^{38}$ erg s$^{-1}$. The duration of hot stages is determined by gas expansion after shock waves reach external
boundaries of the clouds and the rarefaction waves start to propagate inward: \( t_d \sim R_c / 3c_s \sim 2 \times 10^6 \) s. Thus, the total energy loss by radiation is \( L_{htd} \sim 2 \times 10^{44} \) erg, i.e. about 30\% of the total kinetic energy of clouds.

Observationally colliding DM-clouds at these stages are short-lived transients (with the life time \( t \sim t_d \sim 10^4 \)), with temperature and luminosity typical for massive stars. The total number of such objects in the Galaxy is \( \nu_G t_d \sim 80(r_0 / 1 \text{ kpc}) \). Only small their fraction \( \sim 2\pi^{-1}\arctg(r/r_0) \), is located inside a region with galactocentric radius less than \( r \), and can be obscured by dust in the galactic central parts: this fraction inside \( r < 1 \) kpc is 0.5 for \( r_0 = 1 \) kpc (i.e. the number of unobscured objects is \( \sim 40 \)), and only 0.06 for \( r_0 = 10 \) kpc. Their characteristics (for \( v_c \geq 100 \text{ km s}^{-1} \) and \( n_c \sim 10^{12} \text{ cm}^{-3} \)) scales as the total number of clouds at hot stage

\[
N_h = \frac{6}{\pi} \left( \frac{1 - \eta}{\eta} \right)^{1/2} f^2 \frac{r_0}{R_c} \sim 80 \left( \frac{r_0}{1 \text{ kpc}} \right) \left( \frac{R_c}{3 \cdot 10^{13} \text{ cm}} \right)^{-1},
\]

cloud luminosity

\[
L_h = \frac{2\pi \eta^2 m_p v_c^2 R_c c}{1 - \eta} \sigma_T \sim 7.5 \times 10^{37} \left( \frac{R_c}{3 \cdot 10^{13} \text{ cm}} \right) \left( \frac{v_c}{250 \text{ km s}^{-1}} \right)^2 \text{ erg s}^{-1},
\]

temperature

\[
T_h \sim \left[ \frac{\eta^2 \rho_0 v_c^2}{1 - \eta \sigma_{SB}} \right]^{1/4} \sim 2.8 \times 10^4 \left( \frac{n_c}{10^{12} \text{ cm}^{-3}} \right)^{1/4} \left( \frac{v_c}{250 \text{ km s}^{-1}} \right)^{1/2} \text{ K},
\]

here \( \eta \simeq 1/6 \). Possible detection of such objects (or contrary, non-detection at given threshold) might allow to infer (or restrict) characteristics of DM-clouds and estimate their contribution to the surface density of the Galaxy.

### 5. Emission in 21 cm.

Estimates of emission in 21 cm after collision of clouds can be obtained assuming each cloud to expand isotropically after the primary shock reaches the external surface of the cloud. At such an assumption, initial stages can be described as an expansion with \( \gamma = 4/3 \)

\[
P = P_1 \left( \frac{\rho}{\rho_1} \right)^{4/3},
\]

where subscript 1 refers to variables at the moment of maximal compression: \( P_1 = 4\sigma_{SB} T_1^{4/3} \), \( T_1 = 2.8 \times 10^4 \) K, \( \rho_1 = \rho_c / \eta \). At stages when Thomson optical depth is large, \( \tau_T > 1 \), both
radiation and gas temperatures vary as $T \propto R^{-1}$. For a quasi-spherical expansion with gas density varying as $\rho \propto R^{-3}$, both gas ($P_g$) and radiation ($P_\gamma$) pressure vary as $\propto R^{-4}$, thus the initial ratio $P_g/P_\gamma \simeq 0.05$ is kept up to stages when electron density decreases substantially and $\tau_T$ becomes less than one. It can be readily shown that $\tau_T = 1$ is reached when temperature decreases to $T_2 = 5.8 \times 10^3$ K. At this moment $n_2 = 0.016 n_1 \simeq 10^{11} \text{ cm}^{-3}$, $x = 0.12$, and column density of neutral hydrogen is $N_2(\text{HI}) \simeq 6 \times 10^{23} \text{ cm}^{-2}$. Note, that hydrodynamical instabilities in post-collisional gas, found in recent numerical simulations, produce non-homogeneous density distribution in clouds and their fragments, however, the density contrast between different regions does not exceed factor of 3-4 at times $t > 50 - 60$ dynamical times [26], which in our case corresponds to $t \sim 10^6 - 10^7$ s. This means, that our description based on the assumption of smooth structure of post-collisional clouds, gives correct estimates by the order of magnitude.

Subsequent expansion is adiabatic with $\gamma = 5/3$, and at $n_3 = 10^6 \text{ cm}^{-3}$ gas temperature is $T_3 \simeq 3$ K. The duration of this stage is $\sim R_3/c_s \sim 2 \times 10^{11}$ s, where $R_3 \sim (n_1/n_3)^{1/3} R_c$ is the characteristic size of the cloud corresponding to density $n = n_3$: for adopted numbers $R_3 \sim 10^{15}$ cm. Note, that possible existence of such cold cloudlets in the gaseous galactic halo is argued in [28] from analysis of turbulent motions in the neutral halo gas. Further the cloud expands isothermally with temperature $T \simeq 3$ K, which is supported by deactivating inelastic collisions of hydrogen atoms with electrons $H(F = 1) + e \rightarrow H(F = 0) + e'$, with a rate $q_{10} = 3 \times 10^{-11} T^{1/3} \text{ cm}^3 \text{ s}^{-1}$ [29] – the corresponding characteristic time $t_{10} \sim 2 \times 10^4$ s. Isothermal phase stops when gas density decreases to $n_4 \sim 3 \times 10^3 \text{ cm}^{-3}$ and the cloud comes to pressure equilibrium with the ambient interstellar gas. At this state heating by the background X-ray emission gets important with characteristic time $t_X \sim 4 \times 10^{11}$ s (the heating rate $\Gamma_X \simeq 10^{-27} \text{ erg s}^{-1} \text{ H}^{-1}$ is taken from [30]). Subsequently, the cloud expands slowly with characteristic time $t_X$, and becomes transparent to 21 cm when III column density falls to $N(\text{II}) \sim 10^{19} \text{ cm}^{-2}$ – it occurs at $t = t_{\text{HI}} \sim 10^{13}$ s when $n = n_5 \sim 10^3 \text{ cm}^{-3}$. Apparently, at $t > t_{\text{HI}}$ the cloud mixes with the interstellar gas. The total number of such clouds in the Galaxy is estimated as $N_{G} t_{\text{HI}} \sim 3 \times (10^8 - 10^9)$, and their total mass as $3 \times (10^5 - 10^6) M_\odot$ for $r_0 = 1 - 10$ kpc, respectively. A distinctive feature of these clouds is their high velocity dispersion which is close to the dispersion of DM-clouds $v_c$ (for DM-clouds with Maxwellian velocity distribution the mean center-of-mass velocity for pairs of clouds is $\sim \sqrt{3/2} v_c$) – much larger than the local velocity dispersion of the interstellar III. This circumstance can be used for identification of such clouds. It should be mentioned, however, that when cloud fragments and
debris mix with surrounding gas, a fraction of their kinetic energy converges to thermal energy due to viscosity, and thus a fraction of their mass will be heated up to high temperatures and thus will be unseen in 21 cm. To evaluate this effect, note that drag force for a cloud moving through interstellar gas is proportional to ram pressure $\propto \rho_i u_i^2 R_c^2$, even for subsonic clouds [31]. In these conditions the length scale for velocity decay is $\ell_d \sim \delta R_c$, where $\delta$ is the density contrast between cloud and intercloud gas [32]. At stages when fragments become transparent to 21 cm gas density is of order $n_5 \sim 10^3 \text{ cm}^{-3}$ and radius $R_4 \sim 10^{16}$ cm. Thus, cloud velocity decays on scales $\ell_d \sim 30 - 300$ pc for density of ambient gas $n_i \sim 0.1 - 0.01 \text{ cm}^{-3}$, respectively. The corresponding characteristic time $t_d \sim 3 \times 10^{12-13}$ s is comparable to $t_{HI}$. Therefore, although dynamics of cloud fragments at late stages can depend on environment crucially, time interval for fragments to be seen in 21 cm is close to $t_{HI}$. At these stages, before mixing with the ambient gas, fragments form a network with covering factor of $\sim 0.01 - 0.3$ and resemble the tiny-scale atomic structures described in [33].

DM-clouds of smaller radii, $R_c \lesssim 3 \times 10^{12}$ cm, have small Thomson optical depth and due to putchy density distribution generated after collision by hydrodynamical instabilities, [26], they are apparently transparent. In this case, as pointed in [34], after collision they quickly lose their energy radiatively and escape the hot phase. However, subsequent expansion, starting from stages when temperature has fallen to several thousands, is qualitatively similar to the described above, though it is less rapid since at given pressure clouds have larger densities.

6. $H_\alpha$ emission from isolated DM-clouds.

By isolated clouds we mean clouds escaping collisions. Gas temperature in extended ionized gas around DM-clouds is of order $T \sim 10^4$ K, which for electron density $n_e \sim 10^3 \text{ cm}^{-3}$ produces pressure by 3-4 orders of magnitude in excess of typical interstellar pressure. In such conditions ionized gas expands freely with the velocity $u_0 = \sqrt{2/\gamma - 1} c_0$, where $c_0 \sim 10$ km s$^{-1}$ is the sound speed. Therefore, ionized atmospheres of DM-clouds are in steady outflow regime with density and velocity distributions described by the equations (see, e.g. [35])

$$\rho u r^2 = \rho_0 u_0 R_c^2,$$

$$\frac{u^2}{2} + \frac{P_0}{\rho_0} \ln \frac{\rho}{\rho_0} = \frac{u_0^2}{2}.$$
\[ P = P_0 \frac{\rho}{\rho_0}, \]

which give for density distribution the solution

\[ \left( \frac{\rho}{\rho_0} \right)^2 \left[ 1 - \frac{2}{5} \ln \frac{\rho}{\rho_0} \right] = \left( \frac{R_c}{r} \right)^4. \]  \( (6) \)

The equation of ionization equilibrium

\[ 4\pi \alpha_r R_c^3 n_e^2 \int_1^\infty \left( \frac{\rho}{\rho_0} \right)^2 \zeta^2 d\zeta = 4\pi R_c^2 J, \]

with \( n_e \propto \rho \) taken from equation (6) determines the boundary value \( n_{e0} \) at \( r = R_c \) as

\[ n_{e0} \approx \sqrt{\frac{2J}{\alpha_r R_c}}, \]

where \( \zeta = r/R_c \), and \( J \) \( [cm^{-2} \text{ s}^{-1}] \) is the intensity of ionizing photons at Lyman edge, \( \alpha_r \), the recombination rate. The corresponding emission measure is

\[ EM = \int_{R_c}^\infty n_e^2 dr = 0.236 n_{e0}^2 R_c = 1.8 \text{ cm}^{-6} \text{ pc}, \]

here we adopted \( J \) obtained in [36] at high galactic latitude \( J = J_0 \approx 10^6 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), or the intensity of \( H_\alpha \) photons of \( \sim 1 \text{ R} \) \( (= 10^6/4\pi \text{ phot cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \). This number is by an order of magnitude higher than obtained in [37] for high-velocity HI clouds. However, because of small angular sizes \( H_\alpha \) fluxes from distant DM-clouds at \( d > 1\text{ pc} \) with angles \( \Delta\phi < 0'.2 \) are too weak to be detected at present. At the same time, clouds at distances \( d \sim 0.03 \text{ pc} \) with angular sizes \( \Delta\phi \sim 7' \) could be seen in \( H_\alpha \). For adopted parameters and \( r_0 = 1 \text{ kpc} \), a volume \( d^3 \sim (0.03)^3 \text{ pc}^3 \) in solar vicinity contains in average one DM-cloud; for \( r_0 = 10 \text{ one cloud is contained in a volume with radius 0.07 pc} \) – at such distance cloud angular size is only \( \sim 3' \), and \( H_\alpha \) flux decreases by factor of 5.

Much larger emission measures have clumpuscules located in close vicinity of hot stars where the intensity of ionizing photons is higher than the background value \( J \gg J_0 \). For O7 stars this condition holds at \( r < 30 \text{ pc} \). The emission measure increases proportionally to \( J/J_0 \), and thus a DM-cloud at distance \( \sim 1 \text{ pc from hot star can be seen as an ultracompact} H_\alpha \)
nebula as pointed in [12, 18]. However, because of small angular sizes (∼ 0′′.1 for a cloud at ∼ 100 pc from Sun), expected fluxes are too low: \( F_{H\alpha} \sim 3 \times 10^{-3} \text{ phot cm}^{-2} \text{ s}^{-1} \) from a single cloud within 1 pc near an O7 star. In general, the total number of \( H\alpha \) photons emitted by a single cloud is

\[
L(r) \simeq 0.025 \frac{L R_c^2}{r^2} \text{ phot s}^{-1},
\]

(7)

where \( L \) [phot s\(^{-1}\)] is the number of ionizing photons from a star, \( r \), the distance to the star. A distance from the star where the background UV flux is equal to the flux produced by star is

\[
R_m = \sqrt{\frac{L}{4\pi J_0}},
\]

\( R_m \simeq 30 \text{ pc} \) for an O7 star. Total number of \( H\alpha \) photons emitted by all DM-clouds inside \( r \leq R_m \) is then determined as

\[
L_m = 4\pi N \int_0^{R_m} L(r) r^2 dr
\]

and is equal

\[
L_m = 0.3 \frac{L^{3/2} R_c^2 N}{\sqrt{4\pi J_0}} \text{ phot s}^{-1}.
\]

For adopted numerical values this gives \( \simeq 7 \times 10^{44} \) phot s\(^{-1}\), however the corresponding surface brightness is extremely small – the equivalent emission measure is only \( EM \simeq 0.0025 \text{ cm}^{-6} \text{ pc} \).

One of possible observational manifestations of DM-clouds is connected with the fact that outflowing ionized gas fills the space around an O star, and if the outflow rate is high enough it can support high density of electrons and can be observed as a luminous halo. In order to estimate this effect let us write the approximate equation of mass balance at distance \( r \) from an ionizing star as

\[
\frac{\partial}{\partial r} (\rho u) = N \dot{M}_c(r) r^2,
\]

(8)

where \( \dot{M}_c = 2\pi R_c^2 m_p n_{e0}(r) u_0 \) is the mass loss rate by a single cloud (factor 2\( \pi \) accounts that only one side of the cloud is ionized by the star), \( n_{e0}(r) = 4.8 \times J^{1/2} R_c^{-1/2} \), (thus \( n_{e0} \propto r^{-1} \) in virtue of \( J \propto r^{-2} \)). Note, that a volume with \( r \sim 10 \text{ pc} \) contains \( \sim 10^6 \) to \( \sim 10^7 \) clouds, and this substantiate the assumption of steady state mass and energy balance. In this case, integration over \( r \) gives

\[
m_p \rho u = N \dot{M}_c(r) r,
\]
or finally

\[ n = 8.5 \times 10^6 \, L^{1/2} R_c^{3/2} \frac{N u_0}{u}. \]  

(9)

To complete description, Bernoulli and energy equations must be written. As we will show below, gas pressure in regions filled by gas from HII-atmospheres is much higher than pressure in surrounding interstellar gas, and thus one can assume the outflow velocity \( u \) to be independent of \( r \) and equal with the factor \( \sqrt{2/\gamma - 1} \) to the sound speed, which in turn is determined by energy equation. It is readily seen that in this case \( n = \text{const} \). Energy budget of the gas is determined by heating radiation from central star and by dissipation of high-velocity turbulent motion of the gas lost by DM-clouds from one side, and radiation cooling from the other. The mean velocity of the gas lost by clouds relative to intercloud gas is approximately equal to clouds velocity \( v_c \), and thus the heat released due to dissipation of kinetic energy of evaporated gas can be considerable, \( \sim 10^{14} \, \text{erg} \, \text{g}^{-1} \) (the corresponding temperature \( T \sim 10^7 \, \text{K} \)). At such assumptions energy equation can be written as

\[ H_{UV}(T)n^2 + \frac{1}{2} N M_c v_c^2 = \Lambda(T)n^2, \]  

(10)

where \( H_{UV}(T)n^2 \) is the heating rate by UV radiation from central star, \( H_{UV}(T) = \alpha_r(T)\epsilon_0, \epsilon_0 \), the mean energy of photoelectrons (see [29, 38]), \( \Lambda(T) \), the radiation loss rate. Assuming DM-clouds to be of primordial chemical composition [6, 13], one can accept that radiation cooling in interval \( T = 10^4 - 10^6 \, \text{K} \) is determined by recombinations and equal to \( \Lambda(T) \approx 9.5 \times 10^{-17} T^{-3/2} \) erg cm\(^3\) s\(^{-1}\) at \( T = 10^4 - 6 \times 10^4 \, \text{K} \) and \( \approx 3 \times 10^{-21} T^{-1/2} \) at \( T = 6 \times 10^4 - 10^6 \, \text{K} \) (see [29]). Eliminating \( n \) from (9) and (10) and assuming \( u = \sqrt{2/\gamma - 1} c \), we find that temperature varies from \( T \approx 10^4 \, \text{K} \) at \( r = 1 \, \text{pc} \) to \( T = 3 \times 10^4 \, \text{K} \) at \( r = 30 \, \text{pc} \). Therefore, one can accept in estimates \( T = 10^4 \, \text{K} \) in the whole range of \( r \), which gives \( u \approx 20 \, \text{km s}^{-1} \). Substituting \( u \) in (9) we arrive at

\[ n \approx 4.2 \times 10^6 \, L^{1/2} R_c^{3/2} N, \]  

(11)

and

\[ EM \approx 1.2 \times 10^{-6} L R_c^2 N^{4/3} \, \text{cm}^{-6} \, \text{pc}, \]  

(12)
which gives \( n \simeq 0.65 \text{ cm}^{-3} \) and \( EM \simeq 20 \) for adopted parameters and \( r_0 = 10 \text{ kpc} \). The surface brightness in \( H_\alpha \) is large enough \( I_{H_\alpha} \gtrsim 8 \text{ R} \), and thus such III halos can be observed.

7. Contribution of DM-clouds to energy balance of the Galactic corona.

DM-clouds spend most time in the halo, where their ionized atmospheres are supported by the background UV radiation [18]. The mass loss rate by a single cloud is at such conditions

\[
\dot{M}_c = 4\pi m_p \sqrt{\frac{2J_0}{\alpha_r}} u_0 R_c^{3/2},
\]

or numerically \( \dot{M}_c \sim 10^{-13} M_\odot \text{ yr}^{-1} \). The evaporating gas loses its relative velocity due to viscous forces on characteristic length of \( \ell_d \sim \delta R_c \) (see §5), where radius of ionized atmosphere is accepted to be of order of cloud radius. For mean densities of halo gas \( n_h \sim 10^{-3} \text{ cm}^{-3} \) and of ionized atmosphere \( n_e \sim 10^3 \text{ cm}^{-3} \) this gives \( \ell_d \sim 10^6 R_c \sim 10 \text{ pc} \) which is much less than typical galactic scales. Thus, the energy input rate from kinetic energy of evaporating atmospheres is order of \( H_c \sim \dot{M}_c N v_0^2/2 \sim 2.5 \times 10^{-25} \text{ erg cm}^{-3} \text{ s}^{-1} \), which gives \( \int H_c dz \sim 2.5 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1} \) per unit area (here \( N \sim f/\pi R_c^2 r_0 \), see §2, \( R_c = 3 \times 10^{13} \text{ cm} \) and \( r_0 = 10 \text{ kpc} \) are substituted). For comparison, the total energy input rate from SNe II is \( \sim 2 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \) for SNe II galactic rate \( 1/30 \text{ yr}^{-1} \). The radiation loss rate for gas with temperature \( T \sim 10^6 \text{ K} \) and density \( n \sim 10^{-3} \text{ cm}^{-3} \) is order of \( \Lambda(T)n^2 \sim 3 \times 10^{-29} \text{ erg cm}^{-3} \text{ s}^{-1} \). In principle, observations show that the halo gas has extremely non-homogeneous density and temperature distributions. In this case, one can expect the total rate of radiation energy losses to be higher than the above estimate. In particular, in regions with \( n \sim 10^{-2} \text{ cm}^{-3} \) and \( T \sim 10^5 \text{ K} \) radiation takes away \( \sim 10^{-25} \text{ erg cm}^{-3} \text{ s}^{-1} \). However, energy input rate from evaporating clumpuscles \( H_c \) is much larger than possible energy losses.

In this connection, one should mention a problem of energy balance in galactic halo gas, still far from being understood well. It is commonly believed that clustered SNe II in OB associations are the source which replenishes energy losses in the halo. Detailed calculations show however, that special conditions are needed to form vertical tunnels able to conduct energy from the disk to halo. It is shown in [39] that hot gas from a clustered SNe explosion can reach heights \( z \sim 1-3 \text{ kpc} \) only if \( \sim 100 \text{ SNe} \) exploded at distance \( z = 80 \text{ pc} \) from the plane. Definitely, such events are rare in the Galaxy. Quite recently additional results have been obtained which exacerbates the problem. Based on recent all sky survey of HI gas, soft X-ray radiation, high
energy γ-ray emission and the 408 MHz survey, it has been found in [28] that radial distribution of halo gas has scale length $R_h \sim 15$ kpc. At the same time, galactic supernovae have different radial distributions: either exponential with radial scale length $\sim 4$ kpc for SNe I, or a ring with radius $\sim 5$ kpc and width $\sim 4$ kpc for SNe II. One might assume that SNe explosions in galactic central regions eject hot gas, which then fills the halo in radial direction over galactic scales $R \sim 10 - 15$ kpc. However, characteristic time for hot ejected gas to expand in radial direction out of solar circle is of order $\sim 10^8$ yr, which is comparable to its radiative cooling time $3 - 10 \times 10^7$ yr. At the same time, the problem can have a simple solution if transfer of kinetic energy of evaporating material of DM-clouds to thermal energy is taken into account. Note, that this mechanism can be comparable (and out of solar circle can exceed) to SNe explosions, even if the total number of DM-clouds is smaller than the value accepted in previous sections – the rate $H_c$ decreased by factor of 10 is still of the same order as the SNe energy input rate. (This circumstance can be important if subsequent observations will restrict from above such parameters of clumpuscules as $N_c$, $M_c$, $v_c$.) It worth to stress that since heating due to evaporating clumpuscules is much higher than radiation losses, it can support energy balance in halo on radial scales larger than $r_0$: clumpuscules with radial scale $r_0 \approx 10$ kpc can maintain radial distribution of halo gas with $R_h \sim 15$ kpc (though $r_0 > 10$ kpc seems more realistic).

8. Discussion and conclusions.

The effects connected with mass loss by DM-clouds due to their collisions with each other and photoevaporation by ionizing radiation, are interesting not only by possible observational manifestation, but also by their impact on dynamical and chemical evolution of the Galaxy. We discuss here only qualitative aspects of such influence – detailed analysis requires a separate consideration. As shown in §7, the mass loss rate by a single cloud ionized by the background UV radiation is $\dot{M}_c \sim 10^{-13} \ M_\odot \ yr^{-1}$. Thus, a clumpuscle of $\sim 10^{-3} \ M_\odot$ loses all its mass on the Hubble time. Moreover, the life time of DM-clouds can be even less than the Hubble time since they cross regions near hot stars with enhanced UV flux. In addition, it is almost certain that the background UV radiation can be more intense in young Galaxy due to violent star formation. If one assumes that all evaporated material is trapped by inner parts of the Galaxy ($R \approx 15$ kpc), it follows inevitably that the total mass of luminous matter in the Galaxy must be comparable with (or higher than) that contained now in DM-clouds. Such a conclusion
would obviously contradict observations, if mean surface density in the Galaxy due to DM-clouds is order of \( \Sigma \gtrsim 10^2 M_\odot \) pc\(^{-2} \) as estimated in [18]. One can escape this paradox by limiting from above the cloud radius \( R_c \). Assuming clumpuscules to be gravitationally bound [6, 18], and with accounting Eq. (13) we obtain for cloud life time against photoevaporation \( t_{ev} \simeq 1.2 \times 10^{23} T_c R_c^{-1/2} \). Thus, clouds survive in the Hubble time \( t_H \) if \( R_c < 1 - 3.5 \times 10^{12} \) cm for cloud temperature \( T_c = 2.7 \) and 5 K, respectively. (Note, that the restriction is weaker for higher temperature of DM-clouds: it scales as \( \propto T_c^2 \)). One should stress, however, that the evaporating gas (as well as dispersed in cloud collisions) can in principle settle down in the outer Galaxy and form an extended ionized disk, as suggested first in [40].

A lower limit for cloud radius \( R_c \) can be obtained if possible interaction of DM-clouds with the Solar system is taken into account. The frequency of DM-clouds crossing the Solar system is

\[
\nu_S \sim \pi R_S^2 N v_c,
\]

where \( N \sim f/\pi R_c^2 r_0 \), \( R_S \sim 40 \) AU. This gives

\[
R_c \sim \sqrt{\frac{f v_c}{\nu_S r_0}} R_S.
\]

One can assume that \( \nu_S \leq (100 \text{ yr})^{-1} \) — more frequent collisions might result in detectable perturbations of planetary orbits. Then, for \( r_0 = 10 \) kpc and adopted parameters we get \( R_c \geq 10^{11} \) cm.

The net mass per unit area deposited by evaporating clumpuscules can be found as

\[
\Delta \Sigma = \Sigma \left[ (1 + 2 t_H/t_{ev})^2 - 1 \right],
\]

where \( \Sigma \) is the present surface density in clumpuscules. Requiring \( \Delta \Sigma < \Sigma_v \), where \( \Sigma_v \sim 50 M_\odot \) pc\(^{-2} \), we arrive at

\[
\Sigma < \frac{\Sigma_v}{(1 + 2 t_H/t_{ev})^2 - 1}.
\]

For the lower limit \( R_c = 10^{11} \) cm this gives \( \Sigma < \Sigma_v \). This estimate conflicts with the lower limit, \( \Sigma > 100 M_\odot \) pc\(^{-2} \), obtained in [18]. The contradiction can be avoided if the covering factor \( f \) is two times smaller than estimated in [16] from the flux monitoring data. Note in this
connection that in [18] \( f \sim 10^{-4} \) is mentioned as a conservative value. [One should stress that since \( 2t_H/t_{ev} < 1 \) and \( t_{ev} \propto R_c^{-1/2} \) the obtained upper limit weakly depends on the parameters: approximately as \( (f\nu_Sr_0/v_c)^{1/4} \), though it is sensitive (inversely proportional) to the fraction of photoevaporated mass confined by the Galaxy.]

Transverse velocity of clouds should decrease proportionally \( v_{c\perp} \propto R_c \) to keep the duration of extreme scattering events constant. This means in turn, that orbits of DM-clouds are strongly stretched, so that the radial component \( (\leq 500 \text{ km s}^{-1}) \) is much bigger than the transverse one.

With such restrictions the current mass rate processed in cloud collisions, \( \nu_GM_c \propto f^2R_c^{-1} \), can reach about \( 2-20 \, M_\odot \text{ yr}^{-1} \) and leads to overproduction of mass in the Galaxy. However, due to strong dependence on \( f \) it can be as small as \( < 0.4 - 4 \, M_\odot \text{ yr}^{-1} \) for \( f < 10^{-3} \).

Although at present the origin of DM-clouds is far from being understood well, one may say tentatively that they were born on prestellar stages of the universe, and are thus the most old objects [13]. This means that they might have primordial chemical composition, and being mixed with the interstellar gas decrease its metallicity. In other words, models of chemical evolution of the Galaxy which incorporate input of mass from photoevaporating and collisionally dispersed DM-clouds, should predict less efficient enrichment by metals than those without DM-clouds. It follows, in particular, that since clouds concentrate to central regions of the Galaxy, it should make radial gradient of metallicity much softer than the observed one, or even to inverse it, (unless \( r_0 \) is large enough, \( r_0 > 10 - 15 \text{ kpc} \) – otherwise, star formation rate must increase strongly in central regions to balance mass input with primeval composition.

We summarise our findings:

1) Collisions of dense gaseous clumpuscules responsible for the extreme scattering of quasar radio emission, are frequent enough: depending on their total number in the Galaxy around \( 10^3 \) to \( 10^4 \) collisions per year can take place.

2) After collisions gas of clumpuscules is heated and then dissipates and mixes with the interstellar gas. The corresponding mass input rate can reach \( 1-10 \, M_\odot \text{ yr}^{-1} \). In this case their impact on dynamical and chemical evolution of the Galaxy can be important. In particular, it might result in softening of radial gradients of the stellar metallicity.
3) On post-collisional stages shocked clumpuscules and their fragments appear as transient optical sources with temperature and luminosity close to those of massive stars, the duration of these stages is about 10 days.

4) On later stages expanding fragments can be seen in 21 cm, with duration of 1 Myr, and the total mass of such fragments in the Galaxy luminous in 21 cm is of $3 \times (10^5 - 10^6) \ M_\odot$. This gas can be distinguished from the interstellar HI gas by its high velocity dispersion.

5) DM-clouds surrounding hot stars form HII halos around them with electron density of $n_e \sim 0.65 \ cm^{-3}$, and can be seen in $H_\alpha$ with emission measure $EM \sim 20 \ cm^{-6} \ pc^{-1}$ even for stars far from the galactic plane where interstellar gas is diluted.

6) Ionized gas outflowing the atmospheres of DM-clouds can be a substantial mass source – with the rate $2 - 20 \ M_\odot \ yr^{-1}$ – for the interstellar gas. If most of this evaporated gas is trapped by the Galaxy, clumpuscule radius can be constrained as $R_c \leq 3.5 \times 10^{12} \ cm$ from requirement the mass deposited to be less than the total luminous mass. In turn, it leads to the conclusion that orbits of clouds are strongly stretched with small transverse velocity component. In this case, the surface mass density in DM-clouds can be as small as $50 \ M_\odot \ pc^{-2}$.

7) In general, gas lost by DM-clouds has high velocity relative to the ISM ($\leq 500 \ km \ s^{-1}$ [18]). Subsequent mixing with the interstellar gas transfers its kinetic energy to heat and is an additional heating source of the ISM. This can explain large radial scale length of the halo gas ($\sim 15 \ kpc$) if the scale length of DM-clouds distribution (1) is high enough ($\gtrsim 10 \ kpc$).

Possible detection (or, contrary, non-detection at given threshold of sensitivity) of optical emission, including $H_\alpha$, and emission in 21 cm from clumpuscules will be of great importance for understanding the nature of dark matter and for more confident estimates (or firm constraints) of the contribution of dense molecular clumpuscules to the galactic mass. In principle, one can expect that dense atomic clouds, suggested in [11] as possible dark matter objects, also may manifest themselves in $H_\alpha$ and 21 cm emissions through photoionization by UV background and collisions. However, their parameters (sizes, densities, velocity dispersion) are too uncertain now to make definite conclusions. In [7, 8, 12, 14, 41] baryonic dark matter is assumed to form aggregates similar to globular clusters – baryonic dark clusters – with a fraction of baryons in gas clouds (see for detailed discussion [12, 14]). Stability of such clusters implies that gas clouds are collisionless, however, even rare collisions might provide substantial mass supply into the ISM if the clouds are numerous enough. Also, photoevaporation due to external UV photons...
must be important for such clouds, however, effects from neighbouring (brown dwarf) stars seem to be more influential [14].

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19
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