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BROWN DWARF ACCRETION: NONCONVENTIONAL STAR FORMATION OVER VERY LONG TIMESCALES

M. M. Ćirković

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia and Montenegro

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SUMMARY: We investigate the process of accretion of interstellar gas by the Galactic population of brown dwarfs over very long timescales typical for physical eschatology. In particular, we use the classical Hoyle-Lyttleton-Bondi accretion model to investigate the rate at which brown dwarfs collect enough additional mass to become red dwarfs, accretion-induced changes in the mass function of the low-mass objects, and the corresponding accretion heating of brown dwarfs. In addition, we show how we can make the definition of the final mass function for stellar objects more precise.

Key words. Stars: low-mass, brown dwarfs – Galaxy: evolution – ISM: general

1. INTRODUCTION

Far future of the universe has been recently considered in a number of papers (Dyson 1979, Tipler 1986, Adams and Laughlin 1997, Krauss and Starkman 2000, Nagamine and Loeb 2003; for a detailed bibliography see Ćirković 2003). One of the crucial processes for determining future fate of our environment is the gradual decrease and final cessation of star formation, physical process most characteristic for the present epoch. Thus, we live in the *stelliferous* epoch (Adams and Laughlin 1997), which started $\sim 10^7$ years after the Big Bang, and will last at least several times 10^{10} years in the future, and probably much longer. This epoch is characterized by active star formation from dense interstellar clouds in accordance with increasingly well-understood physics (for thorough recent reviews see Elmegreen 2002, Larson 2003). Star formation is a process of limited efficiency, though, and a fraction of available baryonic matter is inexorably being lost from "galactic ecology" by being incorporated into brown dwarfs, very long-living red dwarfs, as well as in inert stellar remnants: white dwarfs, neutron stars and black holes. Thus, the stelliferous epoch is bound to end, although at present we have only a vague idea for how long it will last.

However, even after the conventional star formation ceases and we pass into next, *degenerate* era, some non-conventional star formation modes will remain plausible, and will become dominant in the dying Galaxy on ever-increasing time scales. Two of these non-conventional modes are envisaged at present:

1. Constructive brown dwarf collisions and merging into objects above the hydrogen-burning limit; and
2. accretion of remaining interstellar matter (ISM) by brown dwarfs which will eventually push them above the hydrogen burning limit.

The first process has been discussed in the paper of Adams and Laughlin (1997), and found to be a viable source of ~ 10 hydrogen-burning stars at any given epoch prior to the dissolution of the Galaxy (see below).[1] The process 2. has not been, however, treated in the literature so far. It is easy to show that it is so slow to be completely unobservable at present; hence the usual assumption that for brown dwarfs the present-day mass function (henceforth MF) is equal to the initial MF (Chabrier 2003). However, on ever-increasing timescales of the future, this assumption ceases to hold. The purpose of this paper is to investigate the importance of the brown dwarf accretion process for the physical picture of our Galaxy in the very far future, after the stelliferous epoch ends. Needless to say, this discussion is applicable to gas-rich disk galaxies in general.

We accept the notation of *cosmological decades* of Adams and Laughlin (1997) as particularly convenient for physical eschatology. A cosmological decade η is simply the logarithmic measure of cosmic time:

$$\eta \equiv \log_{10}\left(\frac{\tau}{1 \text{ yr}}\right). \tag{1}$$

Thus, we are currently living at the beginning of the cosmological decade $\eta = 10$ ($\tau = 1.3 \times 10^{10}$). Big Bang corresponds to $\eta \to -\infty$. Since about 1998, we have strong reasons to believe that the universe will expand forever, implying that the entire interval $(-\infty, +\infty)$ is accessible to cosmological decades. With τ_R we denote the epoch of the end of conventional star formation ("Roberts time"; Roberts 1963). τ_R is currently insufficiently well-known, but is certain to lie within the $10^{11} - 10^{13}$ yrs range, dependent mainly on the unknown properties of infall to the disk from galactic halo and intergalactic medium. Thus, we expect the stelliferous epoch to last until $\eta = 11 - 13$ (Adams and Laughlin 1997, Tutukov et al. 2000).

It is easy to give a qualitative argument as to the importance of brown dwarf accretion on very long timescales characteristic for physical eschatology. Some gas will certainly remain in the disk after the end of the stelliferous era, since the conventional star formation is even today governed by the *star-formation thresholds* (e.g. Kennicutt et al. 1995, Martin and Kennicutt 2001). The current values for star-formation thresholds obtained from the Toomre (1964) criterion:

$$\sigma_{\rm crit} \sim \frac{0.7 c\kappa}{3.36\, G}, \tag{2}$$

(c being the velocity dispersion and κ epicyclic frequency) agree well with observations of the star formation in external galaxies. If the vertical distribution of ISM retains the same general profile as the one observed today, this corresponds to the average physical density in the plane of the disk of $\langle n_0 \rangle \sim 0.1$ cm^{-3} *after* the star formation ceases everywhere. Since the metallicity will significantly increase (to mass fraction of about $Z \sim 0.2$), the residual dust-to-gas ratio is likely to be correspondingly higher than today. Thus, even after the end of the stelliferous era, a substantial amount of gas and dust will remain in the disk. The major consideration is whether characteristic timescale for brown dwarf accretion is smaller than the characteristic timescale for the dissolution of the Galaxy through dynamical evaporation.[2] The estimate of Adams and Laughlin (1997) for the latter is $\eta_{\rm evap} \approx 19$. One can argue that this estimate is conservative if we take into account the abundance of MACHOs inferred from microlensing optical depths (Samurović et al. 1999 and references therein). But even in comparison to this estimate, timescales for accretion over the hydrogen-burning threshold are significantly shorter, as we shall see in the next section, at least for the disk population of brown dwarfs. We take the $\eta_{\rm evap} = 19$ as the epoch of the dynamical death of the Galaxy and investigate the ISM accretion prior to that epoch in the rest of the paper.[3] In fact, we can expect that even the remnants of the ISM will become depleted significantly before that date, through either evaporation of the gas, expulsion by Type I supernovae and by accretion (by both brown dwarfs and stellar remnants).

We shall use the simplest approach, based on the classical accretion theory of Hoyle, Bondi, and Lyttleton (Hoyle and Lyttleton 1939, Bondi and Hoyle 1944, Bondi 1952), in order to obtain rough estimates of the timescales involved, which could then be compared to other relevant timescales in physical eschatology. In absence of even crude models so far, we are generally in the dark concerning the future evolution of the Galactic ISM, so we shall use only the simplest and rough approximations. We leave the more realistic approach based on numerical modeling of the accretion (along the lines of, for instance, models of Ruffert and Arnett 1994) to a future study.

Ironically enough, we employ the Hoyle-Lyttleton-Bondi results for a purpose antithetical to the context in which they were originally sought.

[1] Strictly speaking, collisions of helium white dwarfs and the brown dwarf-white dwarf collisions would be capable of creating short-lived helium burning stars (and perhaps some still much shorter-lived higher-order fusion stars). However, they will burn almost instantaneously by physical eschatological standards and will contribute negligible amount of light to the overall galactic luminosity at future epochs, in contradistinction to hydrogen-burning red dwarfs. These processes will be the subject of a future study.

[2] Important side result of Adams and Laughlin (1997) is that this process is the dominant mechanism of galaxy degradation, by a large margin faster than the stellar orbit decay through gravitational wave emission.

[3] One could object that, according to several studies, there is a high probability of the Galaxy colliding and coalescing with M31 long before the end of the stelliferous era (e.g. Peebles 1994). This could have the effect of creating a single early-type galactic system without recognizable disk structure, thus invalidating the reasoning followed in this paper. However, (i) the conclusions would still be valid for the future fate of generic spiral disks, and (ii) the fate of the Local Group is still very uncertain (Nagamine and Loeb 2003, Busha et al. 2003).

According to a long ago discredited idea by Shapley, which Hoyle and Lyttleton developed into a serious astrophysical hypothesis, *very massive* stars currently seen in the Galaxy have arrived at their high luminosities by *rapid* accretion of dense ISM clouds. McCrea (1953) defended the idea, noticing that very massive stars are found in the densest ISM regions, where accretion is supposed to be most efficient—an erroneous interpretation of the true link between massive stars and dense molecular clouds interesting, perhaps, for historians and epistemologists of astronomy. For a critical view see, e.g. Talbot and Newman (1977). Here, we consider the evolution of *very small* (substellar) objects with no mass loss in the very *slow* accretion regime.

2. BROWN DWARF ACCRETION RATE: BASIC MODEL

Brown dwarfs are objects below the hydrogen-burning limit of $0.0767 M_\odot$ (Burrows and Liebert 1993; for a review of the modern brown dwarf theory, see Chabrier and Baraffe 2000). In this study we explicitly neglect the poorly-understood possibility that the hydrogen-burning limit may significantly decrease at large metallicities which will be reached in the physical-eschatological context (Sec. II. B of Adams and Laughlin 1997). Although the numbers and mass distribution of brown dwarfs are still rather uncertain, great progress has recently been made in both respects. Thus, we estimate that the total number of brown dwarf in the Milky Way is huge, comparable to the number of Main Sequence stars $\sim 10^{11}$, belonging to both main stellar populations (disk and halo), although the mass fraction contained in them is rather modest $\sim 5\%$. Here we consider only objects with present-day mass $M \geq 0.01\, M_\odot$, since $0.01\, M_\odot$ is the limit of accuracy of the existing theoretical models of substellar objects (e.g. Dobbie et al. 2002). Their mass function (henceforth MF) is observationally well approximated by a power-law (Salpeter) mass spectrum

$$\xi_S(M) \equiv \frac{dn_*}{dM} = f_* M^{-\alpha}, \qquad (3)$$

(where n_ast is the number of stars and f_* is the normalization constant) continuous with the distribution of the lowest-mass red dwarf stars. We use the notation of Chabrier (2003) throughout, reserving the expression $\xi(\log M)$ for MF itself; the two are related as $\xi(M) = (1/M \ln 10)\, \xi(\log M)$. The *Hipparcos* data enable fixing f_* and α for the disk population of small stellar objects as:

$$\xi(M) = 0.024 M^{-1.2} \text{ pc}^{-3}. \qquad (4)$$

If this is representative for the entire Milky Way disk, it is easy to see that the total brown dwarf disk population in the mass limits quoted above is $N_{BD} \sim 2.5 \times 10^{10}$, comprising the mentioned ~ 5 % of the disk mass.

Following the classical results of Bondi and Hoyle (1944), we may write the accretion rate of a brown dwarf of mass M and velocity with respect to the interstellar matter v as

$$\begin{aligned} \frac{dM}{dt} &= \alpha_{\rm acc} \pi \rho_{\rm ISM} R_A^2 v = \\ &= \alpha_{\rm acc} \pi R_A^2 \mu m_H \langle n_{\rm ISM} \rangle v, \end{aligned} \qquad (5)$$

where μ is the mean molecular weight, m_H mass of the hydrogen atom, $\rho_{\rm ISM} \equiv \langle n_{\rm ISM} \rangle \mu m_H$ mass-density of the interstellar medium at large distances, and R_A is the *accretion radius* of the gravitating object. $\alpha_{\rm acc}$ is the coefficient dependent on the previous perturbation of the system; detailed considerations suggest $2 \leq \alpha_{\rm acc} \leq 4$. For the case of quiescent accretion which we shall analyze throughout $\alpha_{\rm acc} = 2.5$, as recommended by Bondi and Hoyle (1944) as a sort of default condition. The accretion radius is given as (Hoyle and Lyttleton 1939):

$$\begin{aligned} R_A &= \frac{GM}{v^2} = \\ &= 1.3 \times 10^{14} \left(\frac{v}{10 \text{ km s}^{-1}} \right)^{-2} \left(\frac{M}{M_\odot} \right) \text{cm}. \end{aligned} \qquad (6)$$

For instance, a disk brown dwarf with $M = 0.05 M_\odot$ and $v = 20$ km s^{-1} has the accretion radius of $R_A = 23.4 R_\odot = 0.11$ AU. As such a seed object moves through a gas, it will capture molecules, atoms or ions within the critical radius R_A. Provided that R_A is larger than the mean free path of the gas (condition marginally satisfied in interesting cases), the captured gas will be maintained as a turbulent cloud surrounding the seed object. Turbulent friction will cause a loss of the gas kinetic energy, and most of the gas will eventually be united with the planet or star. For ISM of non-negligible temperature in which density is not necessarily small Bondi (1952) generalized Eqs. (5) and (6) by substituting v by $\sqrt{v^2 + c_s^2}$, where $c_s \equiv \sqrt{\gamma\, p_{\rm ISM}/\rho_{\rm ISM}}$ is the ambient sound speed. Since in the average disk ISM today ($\langle n_{\rm ISM} \rangle \sim 1$ cm^{-3}, $T \sim 200$ K) we have $c_s \sim 1$ km s^{-1} ≪ v, we shall use (5) and (6) in the rest of the paper without this refinement.[4]

Eq. (5) is a differential equation for $M(t)$, which is particularly appropriate for the brown dwarf case, since—in contradistinction to Main Sequence stars—brown dwarfs are not subject to other mass-changing physical processes (like stellar winds and hydrogen burning). It can be further written in the form

$$\frac{dM}{dt} = k(v, \langle n \rangle, \mu) M^2, \qquad (7)$$

[4]Since all sources of heating of ISM today—heavy-species ionization, cosmic-ray heating, shockwaves, etc.—are expected to decrease in cosmological future, we may be fairly confident that the sound speed will actually decrease far below the present-day value.

which can be easily solved by separation of variables. Using the initial condition $M(t=0) = M_0$, solution can be written as

$$M(t) = \frac{M_0}{1 - M_0 kt}. \tag{8}$$

For the disk population of brown dwarfs, we take the values $v = 20$ km s^{-1}, $\langle n \rangle = 0.1$ cm^{-3}, and $\mu = 1.33$, giving $k(v, \langle n \rangle, \mu) \equiv \alpha_{\rm acc} \pi G^2 \mu m_H \langle n \rangle / v^3 = 6.086 \times 10^{-17} M_\odot^{-1}$ yr^{-1}. Solutions (8) are shown in Fig. 1 for different initial brown dwarf masses. It is important to emphasize that the approximation of independence of k on time is sufficient for the present purposes, but is not expected to be strictly valid for physical eschatological timescales. Notably, the evolution of the Galactic gravitational potential will cause a secular change in the average velocities of the brown dwarf population, and the mean molecular weight will gradually approach some asymptotic value (Adams and Laughlin 1997). These are, however, higher-order effects occurring on timescales which are arguably longer than even the accretion time-scales as given by (8).

In Adams and Laughlin (1997) an important concept of the *Final Mass Function* (FMF) is introduced. FMF is the mass function of stellar and substellar objects after the conventional star formation ends at the cosmic decade $\eta_R \equiv \log_{10} t_R$. However, this arguably is not truly the *final* MF, since very slow processes, like the accretion considered in this paper, or brown dwarf and stellar remnant collisions will take place even after the end of the stelliferous epoch in epochs $\eta_R \leq \eta \leq \eta_{\rm evap}$. The true FMF should be the one evaluated at $\eta_{\rm evap}$. The influence of accretion on the MF can be, for the Salpeter form, written as:

$$\begin{aligned} f(M,t) &= f(M - I[M,t]) = \\ &= f_* \left(M - \frac{M^2 kt}{1 - Mkt} \right)^{-\alpha} = \\ &= f_* M^{-\alpha} \left(1 - \frac{Mkt}{1 - Mkt} \right)^{-\alpha} = \\ &= f(M)|_{\rm now} \left(1 - \frac{Mkt}{1 - Mkt} \right)^{-\alpha}, \end{aligned} \tag{9}$$

where we have denoted the increment in mass of brown dwarf with mass M at epoch t by $I(M,t)$. Analogous relation for the log-normal present-day MF reads:

$$f_{MS}(M,t) = A \exp \left\{ - \left[\frac{\ln \frac{M}{M_C} \left(1 - \frac{Mkt}{1-Mkt} \right)}{\sqrt{2} \langle \sigma \rangle} \right]^2 \right\}. \tag{10}$$

The results are shown very schematically in Fig. 2. In the course of future work, we shall try to investigate the simultaneous changes caused by accretion and collisions on the MF. Only such combined function, evaluated at $\eta = 19$ could represent the true FMF.

3. DISCUSSION

The basic model should be improved in the sense of refining assumptions in such way as to include more phenomena. For instance, the physical state of ISM will certainly change on very long timescales. The decrease in stellar radiation field will certainly occur as the amplitude of star formation decreases. The cosmic ray flux (at least its galactic, low-energy component which is relevant from the point of view of ISM physics) will experience a similar decrease, although for the moment less subject to quantitative analysis because of our ignorance on the details of galactic cosmic ray production and large-scale magnetic structures in the Galaxy. The dark matter content of the Galaxy introduces further uncertainties; if, for instance, the dark matter is unstable (e.g. Sciama 1988, 1993), its decay will become dominant source of the ISM heating after the end of stelliferous epoch (maybe even earlier).

Accretion luminosity is likely to present a significant source of radiation field in disk galaxies in the period between η_R and $\eta_{\rm evap}$. In the classical theory, the accretion luminosity of a single seed object will be given as

$$L_{\rm acc} \approx \phi \frac{dM}{dt} = \alpha \pi G^3 m_H \mu n \frac{M^3}{R v^3}, \tag{11}$$

where R is the brown dwarf radius. Since according to the present theory $R \approx 0.1\, R_\odot$ is essentially independent of mass (e.g. Fig. 3 in Chabrier and Baraffe 2000) in the entire range $10^{-3}\, M_\odot \leq M \leq 10^{-1}\, M_\odot$, we can take an example of a brown dwarf of $M_0 = 0.04\, M_\odot$ which will, by the cosmological decade $\eta = 16$, gain an additional $10^{-3}\, M_\odot$ through accretion (for $\langle n \rangle = 0.1$ cm^{-3}). Its accretion luminosity will be, in this approximation, $L_{\rm acc} = 5.04 \times 10^{21}$ erg s^{-1} or about $1.3 \times 10^{-12}\, L_\odot$. However, by the standards of so remote future epoch, this will in fact be a significant source of radiation, since the only competing galactic sources will be accretion by less numerous stellar remnants, occasional Type I supernova and several red dwarfs formed in a nonconventional manner. (Annihilation of dark matter, proton decay and black hole evaporation will still not become dominant sources of radiation.) The total accretion luminosity of the brown dwarf population of the Galaxy will contribute more to the total radiation density than the red dwarf population. Accretion in general (both by stellar remnants and brown dwarfs) will present by far the dominant source of radiation between the end of the stelliferous epoch and the death of galaxies.

The effective temperature of (quasi)blackbody spectrum emerging from accretion will be, in the first approximation, given as

$$\begin{aligned} T_{\rm acc} &= \left(\frac{GM}{4\pi\sigma R^3} \frac{dM}{dt} \right)^{1/4} = \\ &= \left(\frac{\alpha G^3 \mu m_H n}{4\sigma} \frac{M^3}{R^3 v^3} \right)^{1/4}, \end{aligned} \tag{12}$$

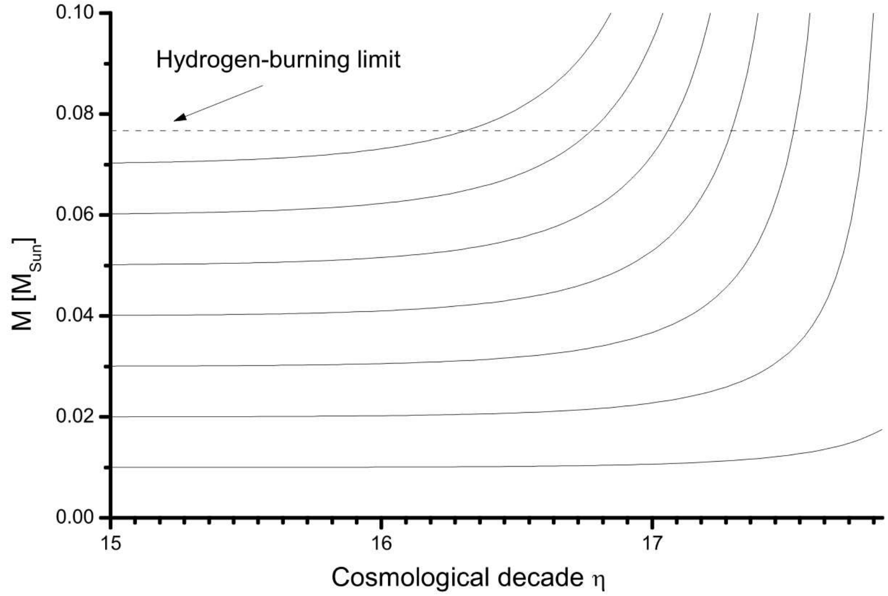

Fig. 1. *Mass increase of brown dwarfs over cosmological decades for the disk population and the following parameters:* $\langle n \rangle = 0.1\ cm^{-3}$, $v = const. = 20\ km\ s^{-1}$. *Different initial (present-day) values of the brown dwarf masses are given.*

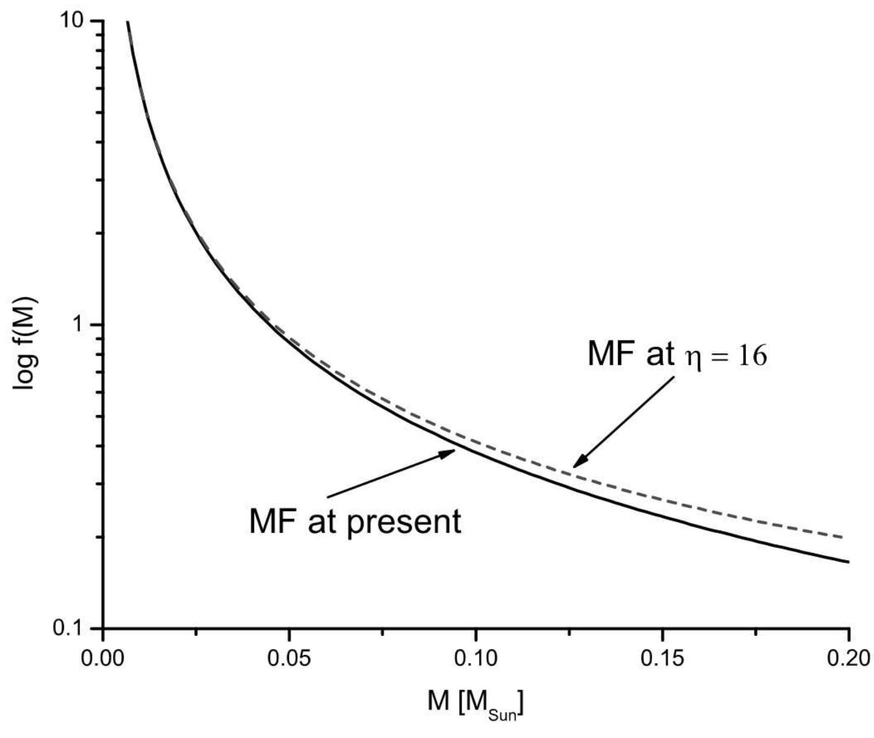

Fig. 2. *Schematical low-mass objects' MF evolution over time. Dotted line is the assumed present-day Salpeter MF (conveniently normalized), while MF for the cosmological decades* $\eta = 16$ *is shown for comparison.*

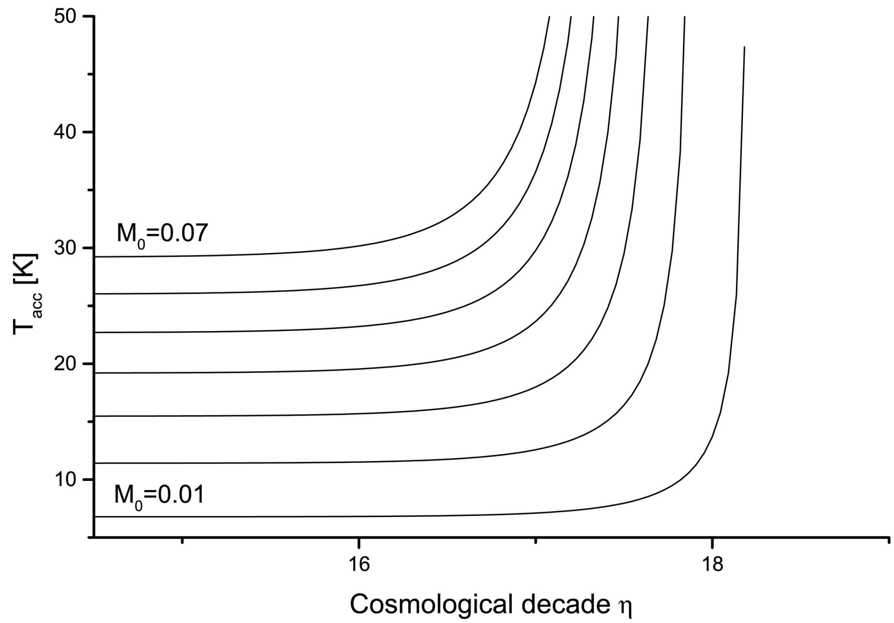

Fig. 3. *Effective accretion temperatures of brown dwarfs with different initial masses (consecutive curves differ by* $0.01\,M_\odot$*) and* $\langle n \rangle = 0.1$ *cm*$^{-3}$*.*

where $\sigma = 5.67 \times 10^{-5}$ ergs cm^{-2} s^{-1} K^{-4} is Stefan-Boltzmann constant. For the same case of a brown dwarf at $\eta = 16$ as above, the effective $T_{\rm acc} = 19.55$ K—not really what one considers hot, but significant in a universe with background radiation temperature decreasing to a tiny fraction of a K. The results are shown in Fig. 3.

Additional dynamical effects of accretion might be important on the timescales of physical eschatology. The accretion drag will act to change the orbits of accreting brown dwarfs as well. They will migrate inward in the Galactic gravitational potential. In general, it will lead to "compactification" of the system, on very long timescales supporting the gravitational-radiation energy loss and opposing the collisional slingshot effect leading to the evaporation of the Galaxy. It remains to be investigated whether this effect will have some impact on the evaporation timescale, as calculated by Adams and Laughlin (1997).

We have neglected effects of binaries here. This topic requires a separate analysis, since the cross-section for accretion by binaries is expected to be significantly larger than the combined cross-sections of both components for a broad class of orbital configurations (Tutukov et al. 2000).

In passing, we mention that ISM accretion in the physical eschatological limit is likely to have other interesting consequences. Notably, we expect that accretion by white dwarfs (and possibly also neutron stars) will occasionally cause a supernova through the so-called accretion-induced collapse (e.g. Colgate et al. 1980). This will cause a non-zero SNe rate up to the epoch of the evaporation of the Galaxy, a rate obviously dependent on the details of higher-mass FMF and the ISM density evolution. We shall investigate this specific physical-eschatological phenomenon in the course of a future work.

However, it is not enough to show that this process is physically viable. In order to see whether it will truly play some role in the future history of the universe, it should be compared with concurrent processes which tend to damp it. These are (i) removing of brown dwarfs themselves through either the collisions with black holes or neutron stars, or star-forming collisions with other brown dwarfs, or their ejection from the Galaxy, and (ii) removing the galactic disk gas through winds, accretion itself and gradual shallowing of the Galactic gravitational potential. This task requires using global evolutionary models of the galactic ISM which could be extrapolated into the far future of the universe.

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АКРЕЦИЈА НА СМЕЂЕ ПАТУЉКЕ: НЕКОНВЕНЦИОНАЛНО ФОРМИРАЊЕ ЗВЕЗДА НА ВЕОМА ДУГАЧКИМ ВРЕМЕНСКИМ СКАЛАМА

M. M. Ćirković

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia and Montenegro

Оригинални научни рад
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Истражујемо процес којим галактичка популација смеђих патуљака врши акрецију међузвезданог гаса на веома дугачким временским скалама карактеристичним за физичку есхатологију. Конкретно, користимо класични Хојл-Литлтон-Бондијев модел акреције да испитамо брзину којом смеђи патуљци могу сакупити довољно додатне масе да би постали црвени патуљци, затим промене које акреција уноси у функцију масе звезданих објеката мале масе и одговарајуће акреционо загревање самих смеђих патуљака. Уз то, користимо прилику да укажемо на начин на који се дефиниција завршне функције масе за звездане објекте може учинити прецизнијом.