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PRESSURE AT THE ISM-HALO INTERFACE: A REHEATING FREQUENCY DEPENDENCE

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SUMMARY: The dependence of the thermal pressure of hot galactic halos on a model parameter describing the frequency of major reheating episodes during galactic history is investigated. Pressure on the interface between interstellar medium and the halo gas is especially interesting, since empirical evidence here offers one of the simplest constraints on halo models. It is shown that two-phase model of Mo & Miralda-Escudé is sufficiently robust with respect to uncertainties in the average interval between reheating.

1. INTRODUCTION

The existence of very extended galactic halos* has been suspected for a long time (Spitzer 1956) on several grounds. In last two and a half decades, from the observations of *Copernicus* and *IUE* satellites we have learnt that highly ionized gas exists in the halo of Milky Way to much larger scale-heights than it was previously assumed (for a review, see Savage 1988). So-called high-velocity clouds were discovered high above the plane of the Galaxy, and in other nearby spiral galaxies. X-ray observations showed the presence of vast quantities of hot gas in rich clusters of galaxies (Sarazin 1986), as well as in smaller compact groups (Saracco & Ciliegi 1995; Mulchaey *et al.* 1996). Cooling flows phenomena were observed in cluster members (Fabian 1994), as well as in individual elliptical galaxies (Nulsen, Stewart, & Fabian 1984). The extraplanar optical recombination emission was discovered at large galactocentric distances in several nearby galaxies (Donahue, Aldering, & Stocke 1995; Pildis, Bregman, & Schombert 1994). The depletion of globular cluster gas was interpreted as the consequence of ram-pressure stripping, and consequences were drawn thereof (Frank & Gisler 1976; Ninković 1985).

Especially important motivation comes from the QSO absorption line studies. It is now clear that, at least at low redshift, a bulk of both metal and Lyα absorption lines arise in gas which is associated with luminous galaxies (Sargent, Steidel, & Boksenberg 1988; Bechtold & Ellingson 1992; Lanzetta *et al.* 1995; Bowen, Blades, & Pettini 1996; Chen *et al.*

*The term "halo" will be preferred to such frequently used terms as "corona" or "envelope", although it is implied that they all describe the same physical objects.

1998). The idea that the QSO absorbers might arise in halos of normal galaxies originated with Bahcall & Spitzer (1969), but the quantitative models were rare (e.g. Bregman 1981) until recently, when vast accumulated data on absorber statistics enabled establishing strong empirical constraints on model parameters (see discussion in Mo & Morris 1994). Very important simple two-phase model of the galactic gaseous halos was put forward recently by Mo (1994), and Mo & Miralda-Escudé (1996; hereafter MM96). Their work shows quite persuasively that formation of the halo structure as a natural consequence of the galaxy formation and subsequent evolutionary processess.

2. HOT HALO: THE THEORETICAL BACKGROUND

Formation of galaxies implies the collapse of the baryonic content of intergalactic space and its motion through the non-dissipative dark matter halos creating deep gravitational potential well. A halo of hot gas at virial temperature ($T_v \equiv \mu V_{\rm cir}^2/2k$, where μ is the average mass per particle, k is the Boltzmann constant and $V_{\rm cir}$ is the circular velocity, which is assumed to parametrize the total mass of the galaxy) will form as the kinetic energy of the infalling material is thermalized in shocks of this primordial accretion. As the gas collapses, it is shocked and it subsequently cools (for an early treatment, see White & Rees 1978). Afterwards, similar situation (although presumably on smaller scale) arises in course of major galaxy mergers: here we also have a large mass of gas accreted into the system on a short timescale and substantial reheating. In the meantime, accretion of ambiental IGM is small or entirely negligible. When hot gas cools, it forms the *cold phase*: photoionized clouds at $T_{\rm cold} \sim 10^4$ K, in pressure equilibrium with the hot halo, slowly sinking in the galactic gravitational potential. While cold phase may dominate the total gas mass, its filling factor is always small, and we shall not deal with it here separately.

The galactocentric radius r_c where the cooling time of the hot gas is equal to the dynamical time is the *cooling radius*. Quantitatively, it is necessary to satisfy

$$\frac{5\mu k T_v}{2\Lambda(T_v)\rho(r_c)} = t_M, \tag{1}$$

where $\Lambda(T_v)$ is the cooling rate at the virial temperature, and $\rho(r_c)$ is the physical density of hot gas at the cooling radius. Inside it, the conditions of adiabaticity and hydrostatic equilibrium, lead to the equation of state $P \propto \rho^{5/3}$, where ρ is the density of the gas. The ratio of the total gas mass and the virial mass is set by the dimensionless parameter f_g. Isothermal potential of the dark matter creates the density profile

$$\rho \propto \left(1 - K \ln \frac{r}{r_c}\right)^{\frac{3}{2}}, \tag{2}$$

where K is the constant, in the simplest model equal to 0.8. This is obtained directly from the requirement of hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho \frac{GM(r)}{r^2}, \tag{3}$$

where $M(r)$ is the total mass (gas + dark matter) enclosed within galactocentric distance r, and assumption of isothermal singular sphere $M(r) \propto r$ (usually inferred from the flat rotation curves of spiral galaxies, see for example, Binney & Tremaine 1987). Simple calculation shows that pressure at some distance r will behave as $P/k \propto (1 - K \ln \frac{r}{r_c})^{5/2}$.

The cooling rate $\Lambda(T)$ has been recently calculated in detail by Sutherland & Dopita (1993), but since the metallicity of the hot halo phase is presumably low, one can also use a nice low-metallicity analytic expression between $T = 10^5$ K and $T = 10^7$ K (e.g. Lepp *et al.* 1985):

$$\Lambda(T) \approx 1.3 \times 10^{-19}\, T^{-\frac{1}{2}} \ \text{erg cm}^3\ \text{s}^{-1}. \tag{4}$$

In the extension of this work, we shall try to investigate and quantify the effects of metallicity gradients on the halo thermal structure.

We see that one of the model parameters is t_M, the average interval between reheating of the gas, the inverse of what we may call the reheating frequency. It is one of the most uncertain parameters. MM96 use

$$t_M = \frac{t}{1 + \Omega_0} \tag{5}$$

approximation, where t is the age of the universe, and Ω_0 is the total cosmological density parameter. It is used quite successfully by MM96, although admitting that a detailed treatment is difficult (due not only to the uncertainty in Ω_0, but to the power spectrum and physics of structure formation as well). While not questioning the goodness of this approximation, we would like to show that actual physical quantities resulting from their model are not much affected by the choice of t_M.

One of, from the physical point of view, most important predictions is the value of the thermal pressure of the hot halo at small galactocentric distances, where interface with the ISM occurs. Therefore, in this paper, we are investigating the changes in the pressure at this inner boundary of the hot halo, when the average time-scale for reheating of the gas is varied. This is a part of the more comprehensive study of the boundary conditions of the two-phase model, which is currently in progress (Ćirković 1998).

3. THERMAL PRESSURE AT THE HOT HALO BOUNDARIES

Formally, thermal pressure in the adiabatic model diverges as $r \to 0$. Of course, we know, from both theoretical modelling and observations of Galactic ISM, that the real picture is more complicated.

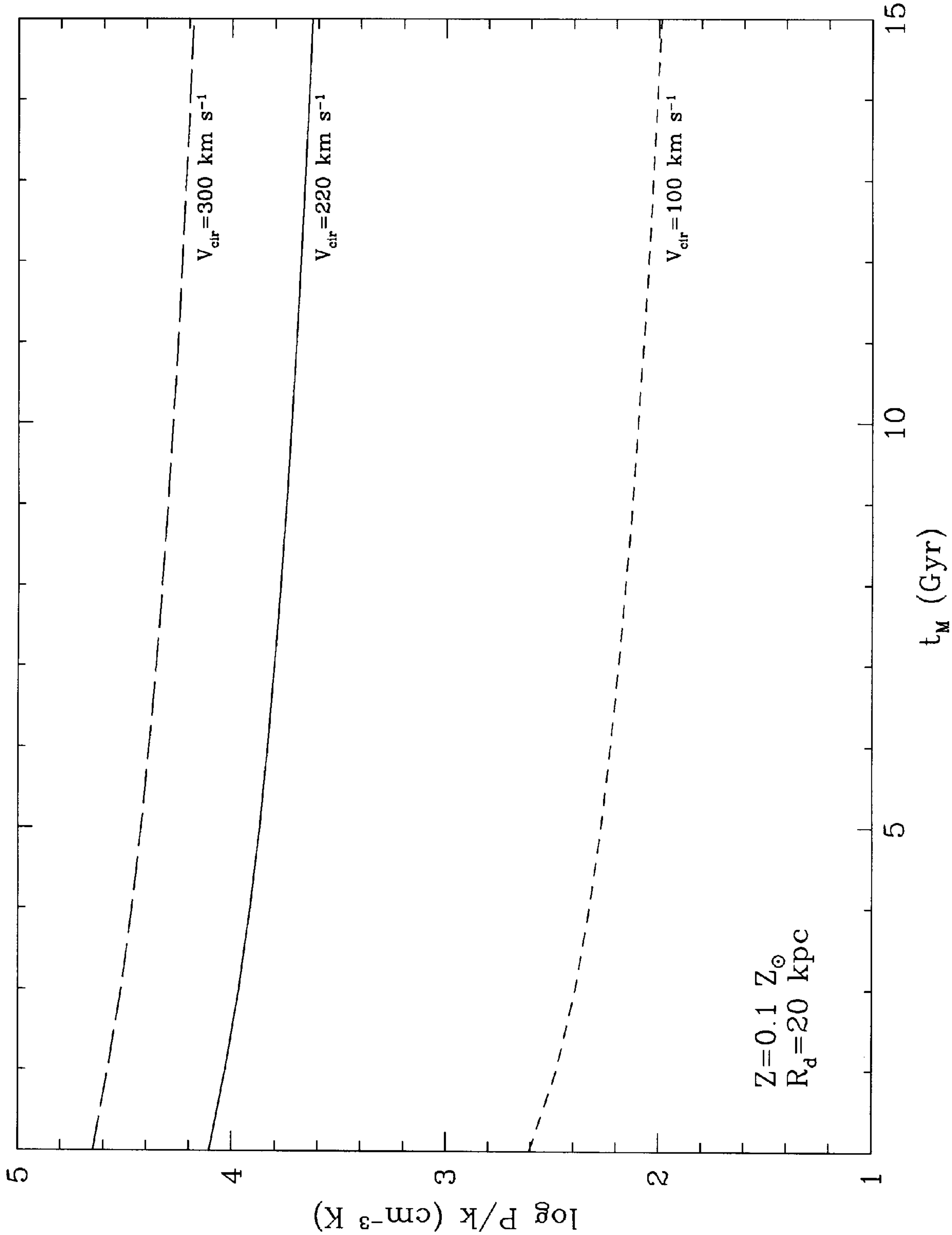

Fig. 1. *Thermal pressure of the hot halo at galactocentric distance* $R_d = 20$ *kpc at present epoch for* $f_g = 0.05$ *and several characteristic values of circular velocities of a galaxy, as a function of average interval between rehetaing* t_M*. Global halo metallicity is set to* $Z = 0.1\ Z_\odot$*. Long-dashed line corresponds to a very massive galaxy (*$V_{\rm cir} = 300$ *km* s^{-1}*), and shord-dashed line to low-mass galaxy (*$V_{\rm cir} = 100$ *km* s^{-1}*). The case of a typical* L_* *galactic halo is shown as the solid line (*$V_{\rm cir} \approx 220$ *km* s^{-1}*). We note that* P/k *stays approximately the same with reheating frequency taking all physically realistic values.*

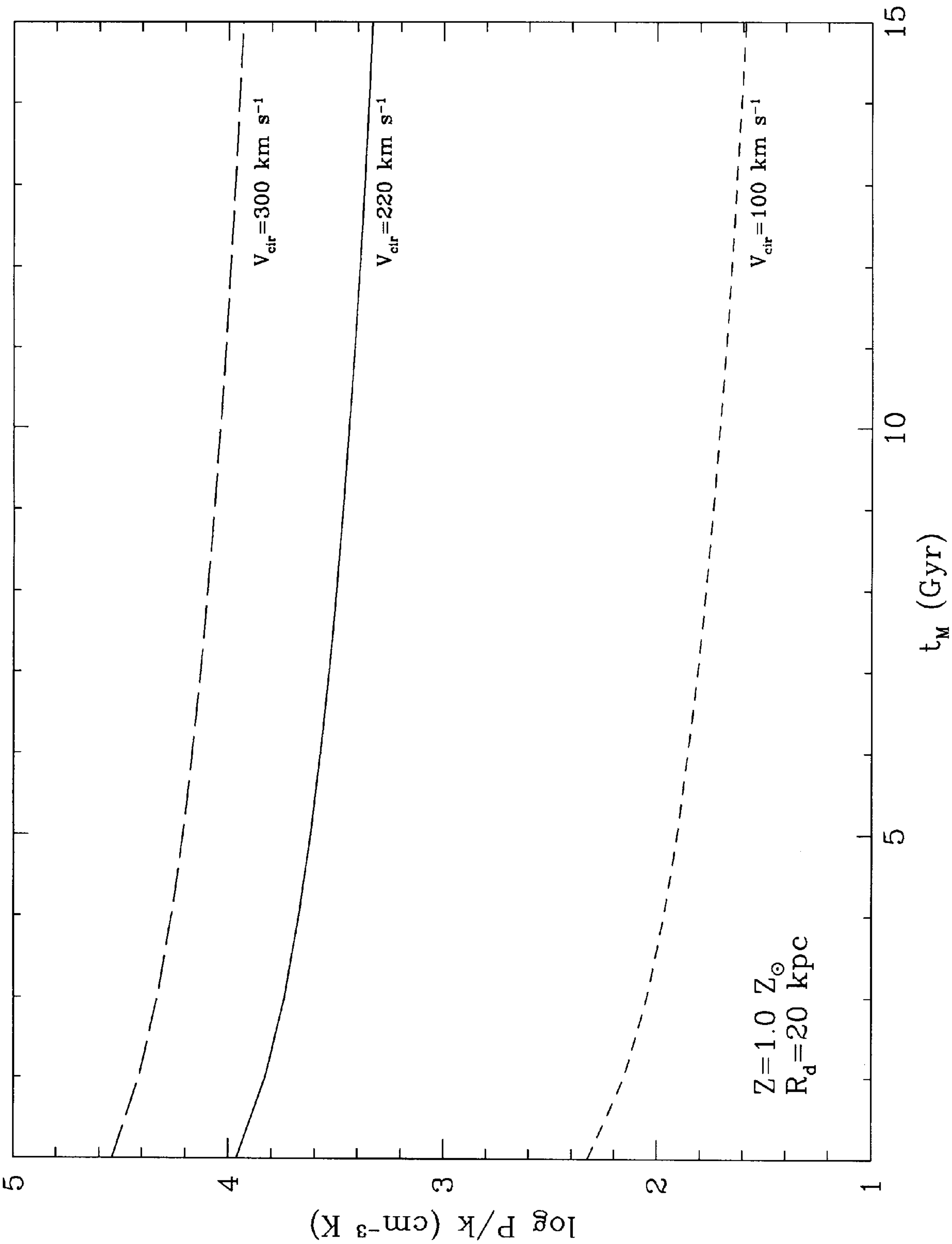

Fig. 2. *The same as in Fig. 1, except for the (unrealistic) case of halo gas having global metallicity equal to standard $Z_\odot$. Average values for the pressure are slightly lower due to more efficient cooling and consequent depletion of the hot phase.*

It seems clear that assumption of (quasi) hydrostatic equilibrium must be abandoned at some fiducial galactocentric radius, comparable to the size of disk in a spiral galaxy. This is not necessarily exact ISM-halo interface, since a lot of non-equilibrium and still poorly-understood phenomena ("galactic fountain", winds, superbubbles, etc.) will conceivably have the desired effect of "softening" the global pressure profile at $R \lesssim 50$ kpc. We shall neglect these dynamical effects, and following Mo (1994) regard rough size of the disk, $R_d = 20$ kpc as the inner boundary of the hot halo gas. This is justified on a qualitative basis, among other arguments, by the fact that no significant large-scale pressure gradients in the ISM of Milky Way were not observed, including observations toward high-latitude stars at galactocentric distance representing significant fraction of our chosen R_d.

It is natural to expect that approximately uniform – when averaged over individual clouds and intercloud medium – ISM pressure is in equilibrium with the thermal pressure of the envelopping halo gas for any reasonable choice of parameters (Spitzer 1978). Therefore, we have calculated pressure P/k at R_d (for $z = 0$, i.e. at the present epoch), as a function of T_M, a mean interval between reheating in major mergers. As is clear from the results obtained (see Figs. 1 and 2), the model is quite robust to the variations in t_M. For the case of a realistic Population II metallicity ($Z = 0.1\ Z_\odot$) shown in Fig. 1, changing t_M by more than an order of magnitude in the case of L_* galaxy results in change of P/k by a factor of ~ 2.5. Even if the metallicities are higher (MM96), the same tendency persists, as is shown in the plot in Fig. 2 (for the global gas metallicity equal to the standard solar, which is unrealistically high).

For comparison, the pressure in the local ISM was estimated by Spitzer (1978) as $P/k_\mathrm{B} = 1700$ K cm^{-3} ($\log P/k = 3.2$), or at large sample of measured clouds (Jenkins, Jura, & Loewenstein 1983)

$$3.4 \leq \log P/k_\mathrm{B} \leq 3.8. \qquad (6)$$

We note that, especially for higher values of t_M (favored also by the equation (5) and other data; see, for example, Keel & Wu 1995) theoretical values of the two-phase model are quite consistent with this empirical range. Other theoretical uncertainties, like that in a fraction of the virial mass contained in gas (parameter f_g in MM96), seem to be much greater than the one considered here.

4. DISCUSSION

Major weaknesses of the theoretical framework this simple, manifest themselves clearly in the fact that mergers are considered only in terms of reheating through arising shocks, neglecting the mass input which undoubtedly occurs. On the other hand, without a detailed understanding of the underlying physics of merging events, it is difficult to proceed in that direction. It is clear, though, that if the bulk of the mass deposition occurs at small enough distances (compared to the virial radius before the merger), hot gas will be just a transient phase before most of the mass goes into cold, photoionized clouds. This can be estimated as follows: if t_M is large compared to the timescale given by $\tau = 5\mu k T_0 / 2\Lambda(T_0)\rho(r_0)$ (where $T_0 = T_v(1 - K \ln \frac{r_0}{r_c})$ and $\rho(r_0)$ is given by the equation (2), with r_0 being the characteristic radius for mass deposition), a quasi-stationary state is reached, and the discussion we have followed applies.

We have so far discussed only rehetaing in major mergers, which undoubtedly occurs from empirical evidence (Keel & Wu 1995, and references therein). Other conceivable reheating mechanisms (starbursts or switching on of a nuclear source) may be important in the inner part of the halo and should be considered in a future work.

We have shown that simple model based on assumptions of adiabaticity and quasi hydrostatic equilibrium gives physically acceptable results for the pressure at the ISM-halo interface, results which are quite insensitive to the assumptions about reheating frequency $1/t_M$. Until our theoretical knowledge on merger frequencies (or other reheating mechanisms) improves, we are justified in using simple approximations like (5).

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ПРИТИСАК НА ГРАНИЦИ ХАЛОА И МЕЂУЗВЕЗДАНЕ СРЕДИНЕ: ЗАВИСНОСТ ОД ФРЕКВЕНЦИЈЕ ЗАГРЕВАЊА

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Оригинални научни рад

Један од значајних параметара сваког модела галактичког халоа јесте просечан временски интервал који протиче између епизода поновног загревања током галактичке историје. Ово је од кључне важности за проверу темељне претпоставке стационарности процеса хлађења и колапса гасне компоненте преостале након епохе формирања галаксија. У овом раду се разматра како промене у фреквенцији загревања гаса кроз сударе и стапања галаксија утичу на термални притисак топлог халоа на његовој граници са галактичким међузвезданим медијумом. То је интересантно с обзиром да се равнотежа притиска нужно формира у сваком стационарном моделу, а термални притисак међузвезданог медијума је опсервабилна величина, која представља једно од најједноставнијих емпиријских ограничења на сваки теоријски модел гаса у галаксијама. Испоставља се да је најједноставнији двофазни адијабатски модел (Mo and Miralda-Escudé 1996) прилично робустан у погледу неодређености у просечном интервалу између поновног загревања.