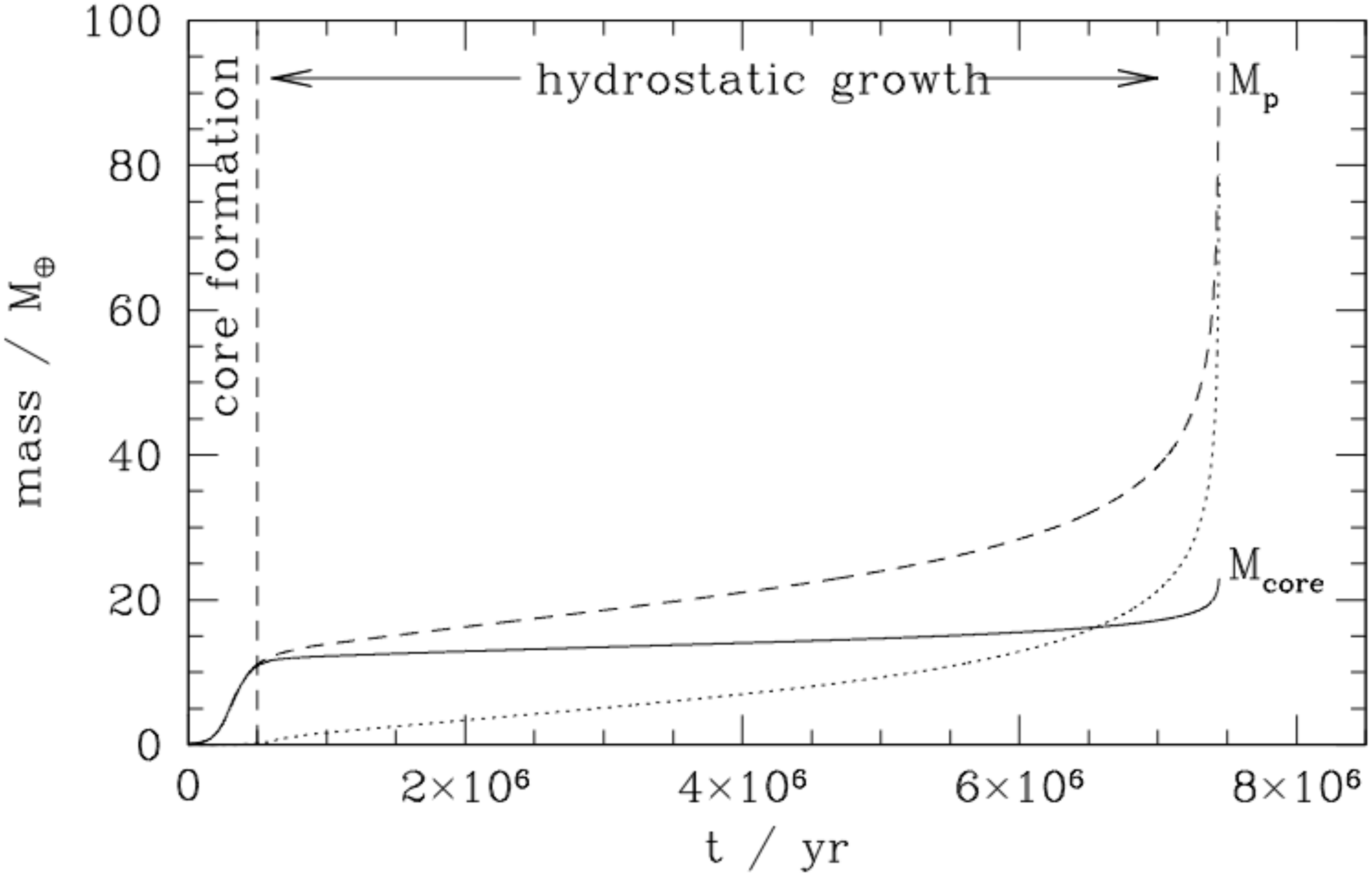
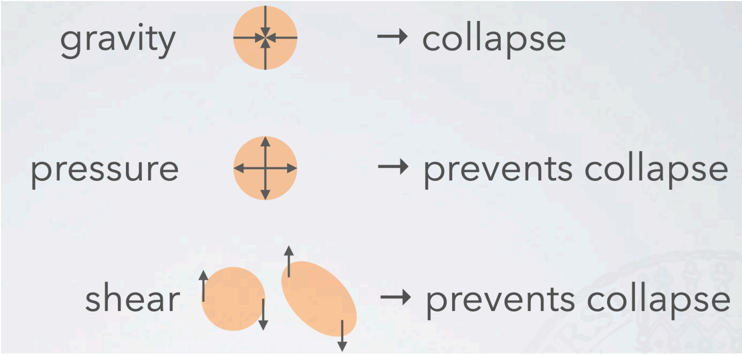
Class 24 – Apr 28^{th}, 2020

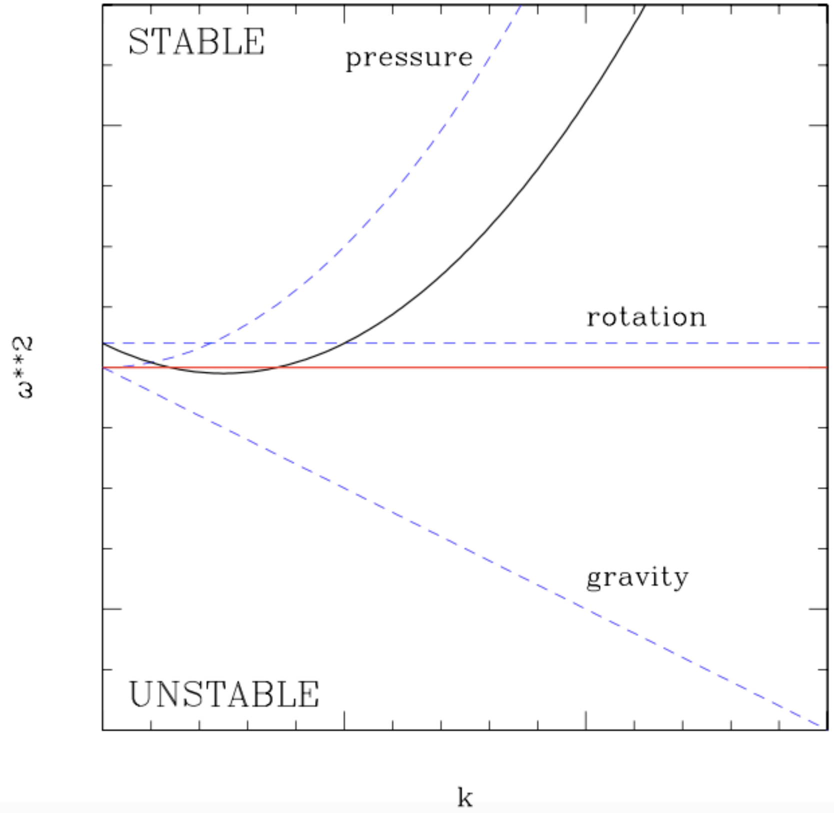
Core accretion



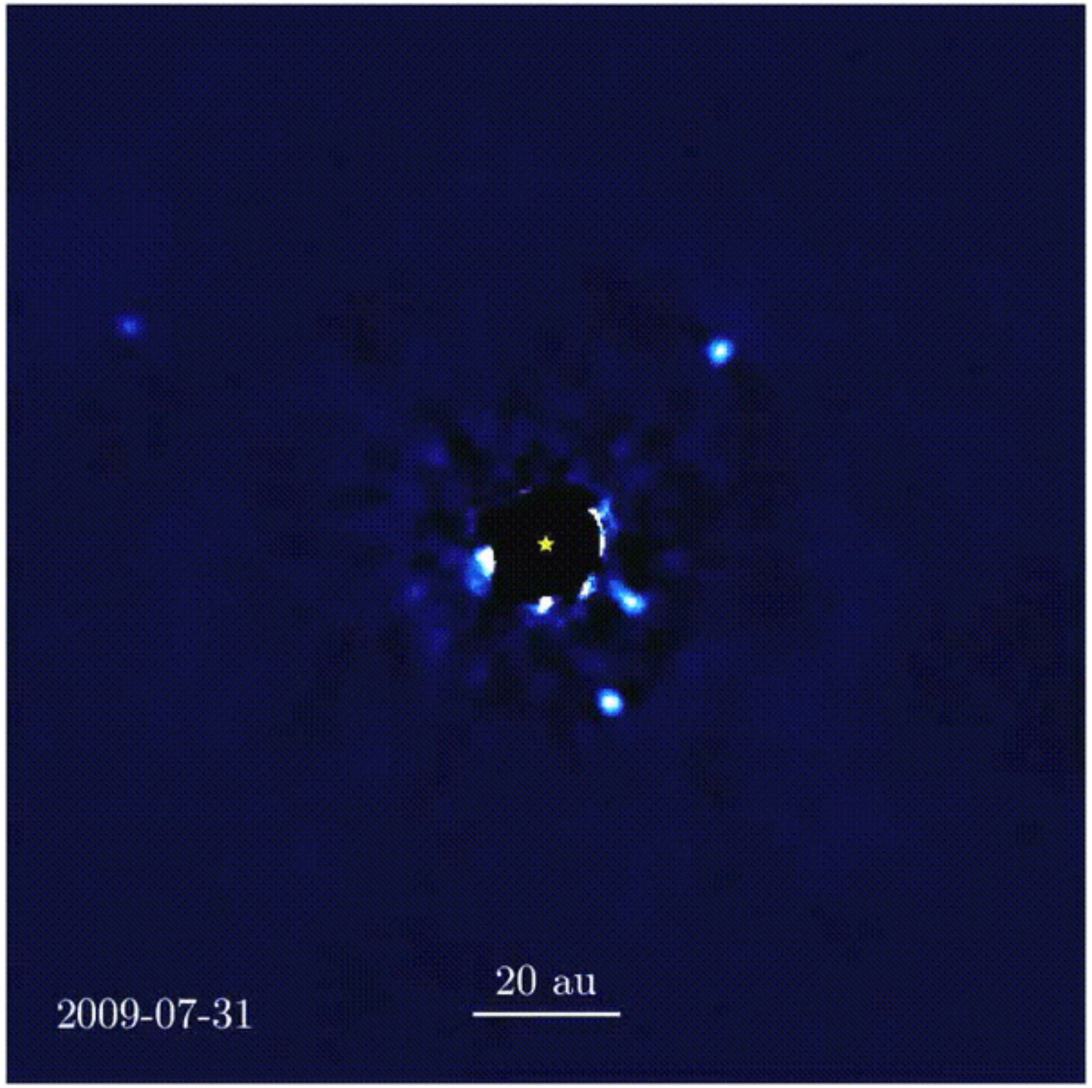
Gravitational Instability



$$\omega^2 = c_s^2 k^2 - 2\pi G \Sigma_0 k + \kappa^2$$



HR 8799

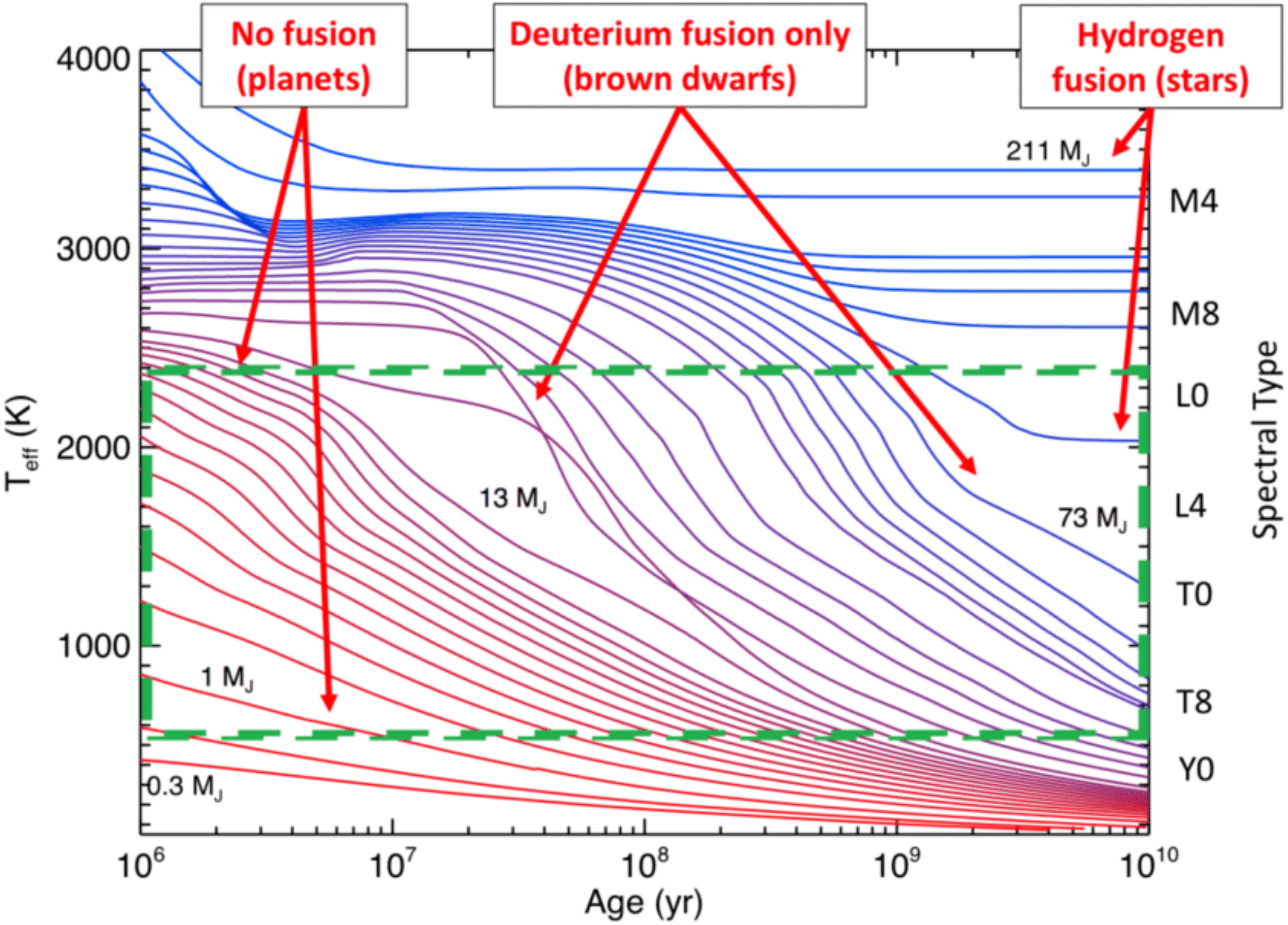


Cold Start

vs

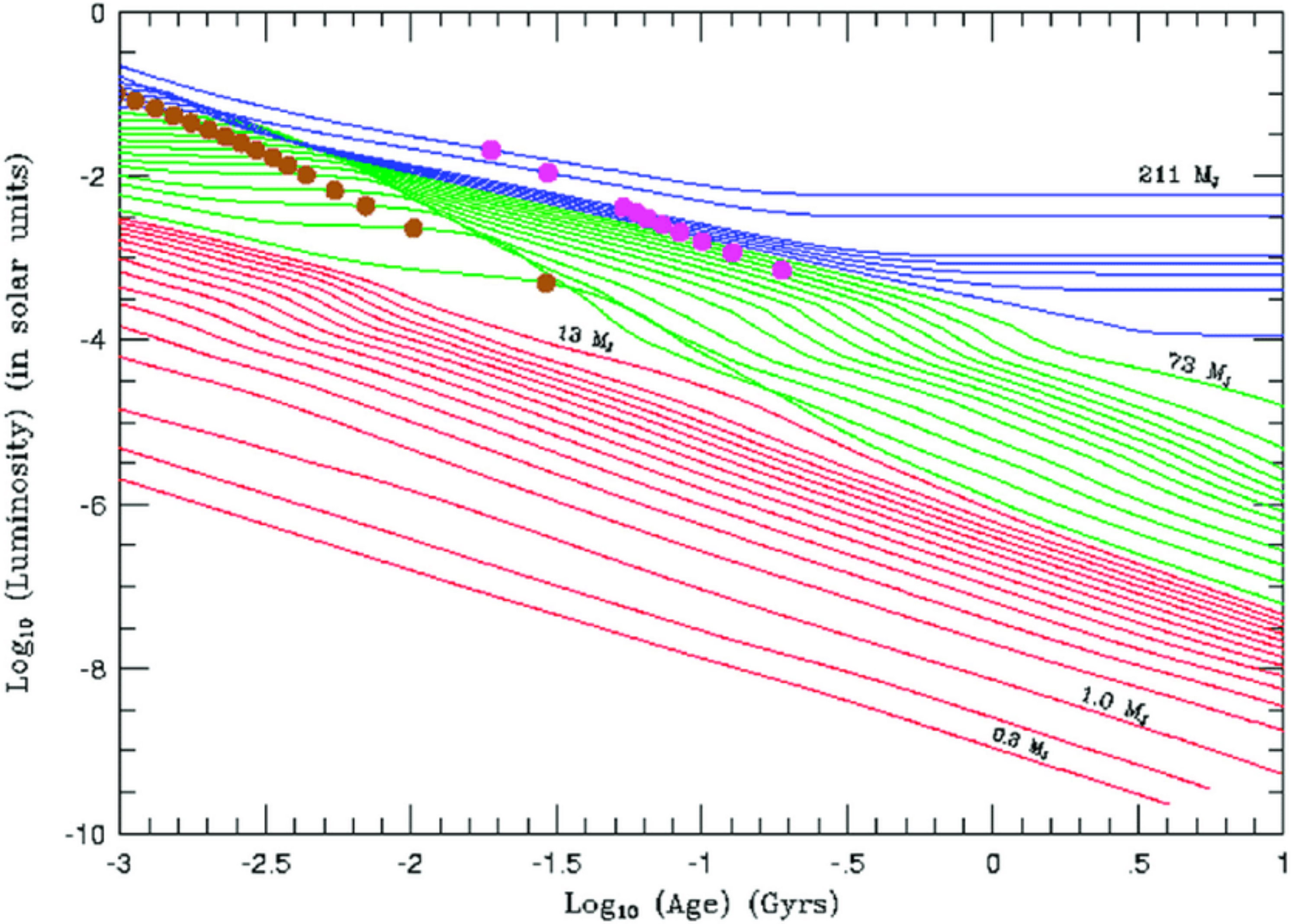
Hot Start

Temperature of Substellar Objects



Burrow et al. 2012

Luminosity of Substellar Objects



Burrow et al. 2012

Cooling curve of "Hot Accretion"

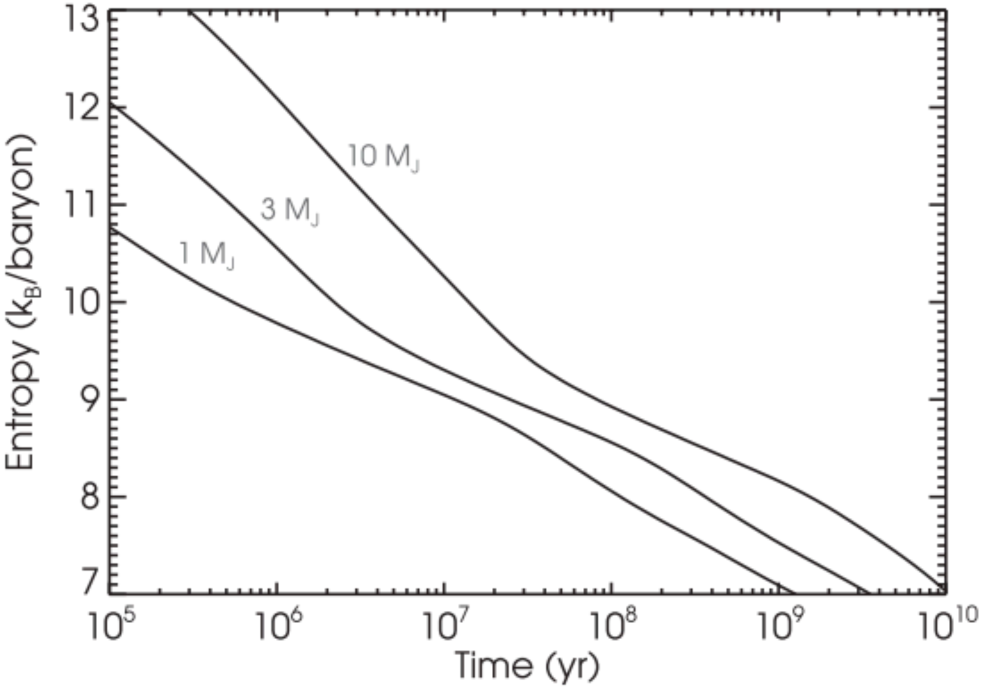
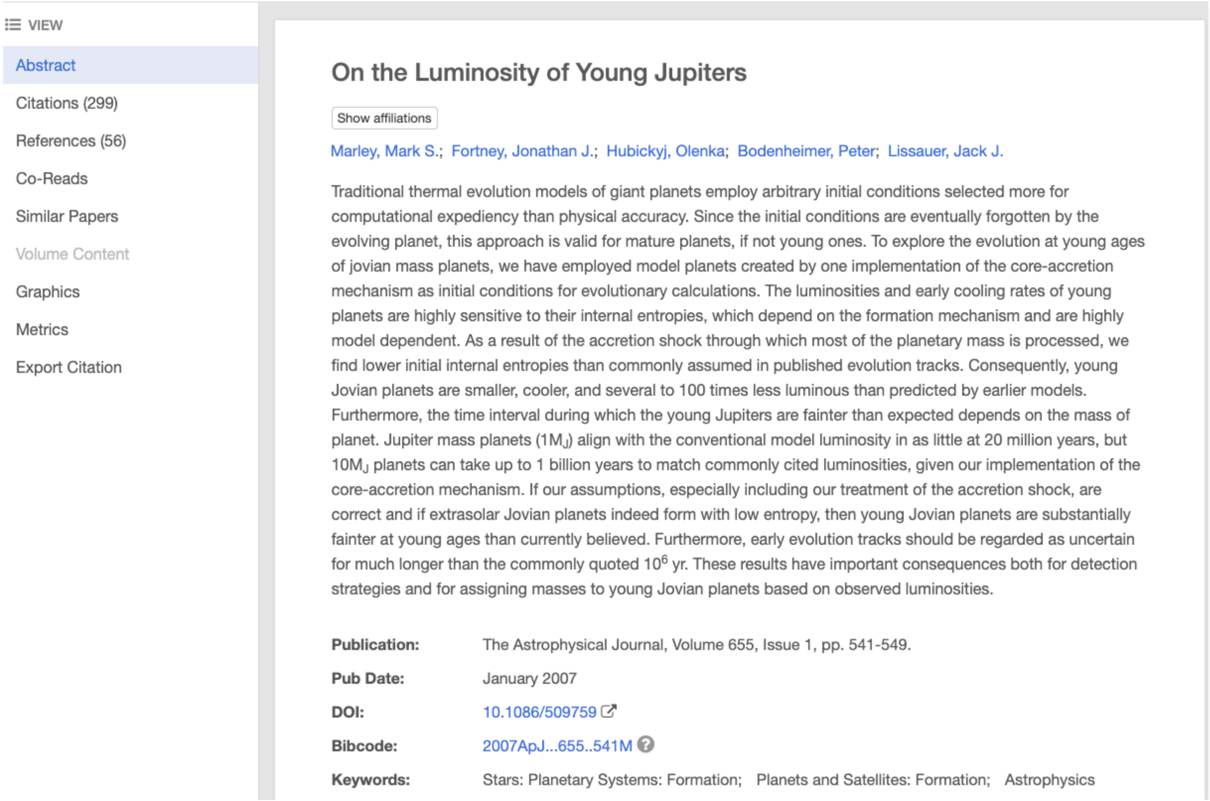


Figure 6. Entropy of hot starts as a function of time for planet masses of 1, 3 and 10 M_J (bottom to top). At a given age, the curve indicates the value of initial entropy above which the 'hot-start mass' applies. For a planet mass larger than the hot-start value, the initial entropy must be lower than the hot-start entropy at the current age.

Marley et al. 2007

Luminosity of Planets formed by Core Accretion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On the Luminosity of Young Jupiters

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Marley, Mark S.; Fortney, Jonathan J.; Hubickyj, Olenka; Bodenheimer, Peter; Lissauer, Jack J.

Traditional thermal evolution models of giant planets employ arbitrary initial conditions selected more for computational expediency than physical accuracy. Since the initial conditions are eventually forgotten by the evolving planet, this approach is valid for mature planets, if not young ones. To explore the evolution at young ages of jovian mass planets, we have employed model planets created by one implementation of the core-accretion mechanism as initial conditions for evolutionary calculations. The luminosities and early cooling rates of young planets are highly sensitive to their internal entropies, which depend on the formation mechanism and are highly model dependent. As a result of the accretion shock through which most of the planetary mass is processed, we find lower initial internal entropies than commonly assumed in published evolution tracks. Consequently, young Jovian planets are smaller, cooler, and several to 100 times less luminous than predicted by earlier models. Furthermore, the time interval during which the young Jupiters are fainter than expected depends on the mass of planet. Jupiter mass planets ($1M_J$) align with the conventional model luminosity in as little at 20 million years, but $10M_J$ planets can take up to 1 billion years to match commonly cited luminosities, given our implementation of the core-accretion mechanism. If our assumptions, especially including our treatment of the accretion shock, are correct and if extrasolar Jovian planets indeed form with low entropy, then young Jovian planets are substantially fainter at young ages than currently believed. Furthermore, early evolution tracks should be regarded as uncertain for much longer than the commonly quoted 10^6 yr. These results have important consequences both for detection strategies and for assigning masses to young Jovian planets based on observed luminosities.

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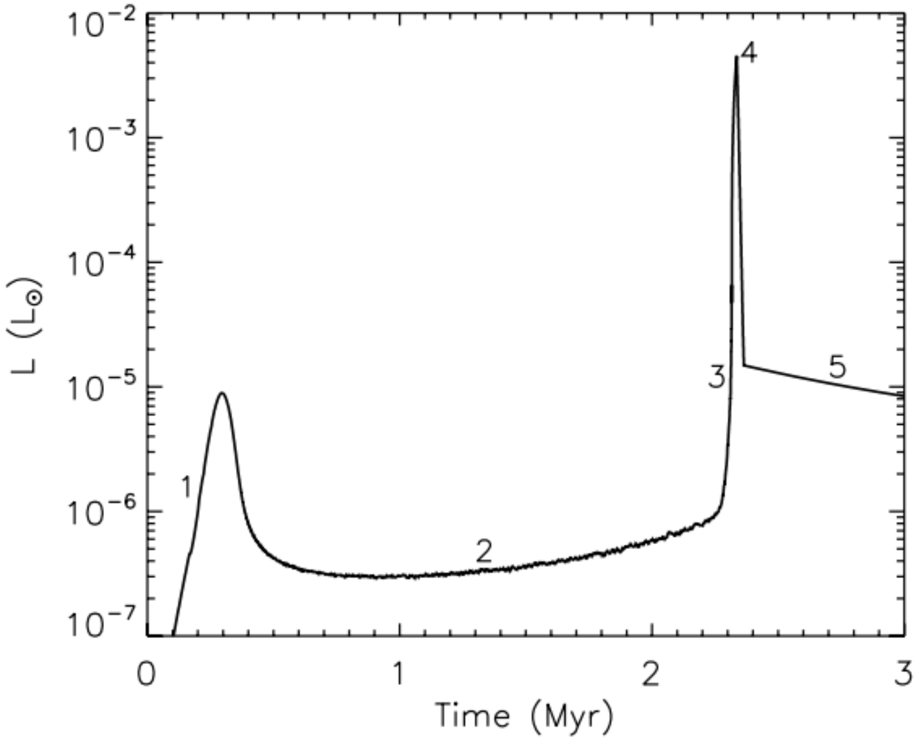

FIG. 1.—Luminosity of a $1M_J$ planet as a function of time. Numbers refer to various stages in the formation/contraction process as discussed in the text. In this figure, time $t = 0$ is chosen to be the start of the growth of the solid core. Model, through stage 4, is the 10L∞ case of Hubickyj et al. (2005). Subsequent evolution is calculated as described in § 3.

Marley et al. 2007

“Hot start” vs “Cold start”

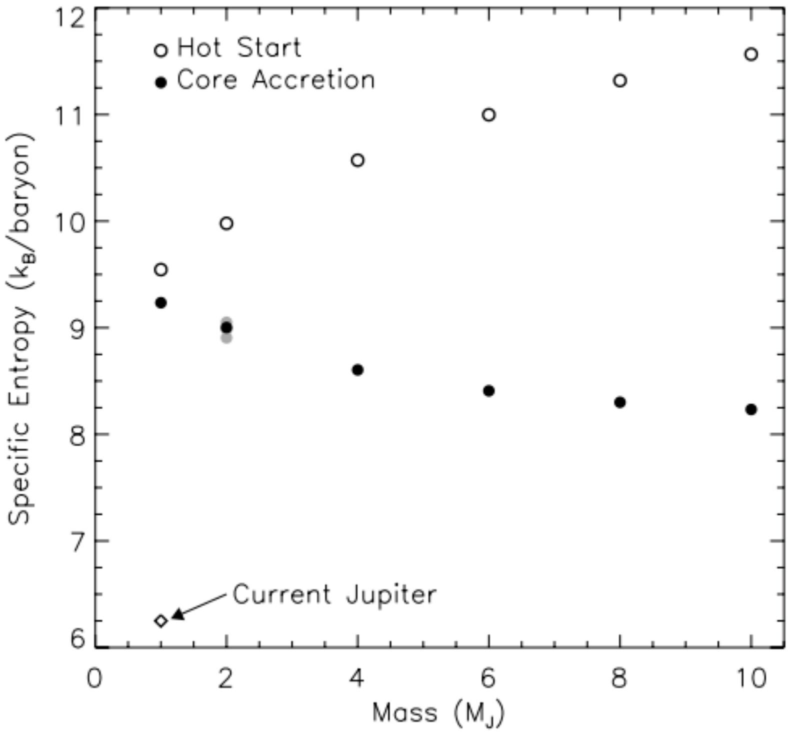

FIG. 2.—Specific entropy of young giant planets formed by the core-accretion and hot-start assumptions. Since almost all of the mass of the planet sits on a single adiabat, the interior temperature-pressure conditions can be characterized by the entropy of that adiabat. For both cases, the entropy plotted is at 1 Myr after the first time step in the evolution model. Shaded circles at $2M_J$ denote entropies of various alternate cases for the core-accretion model, as shown in Fig. 5 and discussed in § 4.3. In the core-accretion case, this is 1 Myr after the end of accretion. The entropy of the current Jupiter is also shown for comparison.

During this time of rapid gas accretion, the accreting gas is assumed to fall from the Hill sphere radius down to the surface of the planet. It arrives at a shock interface where almost all of the initial gravitational potential energy of the gas is radiated away upward, as occurs for accreting stars (Stahler et al. 1980). This produces a rapid increase in luminosity, and the planet briefly shines quite brightly. *Crucial to the problem at hand is that the gas arrives at the surface of the planet having radiated away most of its gravitational potential energy and initial specific entropy and having equilibrated with the local thermal radiation field.*

Marley et al. 2007

Hydrodynamical models of the accretion shock

Thermodynamics of giant planet formation: shocking hot surfaces on circumplanetary discs

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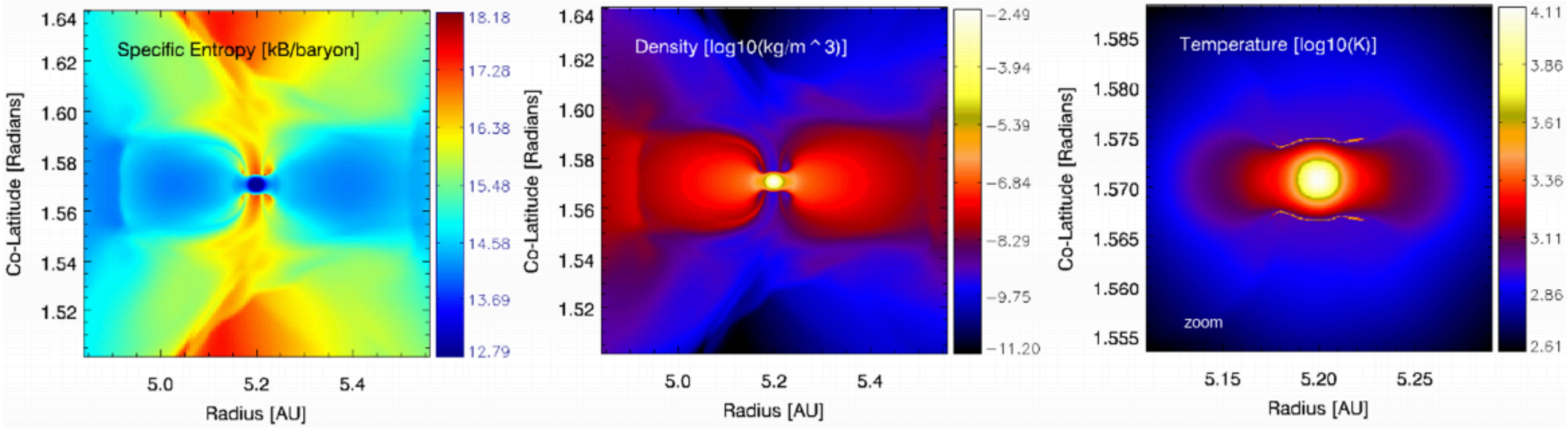
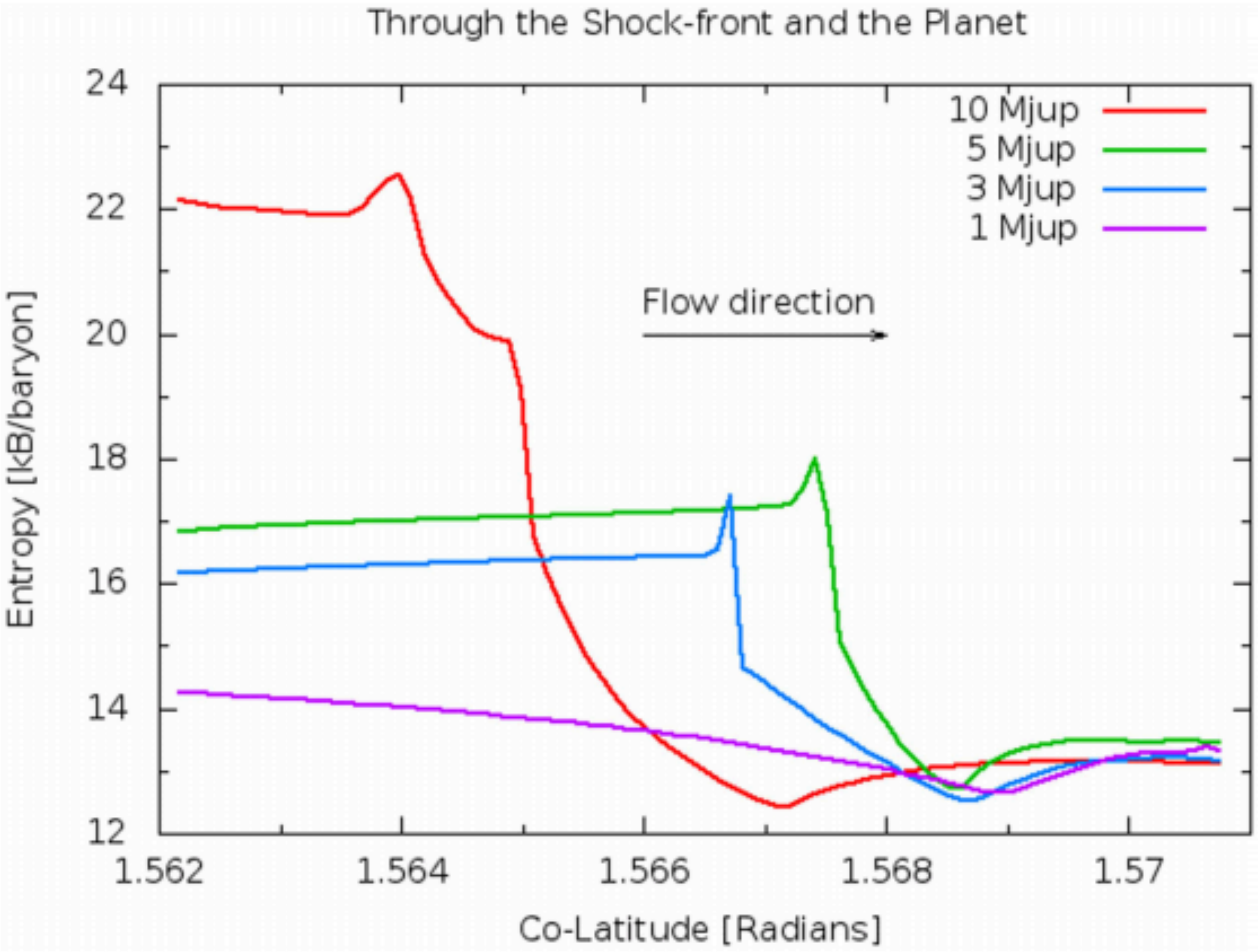


Entropy loss at the shock



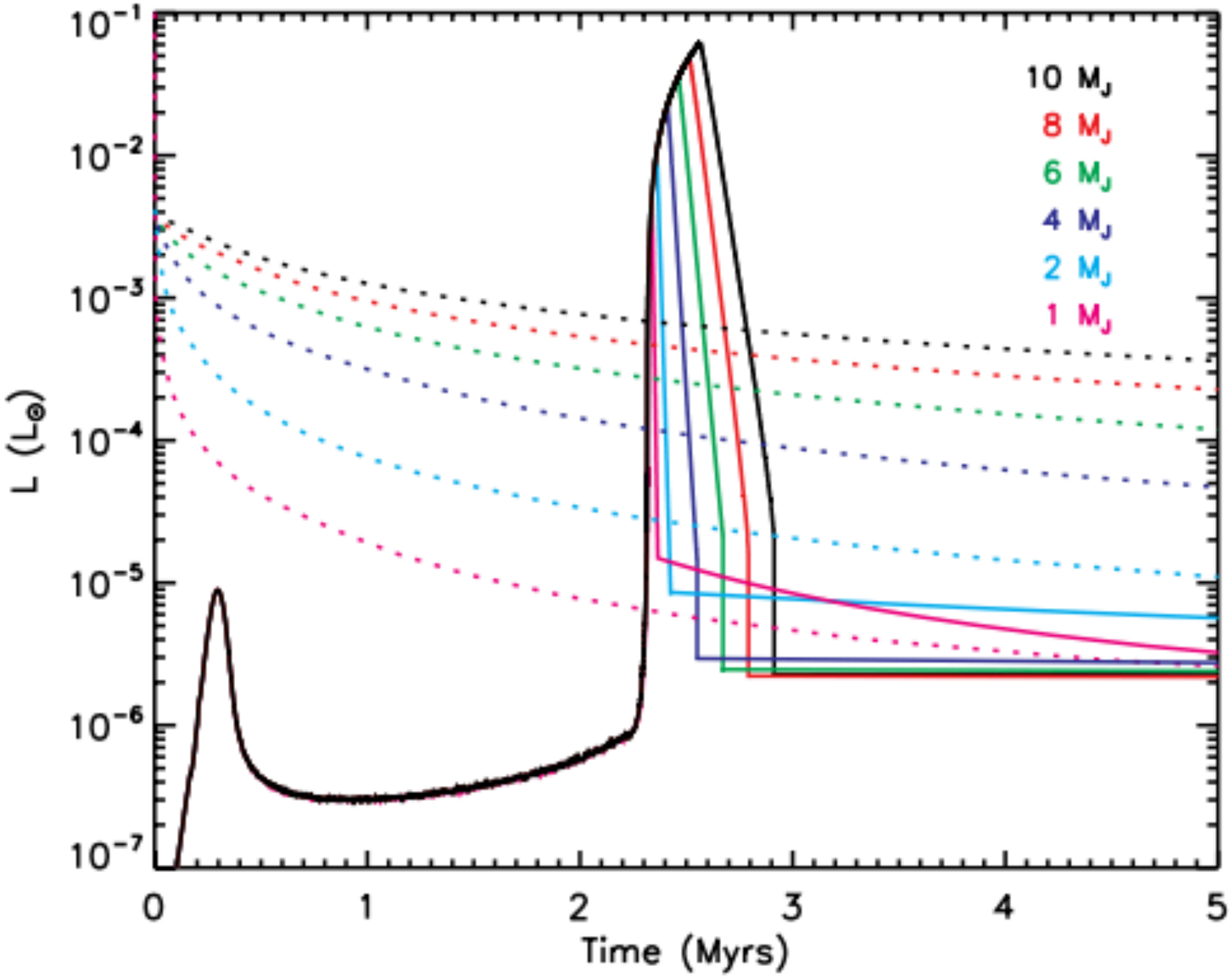
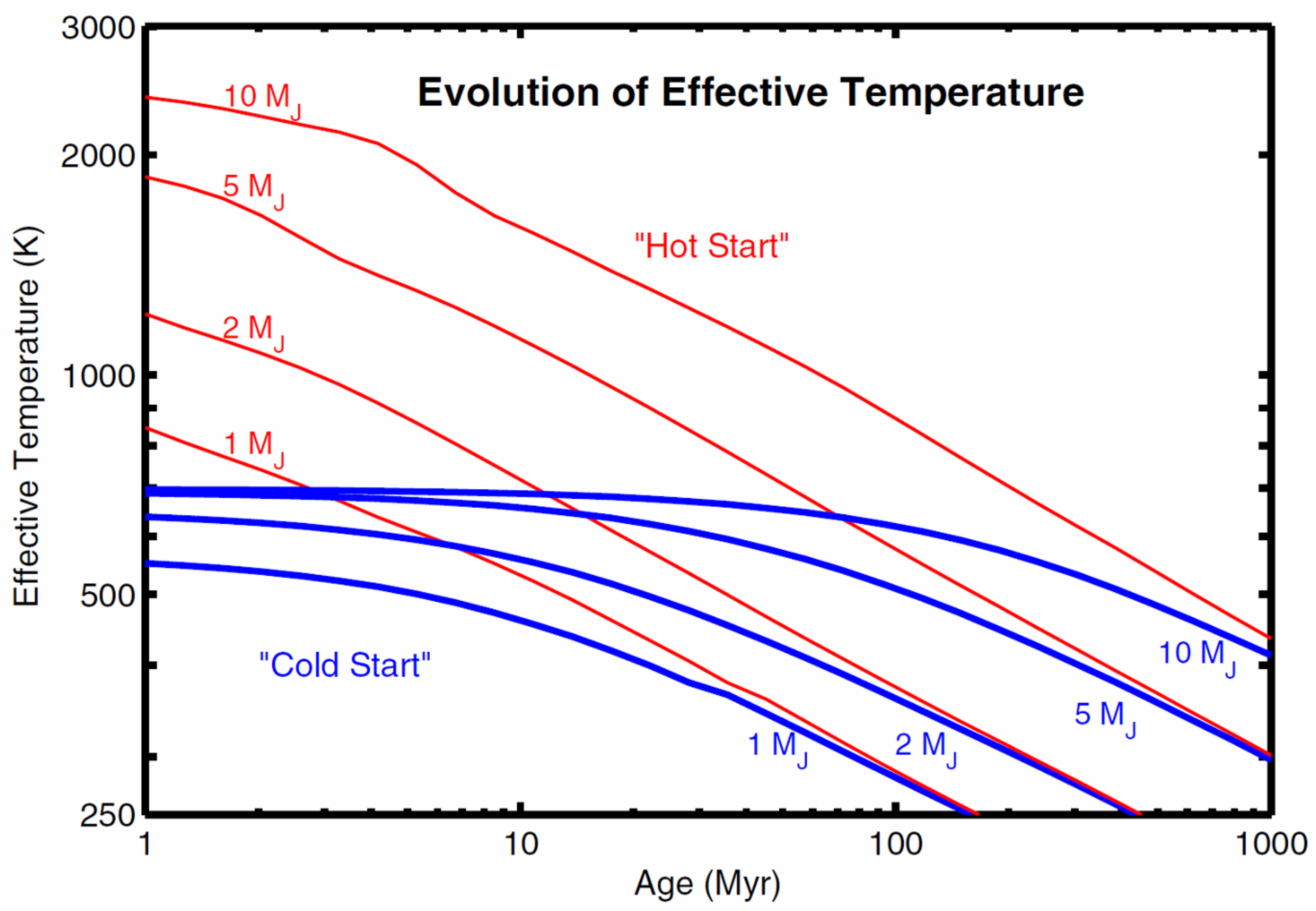
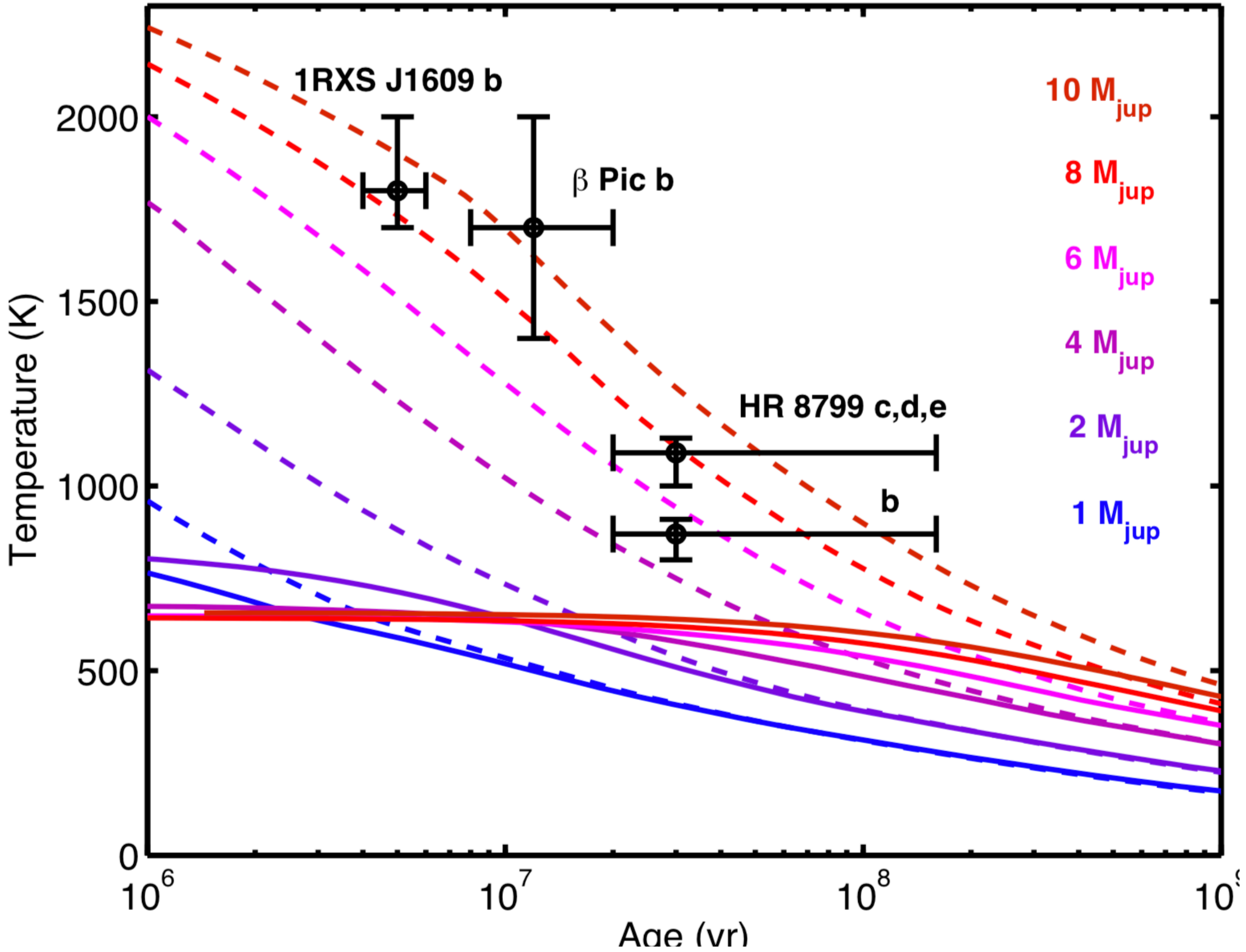


FIG. 3.—Luminosity of young Jupiters of various masses as a function of time. Dotted lines are for a hot-start evolution calculation as described in the text. Solid lines denote the core-accretion case. In this figure, time $t = 0$ is chosen to be the start of the growth of the solid core for the nucleated collapse scenario and the first model of the hot-start evolution.

“Hot start” vs “Cold start”



Comparison to Observations



Janson et al. 2014

“Hot start” vs “Cold start”

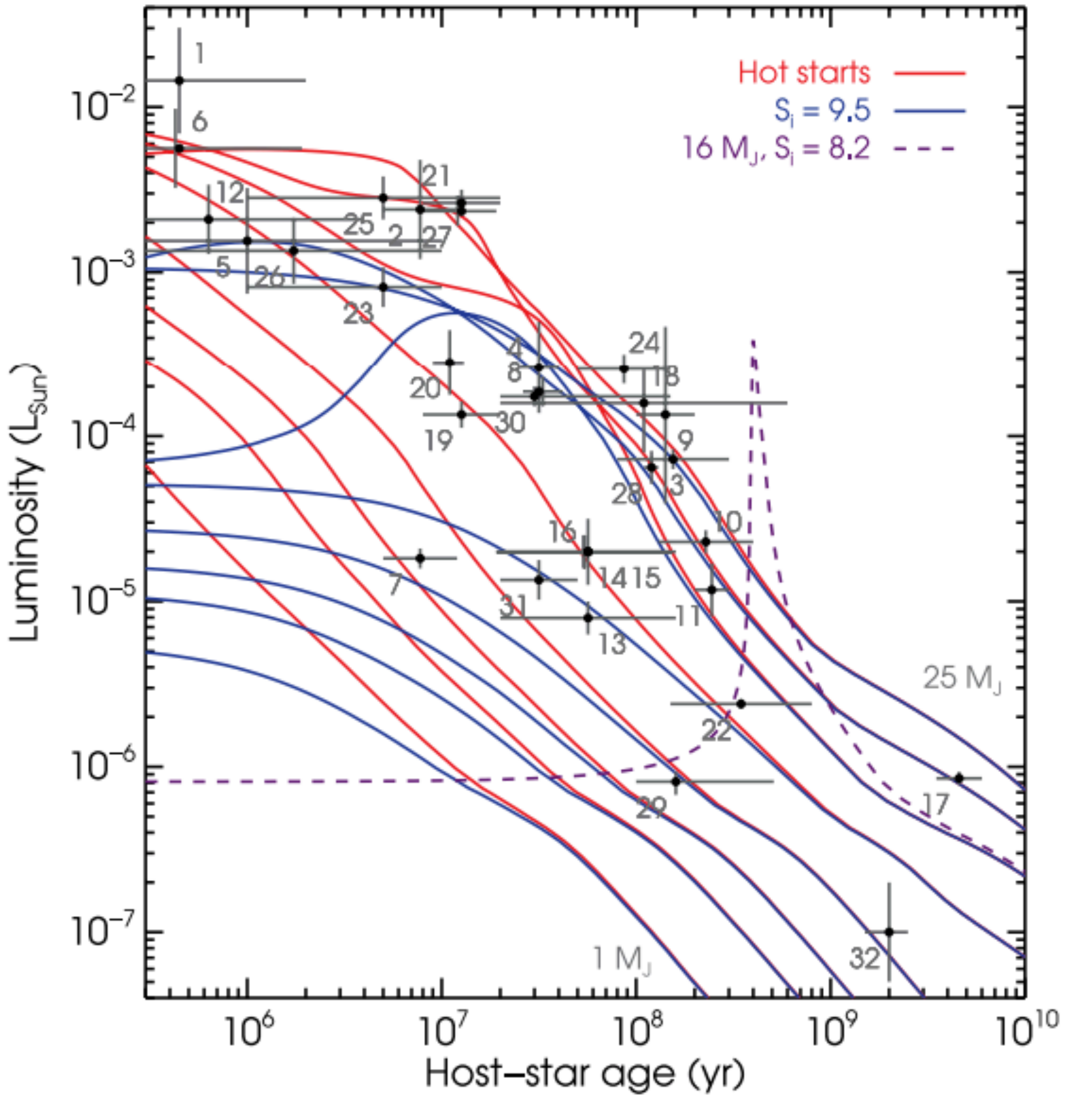
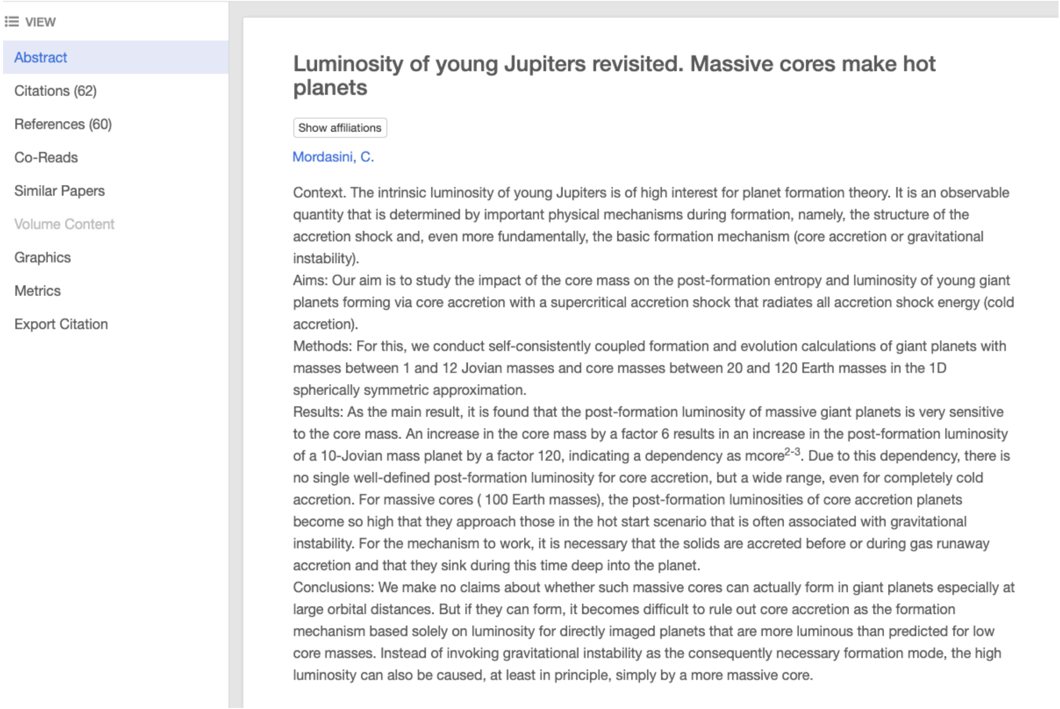


Fig. 8 shows that there are already many data points which – at least based solely on their luminosity – could be explained by cold, warm or hot starts, highlighting the importance of being open-minded about the initial entropy when interpreting these observations. Indeed, as Mordasini et al. (2012a) carefully argue, it is presently not warranted to assume a unique mapping between CA and cold starts on the one hand, and gravitational instability and hot starts on the other hand. [Even in the case of a weak

Marleau & Cumming 2014

Warm and hot start by core accretion



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Luminosity of young Jupiters revisited. Massive cores make hot planets

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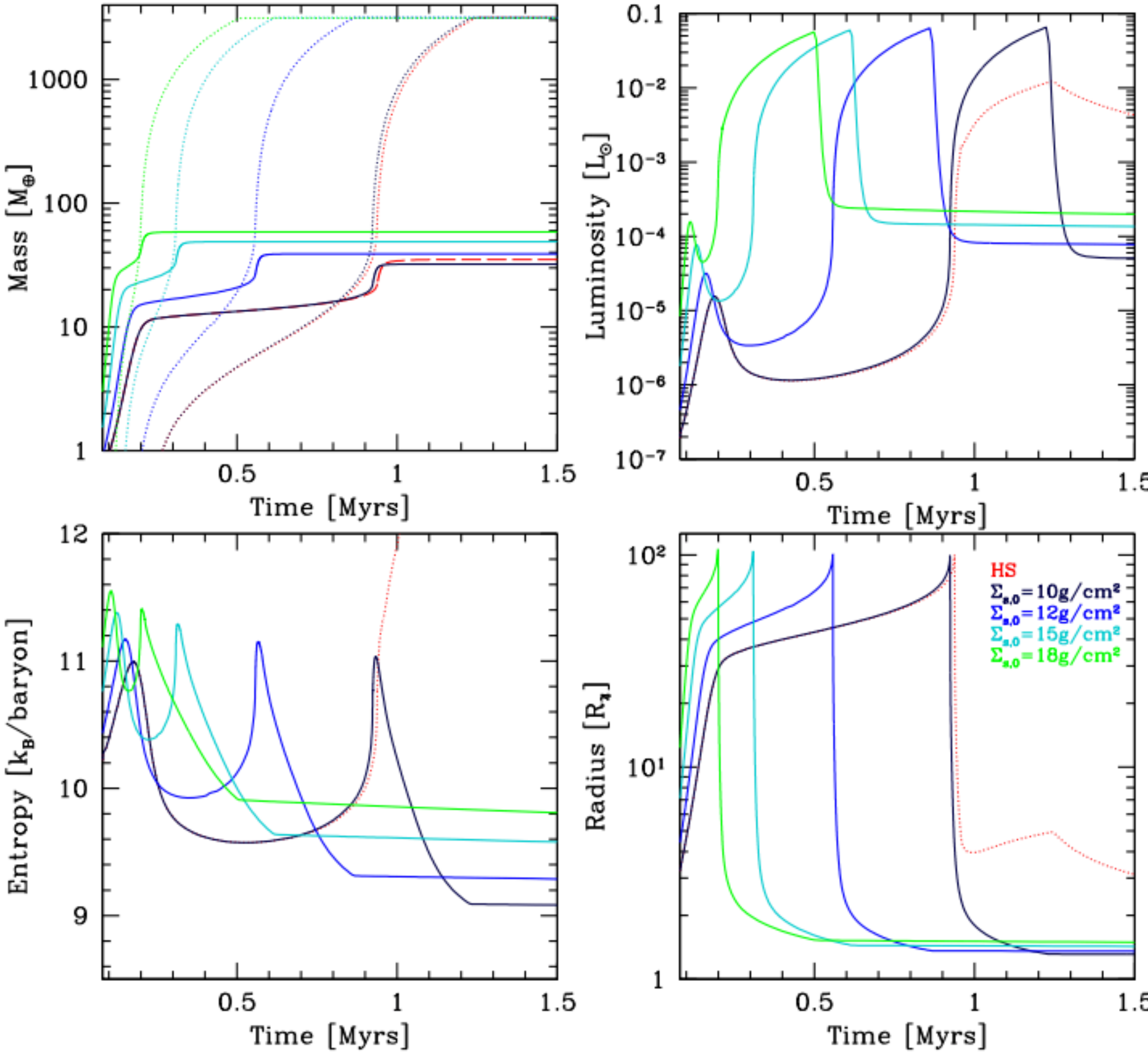
Mordasini, C.

Context. The intrinsic luminosity of young Jupiters is of high interest for planet formation theory. It is an observable quantity that is determined by important physical mechanisms during formation, namely, the structure of the accretion shock and, even more fundamentally, the basic formation mechanism (core accretion or gravitational instability).
Aims: Our aim is to study the impact of the core mass on the post-formation entropy and luminosity of young giant planets forming via core accretion with a supercritical accretion shock that radiates all accretion shock energy (cold accretion).
Methods: For this, we conduct self-consistently coupled formation and evolution calculations of giant planets with masses between 1 and 12 Jovian masses and core masses between 20 and 120 Earth masses in the 1D spherically symmetric approximation.
Results: As the main result, it is found that the post-formation luminosity of massive giant planets is very sensitive to the core mass. An increase in the core mass by a factor 6 results in an increase in the post-formation luminosity of a 10-Jovian mass planet by a factor 120, indicating a dependency as m_{core}^{2-3}. Due to this dependency, there is no single well-defined post-formation luminosity for core accretion, but a wide range, even for completely cold accretion. For massive cores (100 Earth masses), the post-formation luminosities of core accretion planets become so high that they approach those in the hot start scenario that is often associated with gravitational instability. For the mechanism to work, it is necessary that the solids are accreted before or during gas runaway accretion and that they sink during this time deep into the planet.
Conclusions: We make no claims about whether such massive cores can actually form in giant planets especially at large orbital distances. But if they can form, it becomes difficult to rule out core accretion as the formation mechanism based solely on luminosity for directly imaged planets that are more luminous than predicted for low core masses. Instead of invoking gravitational instability as the consequently necessary formation mode, the high luminosity can also be caused, at least in principle, simply by a more massive core.



Warm and hot start by core accretion

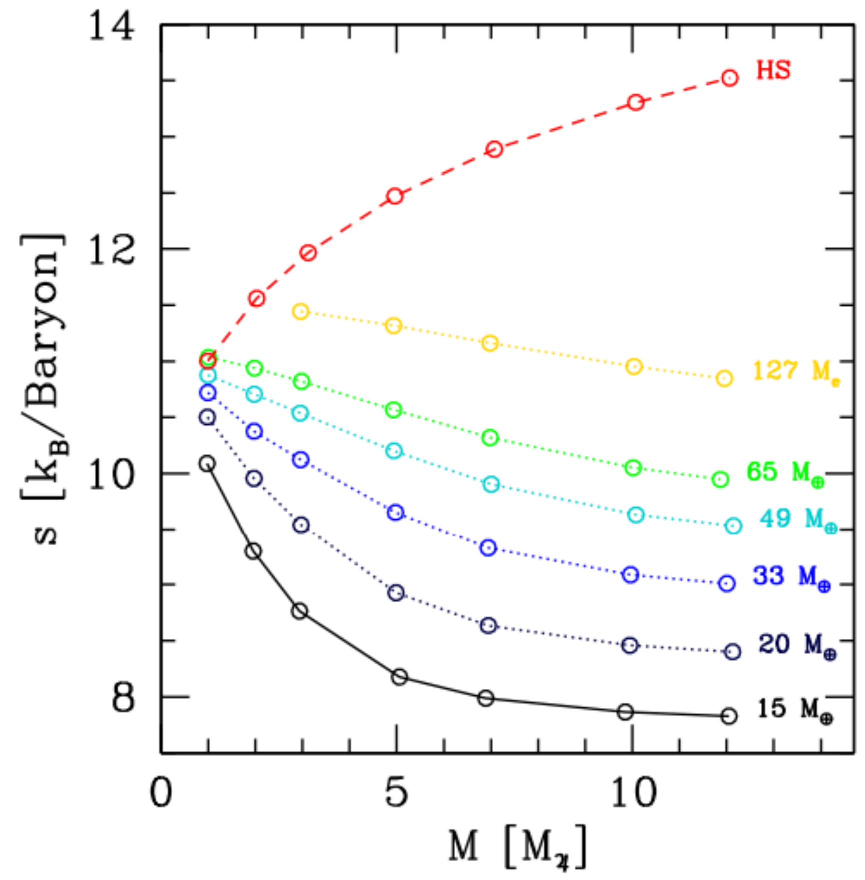


Fig. 2. Post-formation entropy as function of total mass and for six different core masses indicated in the plot for cold accretion. The red dashed line labelled HS is for hot accretion.

Warm and hot start by core accretion

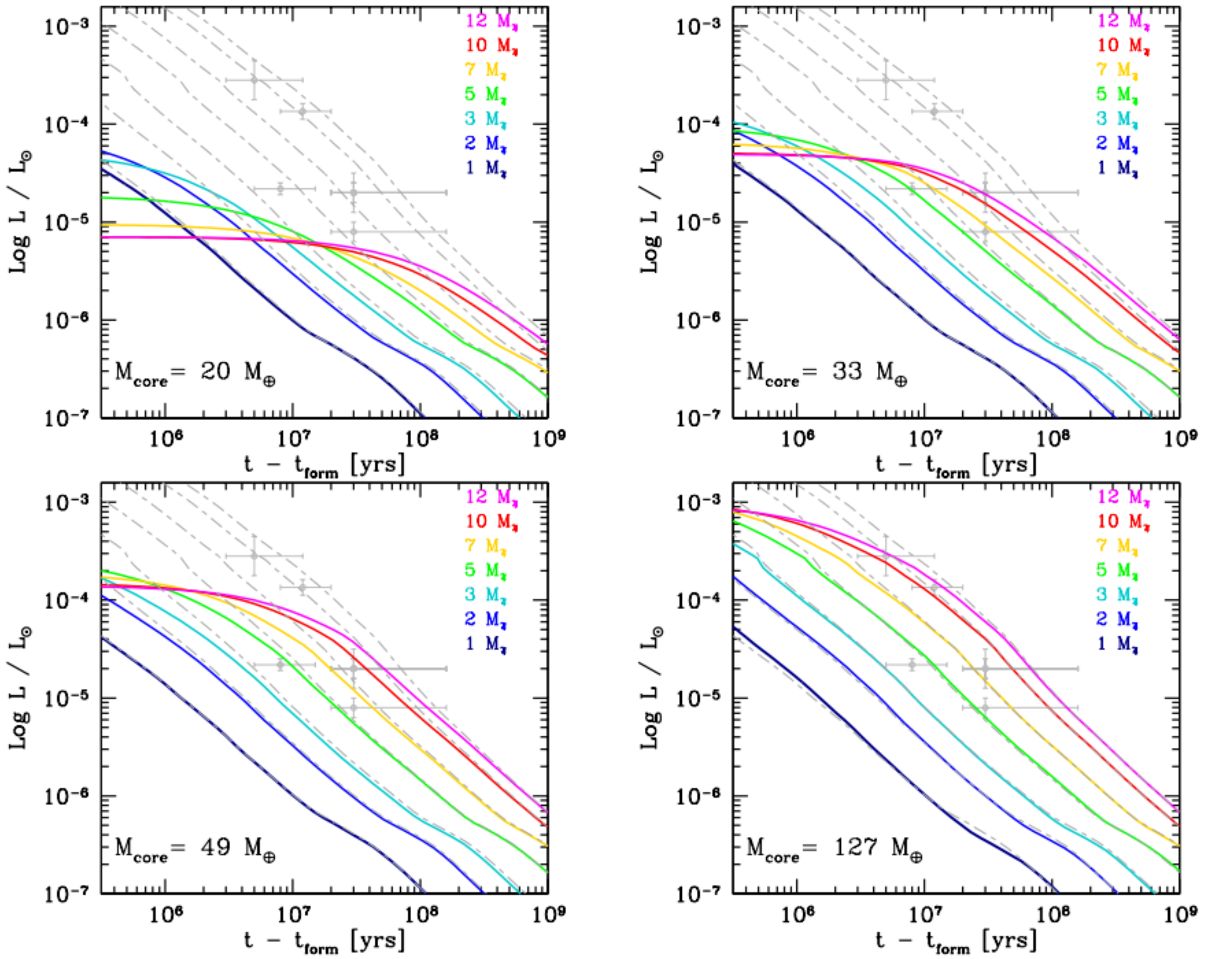


Fig. 3. Luminosity as a function of time after formation for planets with total masses of 1, 2, 3, 5, 7, 10, and 12 M_{J} and core masses of 20, 33, 49, and 127 $M_{\oplus}$ as indicated in the panels. The colored solid lines assume cold accretion. The dashed-dotted gray lines assume hot accretion. The points with error bars are young giant planets (*from top to bottom*: 1RXS1609 b, Beta Pic b, 2M1207 b, HR8799c,d,e, HR8799 b).