Accretion Delay in Massive Star Formation

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It is bona-fide knowledge that, radiative feedback from the core of a pre-main sequence (PMS) star leads to a global accretion delay in stellar formation. How long the accretion delay lasts, remains poorly constrained in existing numerical and analytical model. This problem is more common in massive star formation where the global accretion delay leads to modulated accretion rates which effectively traps massive stars in a pre-ignition bottleneck, where they exhaust their energy supply before achieving stable nuclear fusion. Numerical tools capable of this task are lacking at present. We consider the present investigation an important step in this direction. Here we show that, in a radiative pressure-dominated regime, an unprecedented radiative contraction delay $t_{\rm RD}$, must exceed the Kelvin-Helmholtz timescale ($t_{\rm KH}$). This uncertainty poses a major stumbling block in our current understanding of stellar evolution.

1 Introduction

1.1 Context

According to current and prevailing wisdom, it is well-established scientific knowledge that our current understanding of massive star formation is lacking[1–7]. This is due to the existing theoretical and observational dichotomy[2,3]. In the gestation period of a star's life, its mass will grow via the in-falling envelope (i.e., circumstellar material) and also through the formation of an accretion disk lying along the plane of its equator. This accretion disk is thought to be the birthplace of planets. The transition from the PMS to the main sequence phase therefore constitutes an epoch in the stellar evolution[5]. When represented on the HR diagram, low-mass proto(stars) typically evolve along the nearly vertical Hayashi track, marked by a decline in luminosity at a constant effective temperature.

In contrast, massive proto(stars) spend little to no time on the Hayashi track. Instead, they predominantly evolve along the nearly horizontal Henyey et al. track, where their bolometric luminosity remains nearly constant while their effective temperature steadily rises. Prior to entering the main sequence phase, the proto(star)'s luminosity is sustained by the release of gravitational potential energy from its dense, contracting core. The conversion of gravitational potential energy into radiation takes place in the Kelvin-Helmholtz contraction phase, as the protostar radiates its thermal energy while contracting quasi-statically. As the core further contracts and heats up, the star transitions from being fully convective to having a radiative core where energy is transported primarily by radiation. With the temperature and density of the core approaching the threshold for nuclear fusion, the contraction rate slows, marking the star's transition from the Kelvin-Helmholtz timescale to the nuclear timescale. Hydrostatic and thermal equilibrium is then established when hydrogen fusion ignites in the stellar core, marking the star's arrival onto the zero-age main sequence (ZAMS).

Stars evolve through different phases, each characterized by a distinct timescale, i.e: 1) the rapid adjustment period for a star to restore hydrostatic equilibrium after perturbations in its internal pressure-gravity balance takes place on the dynamical timescale, t_{Dyn}. This timescale varies significantly depending on the stellar type and density. For instance, it can be as short as seconds for highly dense white dwarfs[10] to about an hour in Sun-like main-sequence stars, and tens of days for large, less dense stars like red giants and supergiants; 2) the Kelvin-Helmholtz timescale t_{KH}, measures how long a star can shine by contracting and releasing gravitational energy alone in the absence of nuclear fusion[11]. For the Sun, this would last for around 30 million years[12,13]; 3) finally, the nuclear timescale dominates a star's life[14,15], spanning millions to billions of years, as fusion in the core slowly converts hydrogen into helium and much heavier elements[15].

For the purpose of this study, we shall place (2) into the dock of close scrutiny. In the KH timescale, the star contracts quasi-hydrostatically[12], with the gravitational potential energy being converted into thermal energy, which is then radiated away through its photosphere[13]. The amount of energy radiated in the process is equivalent to its gravitational binding energy[11,13] at its current luminosity, i.e., $t_{\rm KH} = GM_\star^2/RL$ where: L is the luminosity of the proto(star), R is the radius of the star, G is the gravitational constant and $M_\star$ is the mass of the proto(star). The Kelvin-Helmholtz timescale is considerably shorter than the nuclear timescale, the latter of which controls a

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star's main sequence evolution due to hydrogen fusion.

In the literature, it is said that the problem of massive stars arises because as the core of the proto(star) grows, so does its luminosity, leading to stronger radiative pressure on dust and gas in the surrounding envelope. At about $M_\star > 8M_\odot$, radiation pressure becomes a significant barrier to further mass in-fall at this mass scale, making it difficult for stars to grow much larger via steady spherical accretion[2,4]. As far as our theoretical understanding is concerned, the smooth transition from the PMS to ZAMS phase works well for stars less than about $8-10M_\odot$ due to their relatively low luminosity and modest radiation output during the pre-main sequence phase[4,6]. In such stars, the outward radiation pressure is insufficient to significantly counteract the inward gravitational force, allowing quasi-hydrostatic contraction to proceed uninterrupted until the proto(star) enters the nuclear timescale.

In-principle, radiative accretion arrest creates a quasi-stable equilibrium where the proto(star) energy budget is dominated by virialized contraction[16], which occurs in a duration which is determined by the Kelvin-Helmholtz timescale[4,5,17]. The observed evolutionary pathways[8,9,18] suggest that the radiative pressure-induced delay timescale (t_{RD}) must be substantially shorter than t_{KH} for contraction to resume unabated. If this condition is not satisfied (i.e., $t_{KH} > t_{RD}$), then the PMS star transitions into a state of global radiative arrested collapse (RAC). How long the proto(star) endures in the RAC phase, remains poorly constrained in the existing analytical models[19].

From a star-formation perspective, proto(stars) larger than $8M_\odot$ barely have an observable pre-main-sequence phase, but reach the ZAMS phase while still accreting from their surrounding gaseous envelope. However, for nearly fifty years, scholars (e.g., Larson and Starrfield and Yorke) have argued that the radiation field emanating from massive stars is strong enough to cause a global reversal of direct in-fall of material onto the nascent star. A key focus in the study of massive star formation is the effect of radiation pressure on the gas and dust grains[17,22]. When this pressure builds up, it can halt the accretion process or redirect the in-falling material, forming bipolar outflows and radiative-driven cavities[7,23].

A similar study was done by Nyambuya, who supposed that — massive stars have a gravitational field that is much stronger than their radiation field when drawn from the analysis of an isolated* massive star[4,5]. Nyambuya erroneously extended to the case of massive stars enshrouded in gas and dust. He argued that, for the case of a non-spinning gravitating body where the circumstellar material is taken into consideration, at $8-10M_\odot$, the radiation field will not reverse the radial in-fall of matter, but rather a stalemate between the radiation and gravitational field will be achieved, i.e. the in-fall is halted but not reversed[4]. How long this radiation pressure can halt the contraction of the massive star, before accretion can resume has been an open question till today[1,7,23–25].

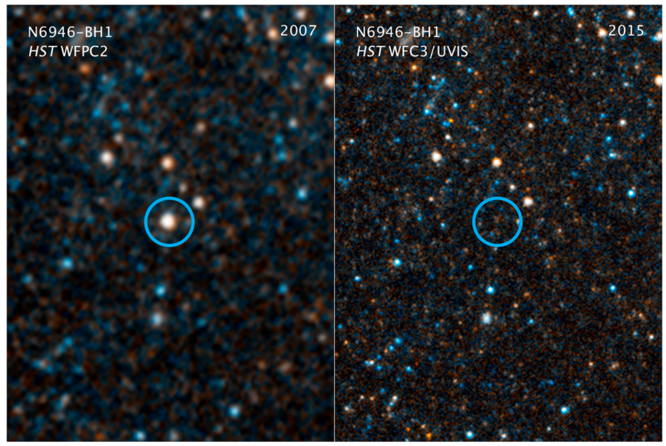

Figure 1 This pair of visible-light and near-infrared Hubble Space Telescope photos shows the giant star N6946-BH1 before and after it vanished out of sight by imploding to form a black hole. The left image shows the 25 solar mass star as it looked in 2007. In 2009, the star shot up in brightness to become over 1 million times more luminous than our sun for several months. But then it seemed to vanish, as seen in the right panel image from 2015. A small amount of infrared light has been detected from where the star used to be. This radiation probably comes from debris falling onto a black hole. The black hole is located 22 million light-years away in the spiral galaxy NGC 6946. Source: NASA, ESA, and C. Kochanek (OSU)

For example, ALMA 1.3 mm continuum (high-resolution) observations of the W43-MM1 (proto)cluster revealed a dense population of massive cores, some with masses up to several tens of solar masses. Despite being gravitationally bound, several of these cores show no signatures of active star formation, such as outflows or embedded proto(star)s[26]. Amongst them, Core #6 stands out as a prominent candidate for a high-mass pre-stellar core Valeille-Manet, M. et al.2025. It shows narrow molecular line widths and lacks both thermal line broadening and signs of hot core chemistry, which is a typical indicator that it is not currently accreting. The absence of molecular outflows and infrared sources further supports its classification as a quiescent, non-accreting core[27]. This quiescent state could be a sign that radia-

∗ An isolated non-spinning star is a non-spinning star without any circumstellar material around it, and the gravitational field beyond its surface is described exactly by Newton's inverse square law[4].

tive feedback and turbulence from nearby massive stars or the surrounding cluster environment are disrupting or halting accretion onto Core #6, thus preventing it from collapsing into an active star-forming core (Motte et al.).

This means that, the detailed mass-growth processes of massive young stellar objects has not been clear till today. Two key questions are to be addressed in this study, both of which are relevant to the timescale regulation in the evolution of the PMS star. These are; 1) Is there a way to proceed with star formation in the face of a radiative pressure barrier when $t_{\rm RD} > t_{\rm KH}$? 2) if so, what is the critical effective temperature required by the core of the proto(star) in-order for radiative pressure to become more dominant over gravity?

What will be done in this paper is simple: firstly, we want to ascertain the critical temperature ($T_{\rm eff}$) at which a proto(star) attains its Eddington Limit. This will be achieved in Section 3 via the Yorke and Sonnhalter's stability criterion. In Section 4 we argue that, the classical Kelvin–Helmholtz criteria is incomplete and often the boundary conditions are not appropriate to achieve quasi-hydrostatic equilibrium. In Section 5, we demonstrate that, if the critical effective temperature is surpassed, then a global accretion delay ($t_{\rm RD} > t_{\rm KH}$) should in-principle trigger accretion-driven instabilities. This disrupts the conventional contraction pathway of the massive star formation process. In Section 6 we show and discuss the results of our study in terms of the effects of the critical temperature on the global accretion delay, whereas in Section 7, we summarize the advantages that our RAC model shall possibly bring.

2 The Radiation Pressure Barrier

For direct radial accretion and accretion via the disk to occur onto the nascent star, it is required that the Newtonian gravitational force, $GM_{\rm star}(t)/r^2$, at a point distance r from the star of mass $M_{\rm star}$ and luminosity $L_{\rm star}(t)$ at any time t (see., Yorke and Sonnhalter [19]), must exceed the radiation force $\kappa_{\rm eff}L_{\rm star}(t)/4\pi cR^2$, i.e:

$$\frac{GM_{\rm star}(t)}{R^2} > \frac{\kappa_{\rm eff}L_{\rm star}(t)}{4\pi cR^2}, \quad (1)$$

:where $\kappa_{\rm eff}$ is the effective opacity which is the measure of the gas' state of being opaque or a measure of the gas' imperviousness to light rays and is measured in $\rm m^2\ kg^{-1}$. This analysis by Yorke and Sonnhalter [19], which is also reproduced in Zinnecker and Yorke [29], is a standard and well accepted analysis that assumes spherical symmetry, but at the same time, neglects the nascent star's circumstellar material and the accretion timescale.

If a condition contrary to (1) was to establish, then in-principle, the resulting radiation pressure, $P_{\rm rad} = \frac{1}{3}aT^4$ becomes more dominant over gravitational attraction. The radiation-dominated regime halts further accretion by reversing gas inflow [30]. This creates a fundamental problem: if radiation pressure exceeds the gravitational pull, how do stars exceeding $8M_{\odot}$ form at all? Some scholars (e.g., Rosen and Krumholz [1], Rosen et al. [31]) suggest that radiation pressure should limit stellar masses, however, observational evidence shows, in some cases, formation of stars with masses well beyond this threshold (i.e., $M_{\star} > 8M_{\odot}$), indicating that the classical spherical accretion picture by Yorke and Sonnhalter [19] is incomplete (also see., Nyambuya [4],[6]).

Rosen and Krumholz [1] examined this issue afresh and argued that, current studies do not necessarily provide a clear timescale [4,30] for the delay of contraction in highly luminous proto(stars). They suggested that, momentum transfer from the trapped infrared and UV photons in optically thick environments can enhance the radiation pressure field, but this effect can at times be mitigated by dust opacity variations and the gas dynamics [32]. In addition, Krumholz et al., also showed that radiation pressure disrupts isotropic in-fall, by reducing accretion rates by 50% compared to purely hydrodynamic collapse models. Here, we work forward with the assumption that, once the accretion delay timescale is constrained, then we will be able to ascertain whether the entire massive star formation process proceeds or not.

However, despite extensive studies on the effects of radiative pressure in the collapse of the giant molecular cloud (see e.g., Chandrasekhar; Mihalas and Mihalas [34]), the critical temperature at which radiative pressure becomes more dominant over gravity remains poorly constrained in existing analytical models. While existing numerical and analytical studies have explored radiation-dominated regimes in accretion disks (e.g., Turner et al.; Jiang et al.) and massive star formation (e.g., Krumholz and Matzner), the critical temperature (or luminosity-to-mass ratio) at which radiation pressure permanently halts accretion—rather than temporarily limiting it—remains a subject of interesting debate due to nonlinear feedback effects [1,38].

Simulations of super-Eddington outflows (Ohsuga et al.) and radiative feedback in galactic nuclei (Ciotti and Ostriker) suggest regimes where radiation pressure becomes more dominant. However, systematic determination of the critical effective temperature threshold—particularly for idealized or polytropic systems—has not been directly addressed in the existing literature. This lack of understanding still persists despite theoretical frameworks by Shakura and Sunyaev) which imply such a transition must exist. Now that we have presented the radiation barrier as it is commonly understood, we are ready to make our case by inspecting: 1) how the critical effective temperature, T_{crit} modifies the expected accretion timescale in star formation processes; 2) the Kelvin-Helmholtz timescale criteria in the presence of strong radiative feedback.

3 The Critical Effective Temperature

Here, we propose what we believe is a key and sine quo non condition which must be met in-order for the proto(star) to reach the RAC phase. We work forward with the assumption that, for radiative disruption to take place, the effective temperature of the proto(star) must exceed a hitherto of an unknown critical effective threshold, $T_{\text{eff}} > T_{\text{crit}}$. If this critical temperature is surpassed, then the outward radiation pressure surely must exceed the inward gravitational force emanating from the core. We show that this approach holds promise in the early protostellar stages, where luminosity is hard to constrain observationally, but temperature estimates from spectral energy distributions are more accessible[8,9,18]. To establish this criteria, we extend Eq. (1), by assuming an isotropic radiation field and adopt a gray-opacity approximation in which the opacity κ is treated as a spatially uniform effective opacity. This yields the Eddington luminosity:

$$L_{\text{Edd}} = \frac{4\pi c G M_\star}{\kappa}. \tag{2}$$

To recast this in terms of a critical effective temperature, we invoke the Stefan–Boltzmann law for a radiating sphere:

$$L_{\text{eff}} = 4\pi R^2 \sigma T_{\text{eff}}^4, \tag{3}$$

:where σ is the Stefan–Boltzmann constant. This therefore suggests that in-principle, the condition $T_{\text{eff}} = T_{\text{crit}}$ surely must establish when the star's effective luminosity reaches the Eddington limit. However, the Eddington luminosity is not arbitrary—it is the maximum luminosity that can be radiated before radiation pressure becomes dominant over gravity, thus $L_{\text{eff}} > L_{\text{Edd}}$. Once this condition is satisfied, radiative momentum drives matter outwards at a rate faster than the in-fall, i.e:

$$4\pi R^2 \sigma T_{\text{eff}}^4 > \frac{4\pi c G M_\star}{\kappa}. \tag{4}$$

Thus, in a radiative pressure dominated regime:

$$T_{\text{crit}} = \left(\frac{c G M_\star}{\kappa_o R_o^2 \sigma} \right)^{0.25}. \tag{5}$$

To ensure numerical stability in our evolutionary model, the critical temperature T_{crit} must be treated as a function of the initial radius and opacity—i.e., $T_{\text{crit}}(M_\star, R_o, \kappa_o)$. Unlike the luminosity-based criteria of Yorke and Sonnhalter, this formulation provides a more direct thermal threshold that is particularly relevant for early-stage proto(stars) where luminosities may be uncertain but local thermal conditions can be inferred.

Table 1 Critical effective temperatures for low mass proto(stars) at entrance into the PMS phase.

Stellar Par.	$3M_\odot$	$1M_\odot$	$0.5M_\odot$
R_o at L_o	19.760 $R_\odot$	14.73 $R_\odot$	20.829 $R_\odot$
κ_o	$5cm^2/g$	$5cm^2/g$	$5cm^2/g$
T_{eff}	4000k	4000k	4000K
T_{crit}	12 235K	10 768 K	7614 K

Based on the results presented in Table 1, it is apparent that, the critical effective temperature required for radiative feedback to inhibit accretion in low to intermediate mass proto(stars) exceeds the physical limits observed (typically 3000–4000 K for a Sun-like star), because low mass stars remain fully convective in the Hayashi phase. These temperatures are significantly above the canonical effective temperatures, of $T_{\text{eff}} \sim 4000$K (see., Heiter, U. et al.) for low mass proto(stars). This means that the energy transport is dominated by convection. Furthermore, the required threshold for radiation pressure to counteract gravitational in-fall is not physically attainable for solar-type stars.

For example, the Sun has a peak effective temperature of approximately 5778 K[43], which is the upper limit for a typical one-solar-mass star. As a result, it cannot reach the critical effective temperature of 10,768 K required for entry into a radiative pressure–dominant regime. Thus, the formation of low-mass stars proceeds with minimal disruption from radiative pressure.

Table 2 Critical effective temperatures for massive proto(stars) at entrance into the PMS phase.

Stellar Par.	$100M_\odot$	$15M_\odot$	$10M_\odot$
R_o at L_o	1.47e+3 $R_\odot$	658.18 $R_\odot$	198.00 $R_\odot$
κ_o	$5cm^2/g$	$5cm^2/g$	$5cm^2/g$
T_{eff}	∼4000k	∼4000k	∼4000K
T_{crit}	3408 K	3171 K	5223 K

In contrast, the critical effective temperatures in massive stars are remarkably low (i.e., $T_{\text{crit}} < T_{\text{eff}}$). Massive stars pass through a much shorter Hayashi phase due to their rapid contraction. Their interiors become partially convective, with convective outer layers and an early-forming radiative core. As they evolve along the Henyey et al. track, massive stars maintain higher initial effective temperatures compared to their low-mass counterparts (see., Table 2). The high mass protostellar core contracts quickly, achieving central temperatures on the order of 10–100 million Kelvins[44] due to their characteristically short Kelvin-Helmholtz timescale, t_{KH}. Rather than remaining in a fully convective state, high-mass stars shift rapidly towards the Henyey et al. track, bypassing the extended convective evolution seen in lower-mass stars. A seen on Table 2, radiation pressure becomes more dominant in the early stages of their evolution and limits the extent of convection. This rapid contraction leads to a distinctively low critical effective temperature (i.e., $T_{\mathrm{crit}} > T_{\mathrm{eff}}$) and an early transition into the RAC phase.

4 Stellar Evolution in the Absence of Nuclear Fusion

The Kelvin-Helmholtz timescale, t_{KH}, was first proposed in the 19$^{\mathrm{th}}$ century by Lord Kelvin (1824 — 1907) and Hermann von Helmholtz (1821 — 1894) in an effort to explain the source of the Sun's luminosity prior to the development of the nuclear fusion theory[14,45]. They argued that the Sun's luminosity could be sustained by the gradual release of gravitational potential energy as it contracts. The KH timescale $t_{\mathrm{KH}} = GM^2/RL$, estimates how long a star can shine via gravitational contraction alone before radiating away all its energy[12]. For the Sun, $t_{KH} = 30$ million years[13], a timescale which is far shorter than its actual age of 4.6 billion years.

This demanded the need for a new theory to explain the energy source of the sun. This paradigm shift began with Arthur Stanley Eddington (1882–1944) in 1920, who originally theorized that the Sun's energy originates from the fusion of hydrogen into helium[28]. The theory was later substantiated and quantitatively formulated by Hans Albrecht Bethe (1906–2005), who, in 1939, described the proton–proton chain and the CNO cycle as viable nuclear fusion processes occurring within the stellar core[46]. This nuclear fusion theory, emerged strongly and later replaced the Kelvin–Helmholtz' theory as the accepted explanation for the Sun's energy source.

Although the Kelvin-Helmholtz timescale was superseded by the discovery of nuclear energy, the idea of a contraction timescale has remained central in the study of the evolution of PMS stars. The classical treatment of the KH timescale posits that, gravitational potential energy is efficiently thermalized and radiated away[11–13] with radiation pressure playing a negligible role in slowing down the contraction. Although a useful first-order approximation for the contraction timescale, the Kelvin-Helmholtz timescale does not account for the role of radiative pressure in the early stages of stellar evolution. Recent theoretical studies of massive or rapidly accreting pre-main-sequence stars (e.g., Nyambuya[4], Yorke and Sonnhalter[19], Rosen et al.[31], Krumholz and Matzner[37]) suggests that, radiation pressure generated by photon momentum transfer, can impede gravitational collapse and thus extend the contraction phase before it enters the nuclear timescale.

This means that, when a proto(star) contracts, the release of gravitational energy increases its internal temperature and luminosity. If the gaseous envelope is optically thick, radiation becomes trapped thus increasing the frequency of photon to particle interaction. Rosen and Krumholz also studied the role of outflows, radiation pressure, and magnetic fields in massive star formation by running simulations which include radiative feedback from both direct stellar and dust-reprocessed radiation fields, and collimated outflow feedback from the accreting stars. Rosen and Krumholz conjectured that — massive stars have short Kelvin–Helmholtz timescales and attain their main-sequence luminosities while they are still actively accreting (also see., Palla and Stahler[47]: Hosokawa and Omukai[23]: Krumholz and Matzner[37]).

In contrast to the bipolar radiation escape channels created by protostellar outflows, our spherical symmetry model proposed herein, suggests a global contraction delay, where radiation pressure uniformly opposes collapse without creating localized optically thin regions. Although this reduces the efficiency of gravitational contraction, the associated enhancement of radiative cooling accelerates the energy loss from the system. As a result, the net effect on the Kelvin-Helmholtz timescale depends on the competition between two factors: 1) the fraction of gravitational energy used to sustain the radiation field, which could in principle prolong t_{KH}, and; 2) the increased luminosity L due to radiative losses, which could shorten t_{KH}.

Although standard stellar evolution models (e.g., Kippenhahn and Weigert[48]) typically treat radiation pressure as dominant only in massive main-sequence stars or post-main-sequence phases, analytical studies by McKee and Ostriker[49] suggest that in very luminous PMS objects—such as those undergoing rapid accretion—radiation pressure plays an important role in regulating contraction[49,50]. However, due to the current limitations in detailed numerical simulations that could account for radiative feedback during protostellar collapse, the validity of this interpretation is still an open question till today (see., Menon et al.: Rosen and Krumholz). The radiative barrier is arguably the most important problem of all in the study of the formation of stars, thus, it is important to make sure that this problem is clearly defined and understood.

The next section explores how radiative pressure affects the evolution timescale of a YSO as it rapidly contracts in the Kelvin-Helmholtz timescale before it enters the nuclear timescale. We note that, for a PMS star of $M_\star < 8M_\odot$, the radiation field will not reverse the radial in-fall of matter but rather a short lived stalemate between the radiation and gravitational fields will be achieved, where in-fall is halted but not reversed. This means that, if the radiation pressure does indeed slow contraction, PMS stars might either spend more time at higher luminosities before descending towards the main sequence or might fail to form at all.

5 Accretion Delay in Star Formation

Neglecting magnetic, turbulence and any other forces (as will be shown later in this section, these forces do not change the essence of our argument, hence we do not need to worry about them here) and considering only the gravitational and radiation field from the nascent star, we assume here that a star is formed from a gravitationally bound system where the giant molecular cloud is collapsing under the Jeans collapse criteria at a free-fall velocity $t_{\rm ff} = (3\pi/32G\rho)^{0.5}$. When the effective temperature $T_{\rm eff}$ exceeds a critical threshold $T_{\rm crit}$ for the MYSO, radiation pressure begins to dominate the dynamics of in-falling material. This transition occurs when the radiative transfer velocity[53], $V_{\rm rad} = \frac{hT_{\rm eff}}{bm_{\rm H}}$ exceeds the free-fall velocity[53], $V_{\rm ff} = -\frac{2R}{3t_{\rm ff}}$.

In this regime, radiative forces slow down the accretion rate, marking the onset of radiation–hydrodynamic coupling, wherein the transfer of radiative momentum is no longer negligible compared to the strength of the gravitational field. Accretion becomes inefficient, and the proto(star) may temporarily decouple from its envelope. But, our main objective here is not to explain the microscopic motion of individual particles but the macroscopic effect this radiative momentum transfer has on the global contraction timescale. Thus, if we substitute the effective temperature $T_{\rm eff} = (L_{\rm eff}/4\pi R^2\sigma)^{0.25}$ into $V_{\rm rad}$, then the radiative transfer equation transforms into macroscopic form as i.e:

$$V_{\rm rad} = \left(\frac{h}{bm_H}\right)\left(\frac{L_{\rm eff}}{4\pi R^2\sigma}\right)^{0.25}. \tag{6}$$

For a proto(star) to reach the Eddington limit, the following condition must be satisfied:

$$\frac{2R}{3t_{\rm freefall}} = \left(\frac{h}{bm_H}\right)\left(\frac{L_{\rm eff}}{4\pi R^2\sigma}\right)^{1/4}. \tag{7}$$

At this quiescent, non-accreting state, radiative effects are finely tuned to gravitational in-fall in such a way that the forward and backward evolution of the system would be indistinguishable. Therefore, in the time-symmetric dynamics of the collapse of the gravitationally bound system, the free-fall timescale is equivalent to the radiative delay timescale i.e., $t_{\rm ff} = t_{\rm RD}$. Solving for t yields:

$$t_{\rm RD} = \left[\frac{2Rbm_H}{3h}\left(4\pi R^2\sigma\right)^{0.25}\right]L_{\rm eff}^{-0.25}. \tag{8}$$

This expression can be written in compact form as:

$$t_{\rm RD} = \left[\eta\left(4\pi R^6\sigma\right)^{0.25}\right]L_{\rm eff}^{-0.25}, \tag{9}$$

:where $\eta = 2bm_H/3h$. For a hydrogen gas dominated giant molecular cloud, $\eta = 4867.68\,{\rm m}^{-1}\cdot{\rm s}\cdot{\rm K}$. Alternatively, Eq. (9) can be expressed in terms of temperature as, $t_{\rm RD} = \eta R/T_{\rm eff}$. This means that, in massive proto(stars), the radiative contraction delay $t_{\rm RD}$ is significantly longer than the Kelvin–Helmholtz timescale, owing to their large radii and quasi-constant luminosity, $\Delta L/L_o < 0.1$. Knowing that t_{RD} is strongly dependent on the radius (i.e., $t_{\rm RD} \propto R^{1.5}L_{\rm eff}^{-0.25}$) and less on the effective luminosity, t_{RD} is significantly longer in massive proto(stars) than in their low mass counterparts.

6 Results and General Discussion

Having established the radiative contraction delay, a key unresolved question persists: How does massive star formation proceeds in the presence of a strong radiative pressure field?[1,29,30]. Krumholz and Matzner suggested that the solution may lie in recognizing that radiation pressure and gravitational collapse are not truly opposing forces, but complementary aspects of a single dynamical system.

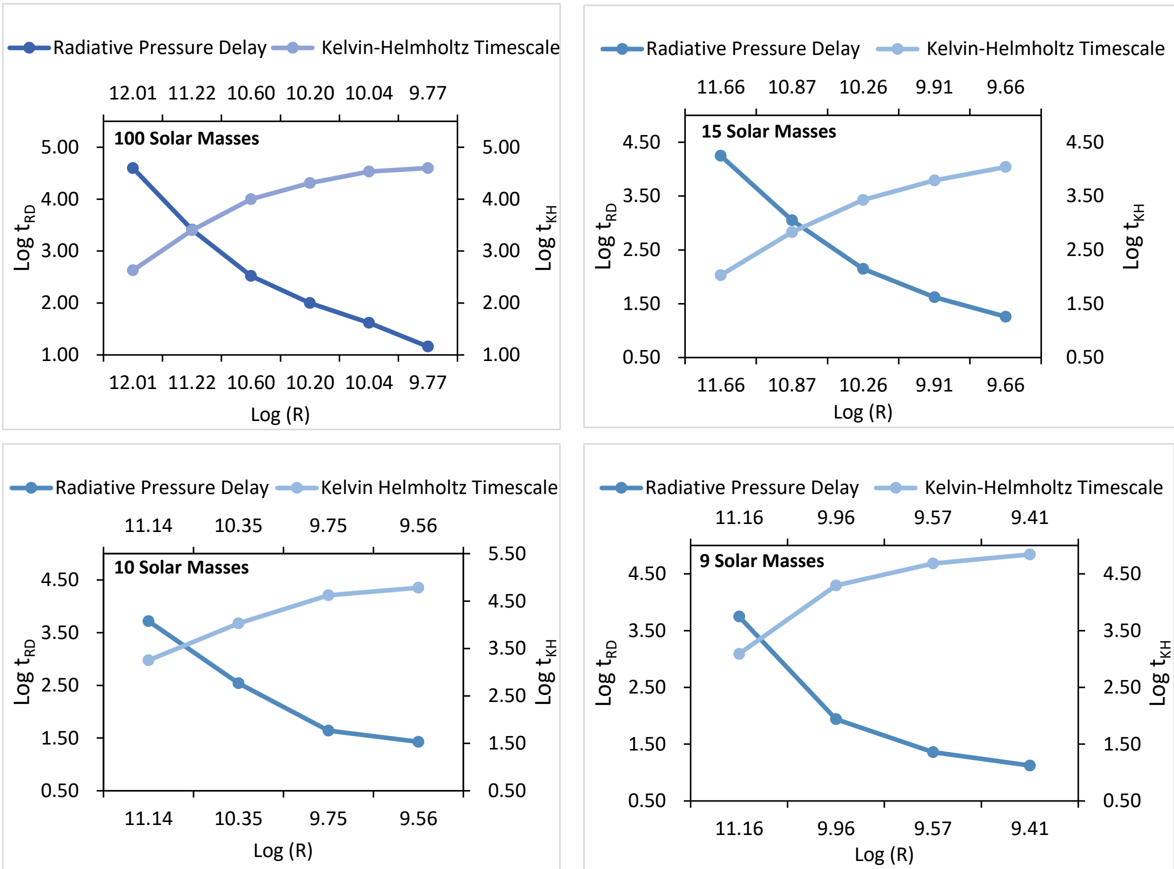

Figure 2 The figure presents a dual-axis logarithmic plot comparing the radiative contraction delay ($\log t_{\mathrm{RD}}$, left vertical axis) and the Kelvin-Helmholtz timescale ($\log t_{\mathrm{KH}}$, right vertical axis) against the protostellar contraction radius ($\log R$, horizontal axis). Four cases are shown: (i) a $100M_{\odot}$, top-left, (ii) $15M_{\odot}$, top-right, (iii) $10M_{\odot}$, middle-left, (iv) 9. Observe that the proto(star) timescales are characterized by an empirical logarithmic relationship of the form $Log(t_{\mathrm{RD}}) = k/Log(t_{\mathrm{KH}})$. The value of k is obtained graphically at the point of interception.

Table 3 Results for t_{RD} and t_{KH} in a $100M_{\odot}$ star, at near-constant luminosity.

T_{eff} ($10^4 K$)	L ($10^5 L_{\odot}$)	R ($R_{\odot}$)	t_{RD} (years)	t_{KH} (years)
4.00e-1	5.00e+0	1.47e+3	3.95e+4	4.28e+2
1.00e+0	5.20e+0	2.40e+2	2.58e+3	2.52e+3
2.00e+0	5.40e+0	6.10e+1	3.28e+2	9.54e+3
3.00e+0	5.60e+0	2.77e+1	9.90e+1	2.03e+4
4.00e+0	5.80e+0	1.59e+1	4.25e+1	3.41e+4
6.30e+0	1.00e+1	8.40e+0	1.43e+1	3.74e+4

In this reading, we work forward with the assumption that, such a resolution may potentially emerge not from choosing between collapse or radiation dominance, but in understanding how their interplay generates new organizational states where both processes coevolve. In this section, we carefully construct a numerical analysis which could potentially reveal the coevolution of the radiative contraction delay and the Kelvin-Helmholtz timescale as a function of the stellar mass.

Accordingly, in Table 3 and Table 4, we examine the correlation between t_{KH} and t_{RD} for a $100M_{\odot}$ MYSO and in intermediate-low mass (i.e., $0.5 < M_{\star} < 15M_{\odot}$) proto(stars). We note that at the onset of gravitational contraction, the MYSO is characterized by an exceptionally high luminosity of approximately $10^6 L_{\odot}$ and an extended photospheric radius of roughly $1470R_{\odot}$. It enters the pre-main sequence with an effective temperature of

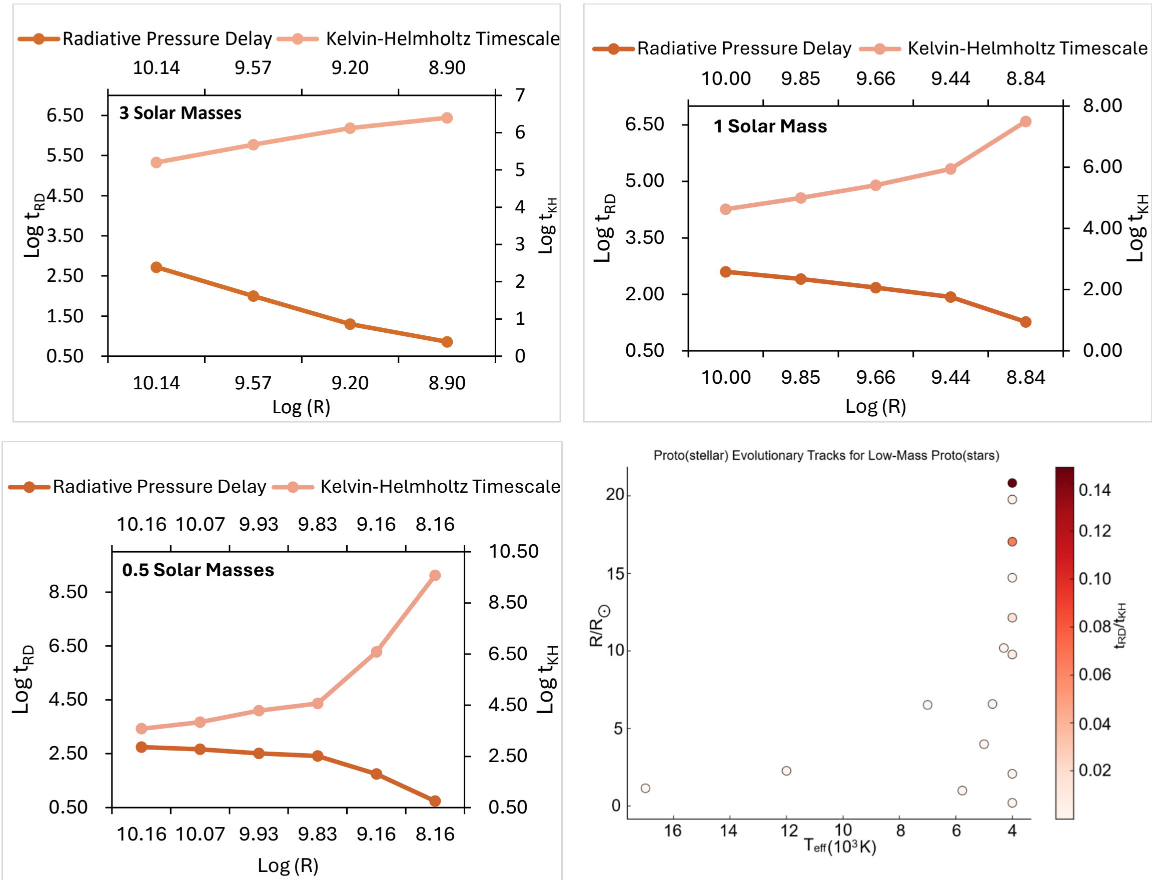

Figure 3 $Log - Log$ plot comparing the radiative delay timescale (t_{RD}) and Kelvin-Helmholtz timescale (t_{KH}) against the radial distance in low-mass YSO. In contrast, the logarithms of the two timescales are decoupled in low mass proto(stars) thus $k = 0$. The bottom-right panel shows the evolutionary tracks in the $T_{\rm eff} - R$ plane for proto(stars) of masses $3M_\odot$, $1M_\odot$ and $0.5M_\odot$. Each point corresponds to a distinct evolutionary phase, with the color coding indicating the ratio $t_{\rm RD}/t_{\rm KH}$. Following the standards of the Hertzsprung–Russell diagram conventions, the x-axis ($R/R_\odot$) is inverted, with larger radii and cooler temperatures representing earlier evolutionary stages. The gradient in red shading illustrates the growing dominance of radiative feedback during gravitational contraction.

$T_{\rm eff} = 4000K$, which far exceeds its critical effective temperature of $T_{\rm crit} = 3408K$. In this regime, the radiative pressure field becomes more dominant over the gravitational field. As the MYSO evolves along the Hayashi phase, the object maintains a high luminosity state for nearly 100 years before transitioning onto the Henyey et al. track. Radiative feedback becomes sufficiently strong to impose a global delay on further gravitational collapse.

In this scenario, the MYSO enters a radiatively arrested accretion state, where its contraction delay timescale, $t_{\rm RD} = 10^4$ years vastly exceeds the Kelvin–Helmholtz timescale, $t_{\rm KH} = 428$ years. This means that the gravitational potential energy available to the MYSO is depleted long before the object can resume significant accretion or reach the ZAMS phase. The absence of continued mass loading during the prolonged delay prevents the protostellar core from accumulating sufficient pressure and temperature ($T_{\rm core} < 10^7$ K) to ignite hydrogen burning[43,44].

We envisage that, if radiative feedback or instabilities in the circumstellar disk inhibit both mass accretion and internal heating, the core is unable to sustain nuclear fusion. In this radiatively suppressed regime, the MYSO bypasses stable stellar evolution and undergoes direct gravitational collapse, possibly forming a stellar-

Table 4 Results for t_{RD} and t_{KH} for $15M_{\odot}$, $10M_{\odot}$, $3M_{\odot}$, $1M_{\odot}$ and $0.5M_{\odot}$ proto(stars).

$M_{\star}$ ($M_{\odot}$)	$T_{\rm eff}$ ($10^4 K$)	L ($L_{\odot}$)	R ($R_{\odot}$)	t_{RD} (years)	t_{KH} (years)
15	4.00e-1	1.00e+5	658.18	1.77e+4	1.09e+2
15	1.00e+0	1.00e+5	105.31	1.13e+3	6.80e+2
15	2.00e+0	1.00e+5	26.33	1.41e+2	2.72e+3
15	3.00e+0	1.00e+5	11.70	4.20e+1	6.12e+3
15	4.00e+0	1.00e+5	6.58	1.77e+2	1.09e+4
10	4.00e-1	9.00e+3	198.00	5.30e+3	1.76e+3
10	1.00e+0	9.20e+3	32.00	3.43e+2	1.07e+4
10	2.00e+0	9.40e+3	8.08	4.33e+1	4.18e+4
10	2.50e+0	9.80e+3	5.28	2.67e+1	6.07e+4
3	4.00e-1	9.00e+1	19.76	5.26e+2	1.61e+5
3	7.00e-1	9.20e+1	6.52	9.94e+1	4.76e+5
3	1.20e+0	9.60e+1	2.27	2.02e+1	1.31e+6
3	1.70e+0	1.00e+2	1.15	7.23e+0	2.48e+6
1	4.00e-1	5.00e+1	14.72	3.95e+2	2.16e+6
1	4.30e-1	3.20e+1	10.19	2.54e+2	3.12e+6
1	4.70e-1	1.90e+1	6.58	1.50e+2	4.83e+6
1	5.00e-1	9.00e+0	3.99	8.58e+1	7.95e+6
1	5.77e-1	1.00e+0	1.00	1.86e+1	3.17e+7
0.5	4.00e-1	1.00e+2	20.82	5.59e+2	3.81e+3
0.5	4.00e-1	6.70e+1	17.04	4.57e+2	6.95e+3
0.5	4.00e-1	3.40e+1	12.14	3.26e+2	1.92e+4
0.5	4.00e-1	2.20e+1	9.77	2.62e+2	3.69e+4
0.5	4.00e-1	1.00e+0	2.08	5.59e+1	3.81e+6
0.5	4.00e-1	1.00e-2	0.21	5.49e+0	3.81e+9

mass black hole[54] in the range $3-100M_{\odot}$, without producing a supernova explosion[55]. For example, the mysterious disappearance of the 25 solar mass progenitor star N6946-BH1 (see., Figure 1). Clearly it can be seen that, the evolutionary tracks of massive proto(stars) displayed in Figure 2 are inversely coupled. Their evolution follow an inverse logarithmic relationship, which is empirical and symmetric in nature, and is of the form:

$$Log(t_{\rm RD}) = \frac{k}{Log(t_{\rm KH})}. \quad (10)$$

The constant k is obtained graphically from a point where the two logarithms intercept. Similarly, in Figure 3, we present the evolutionary tracks for $t_{\rm KH}$ and $t_{\rm RD}$ in the low-mass protostellar regime. We have also seen that the constant k is a non-zero empirical constant (i.e., $k \neq 0$) in massive proto(stars) and vice versa. This means that, radiative diffusion plays a negligible role in the evolution of low-mass proto(stars), thus $t_{\rm KH}$ and $t_{\rm RD}$ are effectively decoupled with $k = 0$.

For each evolutionary track presented in Figure 2, we extracted the values of k through the least-squares fitting of the Log $t_{\rm RD}$-Log $t_{\rm KH}$ intersection points. When substituted into Eq. (10), we found as the condition of dynamic stability, the critical radiative contraction delay timescale $\tau_{\rm crit}$ (see., Table 5) in massive proto(stars).

Table 5 The critical radiative contraction delay, $\tau_{\rm crit}$ in massive proto(stars).

Mass($M_{\odot}$)	$Log(t_{\rm RD})$	$Log(t_{\rm KH})$	k	$\tau_{\rm crit}$(yrs)
100	3.50	3.50	12.25	3162
15	3.00	3.00	9.00	1000
10	3.30	3.50	11.55	1995
9	3.40	3.40	11.56	444

Whether the motion of the radiative envelop is checked or unchecked, the gravitational energy released by the system must be fully reprocessed by radiative feedback. At $\tau_{\rm crit}$, the rate at which gravitational energy is liberated through contraction is matched by the rate at which radiation pressure delays further collapse. By saying that this equilibrium extends the stalling phase in the contraction, we have made a tacit and fundamental assumption that $\tau_{\rm crit}$ surely must be revealing a nontrivial threshold in the interplay between luminosity-driven feedback and the proto(star)'s structural response.

In effect, all available gravitational potential energy is either converted to radiation or absorbed into delaying collapse, and no net acceleration of collapse occurs. The core cannot contract rapidly nor expand. For example, in a $100M_{\odot}$, a $\tau_{\rm crit}$ of 3162 years marks an extended equilibrium, which arises from the near-saturation of Eddington-limited luminosity, where radiation pressure becomes dynamically coequal with gravity throughout most of the envelope. This leads to an extended stalling phase in the contraction than in lower-end massive stars (e.g., a $15M_{\odot}$ is characterized by a lower $\tau_{\rm crit}$ of nearly 1000 years). This lower threshold, defines a regime where radiative pressure delays contraction, but the envelope is still largely sub-Eddington, allowing gravitational energy to eventually dominate.

It is clear here that, $\tau_{\rm crit}$ defines a state of quasi-static radiative equilibrium, where $dR/dt = 0$. If the reader accepts this, then what follows is a straight forward assumption which leads to what we believe is a significant step forward in the resolution of the radiation problem. This quasi-static equilibrium, represents a bifurcation point in stellar evolution: either successful star formation or failed star evolution (e.g. black hole formation without a supernova). While recent scholars (e.g., Rosen and Krumholz) have argued that, radiation pressure drives anisotropic mass loss—creating localized channels or 'holes' that allow partial ejection of the envelope while sustaining accretion along preferential axes—our results strongly suggests that, the dominant dynamical outcome is a global, spherically symmetric accretion delay. Moreover, it is bona-fide knowledge that star formation is not a spherically symmetric process and, from the above, it follows that stars beyond the 8 $M_\odot$ limit must, with no hindrance, form the radiation field and the only limit to their existence is if the gravitationally bound core has enough mass to form them.

7 Conclusion

An important and subtle difference between the present work and that of other scholars (e.g., Rosen and Krumholz, Tan et al., Yorke and Sonnhalter, Zinnecker and Yorke) is that we have identified a previously unrecognized time-dependent dichotomy that changes our understanding of pre-main-sequence evolution. Yorke and Sonnhalter's work identified the radiation pressure barrier in massive star formation. In contrast, our work introduces a detailed quantitative model that unifies the Kelvin-Helmholtz timescale with a radiative-dominated accretion delay. At this point, a complete in-fall reversal is attained. Our approach therefore surpasses earlier models in two key aspects: Firstly, we establish precise temperature thresholds that determine when radiation pressure becomes dominant, a refinement missing in Yorke and Sonnhalter's model. Lastly, we reveal how the timescale disparity (t_{RD} vs. t_{KH}) creates fundamentally different evolutionary pathways, explaining why some stars achieve stable hydrogen burning while others may never enter the nuclear timescale.

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