Massive Star Formation and the Radiation Problem

Can Circumstellar Material – Globally, Stop Infall Reversal?

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Abstract. Central to the on-going debate on how massive stars come into being is the so-called Radiation Problem. It has been argued that for stars of mass greater than $\sim 10\mathcal{M}_{\odot}$, the radiation field emanating from these objects is high enough to cause a global reversal of direct radial in-fall of the material onto the nascent star. We argue here (1) that this accepted argument applies only to an isolated star, *i.e.*, a star in a vacuum – a star without any circumstellar material around it (2) further that, this argument is applicable only for a spherically symmetric gravitation. Correcting the former, *i.e.*, taking into consideration the circumstellar material, we find that at $\sim 10\mathcal{M}_{\odot}$, the radiation field will begin to create a cavity and, *if and only if*, the accretion disk is (1) not destroyed and (2) it acts up as the channel *via* which the star's mass grows; then, the circumstellar material is pushed away gradually until a point is reached when the cavity is the size of the core itself, at which point complete in-fall reversal is attained. If the star is forming inside a gravitationally bound core of mass $\mathcal{M}_{core}$, then according to our findings, complete global reversal of in-fall will occur when $\mathcal{M}_{star} = (\mathcal{M}_{core}/10\mathcal{M}_{\odot})^{1/3}$. This picture is very different from the common picture that is accepted in the literature that at $\sim 10\mathcal{M}_{\odot}$, all the material – from the surface of the star right up to the edge of the core; is expected to be swept away by the radiation field.

Keywords: cavity, circumstellar material, gravitational force, opacity, radiation field, radiation force, radiation problem.
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I. INTRODUCTION

It is now bona-fide knowledge that our understanding of the formation massive stars is lacking both theoretically and observationally. In the gestation period of a star's life, its mass will grow *via* the in-falling envelope and also through the forming accretion disk laying along it's equator. As far as our theoretical understanding is concerned, this works well for stars less than about $10\mathcal{M}_{\odot}$. In the literature, it is said that the problem of massive stars ($\mathcal{M}_{star} > 10\mathcal{M}_{\odot}$) arises because as the central prostar's mass grows, so does the radiation pressure from it, and at about $10\,\mathcal{M}_{\odot}$, the star's radiation pressure becomes powerful enough to halt any further in-fall of matter on to the protostar and the disk (Larson 1972; Kahn 1974; Bonnell *et al.* 2002; Palla & Stahler 1993). So the problem is - how does the star continue to accumulate more mass beyond the $10\,\mathcal{M}_{\odot}$ limit? If the radiation field really did reverse any further in-fall of matter and protostars exclusively accumulated mass *via* direct radial in-fall of matter onto the nascent star and also *via* the accretion disk, it could set a mass upper limit of $10\,\mathcal{M}_{\odot}$ for any star in the Universe. Unfortunately or maybe fortunately this is not what we observe. It therefore means that some process responsible for the formation of stars beyond the $10\,\mathcal{M}_{\odot}$ limit definitely must be a work hence a solution to the problem must be sought.

If this is the case, *i.e.*, the radiation problem really did exist as stated above, and our physics where complete *viz* this problem, the solution to the conundrum would be to seek a star formation model that overcomes the radiation pressure problem and at the sametime allowing for the star to form (accumulate all of its mass) before it exhausts its nuclear fuel. Two such models have been put forward, that is (1) the Accelerated Accretion Model (Yorke 2002, 2003) and (2) the Coalescence Model (Bonnell *et al.* 1998, 2002, 2006, 2007).

The second scenario, *i.e.*, the coalescence model (Bonnell *et al.* 1998) is born out of the observational fact that massive stars are generally found in the centres of dense clusters (Hillenbrand 1997; Clarke *et al.* 2000). In these dense environments, the probability of collision of proto-stellar objects is significant, hence the coalescence model. This model easily by-passes the radiation-pressure problem and despite the fact that not a single observation to date has confirmed it (directly or indirectly), it [the coalescence model] appears to be the most natural mechanism by which massive stars form given the said observational fact about massive stars and their preferential environment.

The other alternative, which is less pursued, would be to seek a physical mechanism that overcomes the radiation pressure problem as has been conducted by the authors Krumholz *et al.* (2004, 2009). These authors (Krumholz *et al.* 2004, 2009) believe that the radiation problem does not exist because radiation-driven bubbles that block accreting gas are subject to Rayleigh-Taylor instability which occurs anytime a dense, heavy fluid is being accelerated by light fluid for ex-

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ample when a cloud receives a shock, or when a fluid of a certain density floats above a fluid of lesser density, such as dense oil floating on water. The Rayleigh-Taylor instabilities allows fingers of dense gas to break into the evacuated bubbles and reach the stellar surface while in addition, outflows from massive stars create optically thin cavities in the accreting envelope. These channel radiation away from the bulk of the gas and reduce the radiation pressure it experiences. In this case, the radiation pressure feedback is not the dominant factor in setting the final size of massive stars and accretion will proceed albeit at much higher rates.

This short reading, as the authors Krumholz *et al.* (2004, 2009) albeit on a different note and point of departure – for the spherically symmetric case, we redefine the radiation problem *via* the overlooked assumption made in the analysis leading to the radiation problem; that the surroundings of the protostar is a vacuum (see *e.g.* Yorke 2002; Yorke & Sonnhalter 2002; Zinnecker & Yorke 2007), this is clearly not true. Having redefined the radiation problem, we argue from there-on that, for as long as the accretion disk is not destroyed by the radiation field; (1) accretion of mass onto the star is not halted and (2) complete in-fall reversal throughout the gravitationally bound core (of mass $\mathcal{M}_{core}$) from which the massive star is forming will not all be reserved, a cavity that grows as the radiation field grow will emerge. When the star's mass reaches $\mathcal{M}_{max} \simeq (\mathcal{M}_{core}/10\mathcal{M}_{\odot})^{1/3}$, all the circumstellar material will be swept away leaving only the material on the disk. The radiation problem is arguably the most important problem of all in the study of massive stars hence thus it is important to make sure that this problem is clearly defined and understood.

Given that the solution to this problem has been sought *via* sophisticated computer simulations and given also the simplicity and naïve-ness of the present reading which seeks to further our understanding of this problem – *perhaps* – this reading presents my misunderstanding of the problem – on the optimistic side of things, I believe the radiation problem has here been understood and that this reading is something worthwhile!

II. THE RADIATION PROBLEM

Following Yorke (2002), for direct radial accretion and accretion *via* the disk to occur onto the nascent star, explicitly, it is required that the Newtonian gravitational force, $G\mathcal{M}_{star}(t)/r^2$, at a point distance r from the star of mass $\mathcal{M}_{star}$ and luminosity $L_{star}(t)$ at any time t, must exceeds the radiation force $\kappa_{eff}L_{star}(t)/4\pi cr^2$ *i.e.*:

$$\frac{G\mathcal{M}_{star}(t)}{r^2} > \frac{\kappa_{eff}L_{star}(t)}{4\pi cr^2}, \tag{1}$$

where c is the speed of light in vacuum, κ_{eff} is the effective opacity which is the measure of the gas's state of being opaque, a measure of the gas imperviousness to the rays of light and is measured in m^2kg^{-1}. This analysis by Yorke (2002) which is also reproduced in Zinnecker & Yorke (2007), is a standard and well accepted analysis that assumes spherical symmetry and at the sametime it does not take into account the material outside the nascent star. On the other hand, star formation is not a truly spherically phenomena (see *e.g.* reviews by Zinneker & Yorke 2007; McKee & Ostrikker 2007) but this simple calculation suffices in as far probing the conditions when radiation pressure becomes a significant player on the star formation podium. What will be done in this reading is simple to perform the same calculation albeit with the circumstellar material taken into account.

This calculation by Yorke (2002) and Zinneker & Yorke (2007), proceeds as follows; the inequality (1), sets a maximum condition for accretion of material, namely $\kappa_{eff} < 4\pi cG\mathcal{M}/L$, and evaluating this we get:

$$\kappa_{eff} < 1.3 \times 10^4 \left(\frac{\mathcal{M}}{\mathcal{M}_{\odot}}\right)\left(\frac{L}{L_{\odot}}\right)^{-1}, \tag{2}$$

where $\mathcal{M}$ and L are in solar units. Given that, $L_{star} = L_{\odot}(\mathcal{M}/\mathcal{M}_{\odot})^3$, implies that:

$$\kappa_{eff} < 1.3 \times 10^4 \left(\frac{\mathcal{M}}{\mathcal{M}_{\odot}}\right)^{-2}. \tag{3}$$

Now, given that the interstellar medium's (ISM) opacity is measured to be about 20.0 m^2kg^{-1}, this sets an upper mass limit for stars of $10\mathcal{M}_{\odot}$ for gravitation to dominate the scene before radiation does, thus halting any further in-fall. It is clear here that the ISM's opacity and or the opacity of the molecular cloud material is what sets the $10\mathcal{M}_{\odot}$ mass limit thus if there is a way to lower the opacity inside the gas cloud in which the star is forming, the radiation problem would be solved.

The AAM finds some of its ground around the alteration of the opacity. For example, if the opacity inside the gas cloud is significantly lower then the ISM value, then accretion can proceed via the AAM Model. To reduce the opacity inside the gas cloud, the AAM posits as one of the its options that optical and UV radiation inside the accreting material is shifted from the optical/UV into the far IR and also the that the opacity may be lower than the ISM value because the opacity will be reduced by the accretion of optically thick material in the blobs of the accretion disk. Thus reducing the opacity or finding a physical mechanism that reduces the opacity to values lower than the ISM is a viable solution to the radiation problem. The above mechanism to reduce the opacity are rather mechanical and dependent on the environment. Is there any physical mechanism that exists naturally that can alter the opacity to values lower than the ISM inside the cloud? On the condition that, *if* the accretion disk where not destroyed and accretion of mass onto the star where to continue *via* this disk up-till all the circumstellar material has been swept off by the radiation field, then, we offer the following solution which appears to us as a perdurable solution capable of shading light on the problem.

III. RADIATION AND THE CIRCUMSTELLAR MATERIAL

Neglecting thermal, magnetic, turbulence and any other forces (as will be shown latter on in this section, these forces do not change the essence of our argument, hence there is no 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 of material enclosed in a volume space of radius $\mathcal{R}_{core}(t)$ and we shall call this system of material the core and further assume that this core shall have a total constant mass $\mathcal{M}_{core}$ at all times. Now for as long as the material enclosed in the sphere of radius $r < \mathcal{R}_{core}(t)$ is such that:

$$\frac{G\mathcal{M}(r,t)}{r^2} > \frac{\kappa_{eff} L_{star}(t)}{4\pi c r^2}, \tag{4}$$

then, radiation pressure will not exceed the gravitational force in the region $r < \mathcal{R}_{core}(t)$ hence thus direct radial in-fall is expected to continue. If $\mathcal{M}_{csl}(r,t)$ is the mass of the circumstellar enclosed in radius r at time t, then $\mathcal{M}(r,t) = \mathcal{M}_{csl}(r,t) + \mathcal{M}(t)$, hence the difference between (4) and (1) is that in (4) we have include the circumstellar material.

Proceeding, (4) can be written differently as:

$$\mathcal{M}(r,t) > \frac{\kappa_{eff} L_{star}(t)}{4\pi G c}, \tag{5}$$

which basically says as long as the amount of matter enclosed in the region of sphere radius r satisfies the above condition, the radiation force will not exceed the gravitational force. Applied to the entire core *i.e.* $r = \mathcal{R}_{core}$, this means, if the star's luminosity is such that:

$$\mathcal{M}_{core} > \frac{\kappa_{eff} L_{star}(t)}{4\pi G c}, \tag{6}$$

then, the radiation field of the star will not disrupt the in-fall of material inside the core. From this, let us define the critical luminosity $[L_*(\text{core})]$ of a core of mass $\mathcal{M}_{core}$ and whose opacity is κ_{eff}, to be:

$$L_*(\text{core}) = \frac{4\pi c G \mathcal{M}_{core}}{\kappa_{eff}}. \tag{7}$$

With this defined, what (6) is saying is that for the radiation field to overcome the gravitational field, the nascent star's luminosity must exceed the critical luminosity of the core, that is:

$$L_{star}(t) > L_*(\text{core}). \tag{8}$$

Now, from (6), if we insert the mass-luminosity relationship of stars $L_{star}(t) = L_\odot (\mathcal{M}(t)/\mathcal{M}_\odot)^3$, the equality in (6) will occur when:

$$\left(\frac{\mathcal{M}_{star}}{\mathcal{M}_\odot}\right) = \left(\frac{\kappa_{eff} L_\odot}{4\pi G \mathcal{M}_\odot c}\right)^{-1/3} \left(\frac{\mathcal{M}_{core}}{\mathcal{M}_\odot}\right)^{1/3}. \tag{9}$$

Given this and taking $\kappa_{eff} = 20\,m^2 kg^{-1}$ and then plucking this and the other relevant values G, c etc in the above, we are lead to:

$$\left(\frac{\mathcal{M}_{star}}{\mathcal{M}_\odot}\right) = \left(\frac{\mathcal{M}_{core}}{10\mathcal{M}_\odot}\right)^{1/3}. \tag{10}$$

What this means is that the mass of the core from which a star is formed may be crucial in deciding the final mass of the star because the mass of the core determines the time when in-fall reversal will occur. The time which the radiation begins to disperse the material of the core, is the time that we can consider that in-fall will be reversed and before then, in-fall is still taking place and at the same time, it is in the approach the halting-point when $L_{star}(t) = L_*(\text{core})$. If in-fall is not taking place, at least the material in the core can not be blown out of the core because the star's luminosity has not reached the critical luminosity of the core to be able to do this – this is in accordance with (6).

From this simplistic and rather naïve calculation, we can estimate the efficiency of the core:

$$\xi_{core}(\mathcal{M}) = \frac{\mathcal{M}_{star}}{\mathcal{M}_{core}} = 0.10 \left(\frac{\mathcal{M}_{core}}{10\mathcal{M}_\odot}\right)^{-2/3}, \tag{11}$$

thus a $100\mathcal{M}_\odot$ core will have an efficiency of about 2% and it will produce a star of mass $2\mathcal{M}_\odot$. A $10\mathcal{M}_\odot$ star will be produced by a core of mass $10^4\mathcal{M}_\odot$ at an efficiency rate of about 0.1%. A $10^4\mathcal{M}_\odot$ core is basically a fledged molecular cloud. The efficiency with which this $10\mathcal{M}_\odot$ star will produce is 0.1% and this is on the assumption that the rest of the material will not form stars. This is not the case as some of the material will form stars. Further, a $100\mathcal{M}_\odot$ star will form in a GMC of mass about $10^7\mathcal{M}_\odot$. The above deductions that high mass stars will need to form in clouds of mass $\geq 10^4\mathcal{M}_\odot$, resonates with the observational fact that massive stars are not found in isolation (Hillenbrand 1997; Clarke *et al.* 2000) since the other material will form stars.

The relationship (10) is interesting *viz* its similarity to Larson's 1982 empirical discovery. With a handful of data, Larson (1982) was the first to note that the maximum stellar mass of a given population of stars is related to total mass of the parent cloud from which the stellar population has been born. That is to say, if $\mathcal{M}_{cl}$ is the mass of molecular cloud and $\mathcal{M}_*$ is the maximum stellar mass of the population, then:

$$\mathcal{M}_* = \left(\frac{\mathcal{M}_{cl}}{\mathcal{M}_0}\right)^{\alpha_L} \tag{12}$$

where $\mathcal{M}_0 = 13.2\mathcal{M}_\odot$ and $\alpha_L = 0.430$. This law was obtained for cloud mass range $1.30 \lesssim \log_{10}(\mathcal{M}/\mathcal{M}_\odot) \lesssim 5.50$. Could the relationship (10) be related to Larson's result? The indices of Larson's relation and relationship (10) have a deviation of about 33% and the constant $\mathcal{M}_0$ has a similar deviation of about 33%. Could Larson's fitting procedure be "tuned" to conform to relationship (10) and if so, does that mean Larson's relationship finds an explanation from this?

Perhaps the deviation of our relation from that of Larson may well be that our result is derived from an ideal situation where we have considered not the other forces such as the magnetic, thermal forces *etc*, also, we have considered star formation as a spherically symmetric process of which it is not and this may also be a source of correction to this result in order to bring it to Larson's result. Let us represent all these other forces by $\vec{\mathbf{F}}_{other}$. Clearly these forces will not aid gravity in its endeavor to squeeze all the material to a single point but aid the radiation pressure in opposing this. Given this, it means we must write (4) as:

$$\frac{G\mathcal{M}(r,t)}{r^2} > \frac{\kappa_{eff} L_{star}(t)}{4\pi c r^2} + \frac{|\vec{\mathbf{F}}_{other}|}{m}, \tag{13}$$

where m is the average mass of the molecular species of the material constituting the cloud. The above can be written in the form:

$$L_{star}(t) < \frac{4\pi c G\left(\mathcal{M}(r,t) - r^2|\vec{\mathbf{F}}_{other}|/m\right)}{\kappa_{eff}}, \tag{14}$$

and writing $\mathcal{M}'(r,t) = r^2|\vec{\mathbf{F}}_{other}|/m$, we have from the above:

$$L_{star}(t) < \frac{4\pi c G\left[\mathcal{M}(r,t) - \mathcal{M}'(r,t)\right]}{\kappa_{eff}}, \tag{15}$$

and from this it is clear that the other forces will act in manner as to reduce the critical luminosity of the core thus our result (10), when compared to natural reality where these other forces are present, it is expected that a deviation from the real observations must occur. As stated in the opening of this section that the inclusion of the magnetic, thermal forces etc will not change the essence of our argument, hence the above justifies why we did not have to worry about these other forces as the essence of our result stands. The situation is only critical when these other forces become significant in comparison to the gravitational force.

In the succeeding section, we provide an alternative approach where we compute the mass distribution and from there show that one arrives at the same result as (6). We hope, that this this alternative approach gives one a more intuitive feeling of what we have presented above. Additionally, this alternative approach gives more information in that it tells us that the radiation field will create a cavity inside the star forming core.

IV. ALTERNATIVE APPROACH TO THE PROBLEM

First we compute the enclosed mass $\mathcal{M}(r,t)$. We know that stellar systems such as cores and molecular clouds are found to exhibit a radial density profiles given by:

$$\rho(r,t) = \rho_0(t)\left(\frac{r_0(t)}{r}\right)^{\alpha} \tag{16}$$

where $\rho_0(t)$ and $r_0(t)$ are time dependent normalization constants. In order to make sense of this density profile (16) we shall have to calculate these normalization constants and this shall be done soon. In its bare form, the power law equation (16) as it stands implies an infinite density at $r = 0$. Power laws have this property. Obvious one has to deal with this. The usual or typical way is to impose a minimum value for r say $r_{min} = r_0(t)$ and assign a density there. Here, this minimum radius has been made time dependent for the sole reason that if the cloud is undergoing free fall as in the case in star formation regions, this quantity will dynamically respond to this, hence it will be time dependent.

Now, for a radially dependent density profile, the mass distribution is calculated from the integral:

$$\mathcal{M}(r,t) = \int_{r_{min}}^{r} 4\pi r^2 \rho(r,t) dr. \tag{17}$$

Inserting the density function (16) into the above integral and then evaluating the resultant integral, we are lead to:

$$\mathcal{M}(r,t) = \frac{4\pi\rho_0(t) r_0^{\alpha}(t)}{3-\alpha}\left(r^{3-\alpha} - r_0^{3-\alpha}(t)\right), \tag{18}$$

The case $\alpha = 3$ leads to the special form of the MDF:

$$\mathcal{M}(r,t) = 4\pi\rho_0(t) r_0^3(t) \ln\left(\frac{r}{r_0(t)}\right). \tag{19}$$

We shall not consider this case as it will not change the essence of our argument.

Now, what we shall do here is to constrain the α and show that $0 < \alpha < 3$. Constraining α will not change the essence of our argument. This exercise is being conducted to define the domain which our result has physical significance.

Let $r_1 > r_2$. For this setting, we expect that $\mathcal{M}(r_1) > \mathcal{M}(r_2)$ and this is obvious thing because as we zoom out of the cloud radial, one would expect in the sphere of radius r_2 that there will be at least more matter than the engulfed sphere of radius r_1. The condition $\mathcal{M}(r_1) > \mathcal{M}(r_2) \Longrightarrow \mathcal{M}(r_1) - \mathcal{M}(r_2) > 0$. Using equation (18), we have:

$$\mathcal{M}(r_1) - \mathcal{M}(r_2) = \frac{4\pi\rho_0 r_{min}^{\alpha}}{3-\alpha}\left(r_1^{3-\alpha} - r_2^{3-\alpha}\right) > 0, \tag{20}$$

and for $\alpha > 3$ we have $3 - \alpha < 0$ so when we divide by the term $(4\pi\rho_0 r_{min}^{\alpha})/(3-\alpha)$ on both sides of the inequality, we must change the sign of the inequality from $>$ to $<$ because $(4\pi\rho_0 r_{min}^{\alpha})/(3-\alpha)$ is a negative number. So doing we will have from this:

$$r_1^{3-\alpha} - r_2^{3-\alpha} < 0, \tag{21}$$

and this implies $r_1^{\alpha-3} < r_2^{\alpha-3}$ and from this follows directly the relationship:

$$r_1 < r_2, \tag{22}$$

and this is a ***contradiction*** because it violates our initial condition $r_1 > r_2 \Longrightarrow \mathcal{M}(r_1) > \mathcal{M}(r_2)$. We therefore conclude that $\alpha < 3$.

Going further, if $3 - \alpha > 3$, it means as one zooms out of the cloud from the center, the cloud's average material density increases. This scenario is unphysical because gravity is an attractive inverse distance law and thus will always pack more and more material in the center than in the outer regions as one zooms out of the clouds from its center and hence the only material configuration that can emerge from this setting is one in which the average density of material decreases as one zooms out of the cloud. This implies $3-\alpha < 3$ which leads to $\alpha > 0$, hence combining the two results we have $0 < \alpha < 3$. As has already been said, constraining α does not change the essence of our argument but is an exercise to define the physical boundaries.

Now we have to normalize the MDF by imposing some boundary conditions. The usual or traditional boundary condition is to set $\mathcal{M}(r_0(t)) = 0$ and this in actual fact means there will be a cavity of radius $r_0(t)$ in the cloud. What we shall do is different from this normal or traditional normalization. We shall set $\mathcal{M}(r_0(t)) = \mathcal{M}_{star}$ where $\mathcal{M}_{star}$ is the mass of the central star. Thus what we have done is to place the nascent star in the cavity. This means we must write our MDF as:

$$\mathcal{M}(r,t) = \frac{4\pi\rho_0(t) r_0^{\alpha}(t)}{3-\alpha}\left(r^{3-\alpha} - \mathcal{R}_{star}^{3-\alpha}(t)\right) + \mathcal{M}_{star}(t), \tag{23}$$

and this applies for $\mathcal{R}_{star}(t) < r < \mathcal{R}_{core}(t)$.
Now, if the mass enclosed inside the core remains constant throughout, then we must have at $r = \mathcal{R}_{core}(t)$ the boundary condition $\mathcal{M}(\mathcal{R}_{core}, t) = \mathcal{M}_{core}$, thus the circumstellar material $\mathcal{M}_{csl}(t) = \mathcal{M}_{core} - \mathcal{M}_{star}(t)$, and hence:

$$\frac{4\pi\rho_0(t) r_0^{\alpha}(t)}{3-\alpha} = \frac{\mathcal{M}_{csl}}{\left(\mathcal{R}_{core}^{3-\alpha}(t) - \mathcal{R}_{star}^{3-\alpha}(t)\right)}, \tag{24}$$

and this means the MDF can now be written as:

$$\mathcal{M}(r,t) = \overbrace{\mathcal{M}_{csl}(t)\left(\frac{r^{3-\alpha} - \mathcal{R}_{star}^{3-\alpha}(t)}{\mathcal{R}_{core}^{3-\alpha}(t) - \mathcal{R}_{star}^{3-\alpha}(t)}\right)}^{\text{Circumstellar Material in Region Radius r}} + \overbrace{\mathcal{M}_{star}(t)}^{\text{Mass of the nascent star}}. \tag{25}$$

We shall take this as the final form of our mass distribution function. If the reader accepts this, then what follows is straight forward exercise and leads to what we believe is a significant step forward in the resolution of the radiation problem.

Now substituting equation (25) into the left hand side of equation (1) [where we place $\mathcal{M}(r,t)$ in the place of $\mathcal{M}_{star}(t)$] we are lead to:

$$\vec{\mathbf{g}}(r) = -\overbrace{\left(\frac{G\mathcal{M}_{csl}(t)}{r^2}\right)\left(\frac{r^{3-\alpha} - \mathcal{R}_{star}^{3-\alpha}(t)}{\mathcal{R}_{core}^{3-\alpha}(t) - \mathcal{R}_{star}^{3-\alpha}(t)}\right)\hat{\mathbf{r}}}^{\text{Circumstellar Gravitation}} - \overbrace{\left(\frac{G\mathcal{M}_{star}(t)}{r^2}\right)\hat{\mathbf{r}}}^{\text{Star's Gravitation}}. \tag{26}$$

Now with all the above, the inequality (3) now reduces to:

$$\left(\frac{G\mathcal{M}_{csl}(t)}{r^2}\right)\left(\frac{r^{3-\alpha} - \mathcal{R}_{star}^{3-\alpha}(t)}{\mathcal{R}_{core}^{3-\alpha}(t) - \mathcal{R}_{star}^{3-\alpha}(t)}\right) + \left(\frac{G\mathcal{M}_{star}(t)}{r^2}\right) > \frac{\kappa_{eff} L_{star}(t)}{4\pi r^2 c}, \tag{27}$$

where the first term on the left hand-side is the gravitational field of the circumstellar material and the second term is the

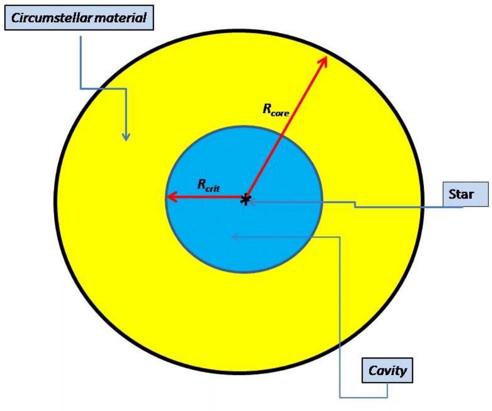

FIG. 1: A cavity is created inside the star forming core due to the nascent star's radiation field.

gravitational field of the nascent star. The equality will occur when $r = \mathcal{R}_{core}(t)$, and this leads directly to (6) and everything else from here follows. What we have done here is simply to take a rather lengthy exercise to arrive at the same result.

V. RADIATION CAVITY

The inequality (6) gives us the global condition that must be met before the radiation field is powerful enough before it can push away all the circumstellar material. As-well, the inequality (27) as does (6), tells us the conditions to be met before the radiation field is powerful enough to halt in-fall albeit (27) sheds more information than (6) because from (27) we deduce that the radiation field will create a cavity in the star forming core and in the this cavity, the radiation field is power enough to halt in-fall in this region. One can not deduce this from (6) hence the alternative root we have taken is a necessary root as it supplies us with vital information. To see this – that (6) entails a cavity inside the core, we have to write (27) with r as the subject of the formula, *i.e.* $r > \mathcal{R}_{crit}(t)$ where:

$$\mathcal{R}_{crit}(t) = \left(\frac{\left(\kappa_{eff} L_{star}(t) - 4\pi c G \mathcal{M}_{star}(t)\right)\left(\mathcal{R}_{core}^{3-\alpha}(t) - \mathcal{R}_{star}^{3-\alpha}(t)\right)}{4\pi c G \mathcal{M}_{csl}(t)} + \mathcal{R}_{star}^{3-\alpha}(t)\right)^{\frac{1}{3-\alpha}}, \tag{28}$$

and what this inequality is "*saying*" is that, at any given moment in time, there will exist a region $r < \mathcal{R}_{crit}(t)$ where the radiation field will reverse the radially in-falling material and in the region $r > \mathcal{R}_{crit}(t)$, for material therein, the radiation field has not reached a state where it exceeds the gravitational field. This region [*i.e.* $r < \mathcal{R}_{crit}(t)$] grows with time thus the radiation field slowly and gradually pushes the material further and further away from the nascent star until $\mathcal{R}_{crit}(t) = \mathcal{R}_{cl}$ where radial in-fall is completely halted; this scenario is completely different from that projected in much of the literature where at $10\,\mathcal{M}_{\odot}$, suddenly the radiation is so powerful it reverses any further in-fall. On the walls of this cavity, the material falling on them [cavity walls] radially will or may be expected to find its way to the equatorial disk which is thought to be the next channel *via* which the stars's mass grows.

We need to point out that we here have considered a spherically symmetric scenario and as is common knowledge, star formation is not a spherically symmetric process. If star formation was a spherically symmetric scenario, the cavity created by the radiation would halt the in-fall of matter on the nascent but because this is not the case, it is foreseeable that mass accretion by the nascent star may continue *via* the equatorial disc. It is also imaginable that the magnetic field of the nascent star may help also in the mass accretion. The main point that we have wanted to drive is that the radiation field will not push away all the in-falling material on the nascent as we have demonstrated that the radiation will gradually push this material away until a point is reached where all the in-falling material is halted when the nascent star's luminosity reaches the critical core luminosity.

In the popular and accepted literature, it is said that at $10\,\mathcal{M}_{\odot}$, all the material from the surface of the star, $r = \mathcal{R}_{star}(t)$, right up to the edge of the core, $r = \mathcal{R}_{core}(t)$, must suffer reversal due the nascent star's radiation field. What we have found here is that, *if and only if* the accretion disk is not destroyed and acts up as the channel *via* which the star's mass grows, then, the circumstellar material is pushed away gradually until a point is reached when the cavity is the size of the core itself, at which point complete in-fall reversal is attained. It is foreseeable that the circumstellar material in the region $\mathcal{R}_{crit}(t) < r \leq \mathcal{R}_{core}(t)$ will find its way to the accretion disk *via* the cavity walls and as-well as the centrifugal forces since it is natural and expected that the core must exhibit some spin angular momentum. So, to the question paused in the subtitle "Can circumstellar material – globally, stop in-fall reversal?", our answer is a clear yes, it does.

The reader will ask, "Why is the accretion disk not destroyed and what mechanism keeps it un-destroyed?". To this question, first we have to take note that the present consideration is based on a spherically symmetric scenario, the gravitational field; *i.e.*, the gravitational field is spherical symmetric. We have been able to show that if one considers an azimuthally symmetric gravitational field, the radiation field will seize to exist and that the accretion disk is not destroyed. We have set up an Azimuthally Symmetric Theory of Gravitation (ASTG) and the reading where this is done has been accepted to the *Monthly Notices of the Royal Academy of Sciences Journal* (see Nyambuya 2009*a*) and a follow-up reading on which we argue that the ASTG solves the radiation problem in currently under review with the same journal (see Nyambuya 2009*a*). Because of this, we have not supplied here our arguments on these matters. All we want is to show that the current definition of the radiation problem has some faults because it does not take into account the circumstellar material and that performing the correct calculation leads us to a different picture to the widely accepted one.

VI. DISCUSSION AND CONCLUSIONS

This contribution answers the question paused in the subtitle, *i.e.*, "Can circumstellar material – globally; stop in-fall reversal?" To this question, we find that the answer is *yes, it* [circumstellar material] *does*. We find that the radiation will create a cavity (whose radius is $\mathcal{R}_{crit}(t)$) inside the star forming core and the circumstellar material inside the region $\mathcal{R}_{crit}(t) < r \leq \mathcal{R}_{core}(t)$ is going to be pushed away gradually as the radiation field from the star grows until a point is reached when the cavity is the size of the core itself, at which point complete in-fall reversal is attained. If the radiation field of the star is to grow, its mass must grow, thus, the cavity must not prevent accretion of mass on the nascent star.

To the question of how does accretion continue *via* the disk, we have been able to show that if one considers an azimuthally symmetric gravitational field, the radiation field will seize to exist and that the accretion disk is not destroyed. We have set up an Azimuthally Symmetric Theory of Gravitation (ASTG) and the reading where this is done has been accepted to the *Monthly Notices of the Royal Academy of Sciences Journal* (Nyambuya 2009*a*) and a follow-up reading on which we argue that the ASTG solves the radiation problem in currently under review with the same journal (Nyambuya 2009*b*). Because of this, we have not supplied here our arguments on these matters. All we want is to show that the current definition of the radiation problem has some faults because it does not take into account the circumstellar material and that performing the correct calculation leads us to a different picture to the widely accepted one.

To this same question "Can circumstellar material – globally; stop in-fall reversal?"; Yorke (2002), Yorke & Sonnhalter (2002), Zinnecker & Yorke (2007) would give the answer: no, the radiation field will (is expected), according to (13) for a star of mass greater than 10 $\mathcal{M}_{\odot}$ – for a spherically symmetric gravitational field; reverse the in-falling circumstellar material. Simple because we we give an answer contrary to Yorke (2002), Yorke & Sonnhalter (2002), Zinnecker & Yorke (2007) *etc*, we consider this contribution to be worthwhile. The real problem in Yorke (2002), Yorke & Sonnhalter (2002), Zinnecker & Yorke (2007) *etc*, is that these researchers have neglected the treatment of the circumstellar material – the inequality (13) applies only for a star in empty space. In empty space, it is correct to say that the radiation field for a star of mass 10 $\mathcal{M}_{\odot}$ and beyond, will exceed the gravitational field everywhere in space beyond the nascent star's surface, but the same is not true for a star submerged in a pool of gas as the stars we observe.

From the alternative approach presented in §IV, one may argue given that the bone of contention here is that the circumstellar material partly solves the radiation problem and given as-well that, the mass in the surroundings of nascent star may not be very large as compared to the stellar mass as for example, in Shu (1976, 1977) models of low mass stars formation, the inner parts of the star forming core contract much faster compared to the outer parts, and this would result in much more mass being concentrated in the center as compared to the surrounding core thus rendering our argument obsolete. In this case in accordance with (6), as long as the material in this region satisfies this condition, the radiation pressure within this region is not going to overcome gravity because the star's luminosity must exceed the critical luminosity for this defined region.

Further one may argue also that the opacity varies with distance in a molecular cloud and this will greatly increase the opacity close to the star, in which case, it will cause the star's radiation pressure to greatly overwhelm the star's gravity; once again this will not hold as long as the material in this region satisfies condition (6), the star's luminosity must exceed the critical luminosity for this defined parcel of material or region. Further-on, one may also argue again that the average density needs not always decrease outward for example in clumpy clouds where one can find denser regions as they zoom out of the cloud. The above argument holds still and besides, it has been argued that the distribution of the material does not really matter here.

It is important to state that star formation is not spherical symmetric phenomena, thus one many also argue here that our model may not be correct because it is based on the wrong geometry, once again this result is not dependent on the geometry, it does not matter how the material in the cloud is distributed. What matters is how much matter is found in that given region? Does it satisfy condition (6)? *If yes*, then the radiation field in this closed region of radius r will not exceed the gravitational field.

In closing, the fact the we were able to derive a relationship similar to Larson's 1982 result which up to now has no theoretical explanation is but encouraging, and gives one the feeling that our result may hold an element of truth in it. Our result – as has been shown – has, a 33% deviation from the result of Larson (1982) and it may well be possible to account for this given that we have not taken into account the other forces as has been argued. As my last words here, allow me to further say that, we do not claim to have solved the radiation problem but merely believe that what we have presented herein, is a significant step forward in the endeavor to resolving this problem.

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