Astrophysical Objects

Star Formation

An introduction to modern Astrophysics chapter 12

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The formation of protostars

Protostar L1527

Our understanding of stellar evolution has developed significantly **since the 1960s**, reaching the point where much of the life history of a star is well determined. This success has been due to **advances in observational techniques**, improvements in our knowledge of the physical processes important in stars, and **increases in computational power.**

Despite many successes, important questions remain, especially about the earliest stage of stellar evolution, the formation of **pre-nuclear-burning objects** known as **protostars** from interstellar molecular clouds.

The formation of protostars

Protostar L1527

The protostar L1527, (image: James Webb Space Telescope) is embedded within a **cloud of material** (the thin **pink line in the center** of the hourglass shape) that is feeding its growth.

Material ejected from the star has cleared out **cavities** above and below it, whose boundaries glow orange and blue in this infrared view.

The upper central region displays bubble-like shapes due to stellar ‘burps,’ or sporadic **ejections**. Webb also detects filaments made of molecular hydrogen that has been shocked by past stellar ejections.

The region at lower right appears blue, as there’s less dust between it and Webb than the orange regions above it.

If globules and cores in molecular clouds are the sites of star formation, what conditions must exist for collapse to occur?

The formation of protostars

If globules and cores in molecular clouds are the sites of star formation, what conditions must exist for collapse to occur?

Sir James Jeans (1877–1946) first investigated this problem in 1902 by considering the effects of small deviations from **hydrostatic equilibrium**. Although several simplifying assumptions are made in the analysis, such as neglecting effects due to rotation, turbulence, and galactic magnetic fields, it provides important insights into the development of protostars.

The **virial theorem,**

$$2K + U = 0,$$

describes the condition of equilibrium for a stable, gravitationally bound system.

We have already seen that the virial theorem arises naturally in estimating the amount of gravitational energy contained within a star. The virial theorem may also be used to estimate the conditions necessary for protostellar collapse.

The formation of protostars

$$2K + U = 0,$$

If twice the total internal **kinetic energy** of a molecular cloud **(2K)** exceeds the absolute value of the **gravitational potential energy (|U|)**, the force due to the gas **pressure will dominate** the force of gravity and the **cloud will expand**.

On the other hand, **if the internal kinetic energy is too low, the cloud will collapse.**

The boundary between these two cases describes the critical condition for stability *when rotation, turbulence, and magnetic fields are neglected.*

Assuming a spherical cloud of constant density, the **gravitational potential energy** is approximately

$$U \sim -\frac{3}{5}\frac{GM_c^2}{R_c},$$

where M_c and R_c are the mass and radius of the cloud, respectively

The formation of protostars

We may also estimate the cloud's internal **kinetic energy,** given by:

$$K = \frac{3}{2} N k T,$$

where N is the total number of particles.

$$N = \frac{M_c}{\mu m_H},$$

where μ is the mean molecular weight. Now, by the **virial theorem**, the condition for collapse (2K < |U|) becomes:

$$\frac{3 M_c k T}{\mu m_H} < \frac{3}{5} \frac{G M_c^2}{R_c}.$$

$$R_c = \left(\frac{3 M_c}{4\pi \rho_0} \right)^{1/3}.$$

The formation of protostars

The radius may be replaced by using the initial mass density of the cloud, ρ_0, assumed here to be constant throughout the cloud,

$$R_c = \left(\frac{3M_c}{4\pi\rho_0}\right)^{1/3}.$$

we may solve for the minimum mass necessary to initiate the spontaneous collapse of the cloud. This condition is known as the **Jeans criterion**:

$$M_c > M_J,$$

where

$$\boxed{M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}}$$

is called the **Jeans mass**.

The formation of protostars

The Jeans criterion may also be expressed in terms of the **minimum radius necessary to collapse a cloud** of density ρ_0:

$$R_c > R_J,$$

Where

$$\boxed{R_J \simeq \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)^{1/2}}$$

is the **Jeans length.**

The formation of protostars

The Jeans mass derivation given above neglected the important fact that there must exist an **external pressure** on the cloud due to the surrounding interstellar medium (such as the encompassing GMC in the case of an embedded dense core).

The critical mass required for gravitational collapse in the presence of an external gas pressure of P_0 is given by the **Bonnor–Ebert mass**,

$$\boxed{M_{\mathrm{BE}} = \frac{c_{\mathrm{BE}} v_T^4}{P_0^{1/2} G^{3/2}},}$$

Where

$$v_T \equiv \sqrt{kT/\mu m_H}$$

is the ***isothermal sound speed*** ($\gamma = 1$), and the dimensionless constant c_{BE} is given by $c_{\mathrm{BE}} \simeq 1.18.$

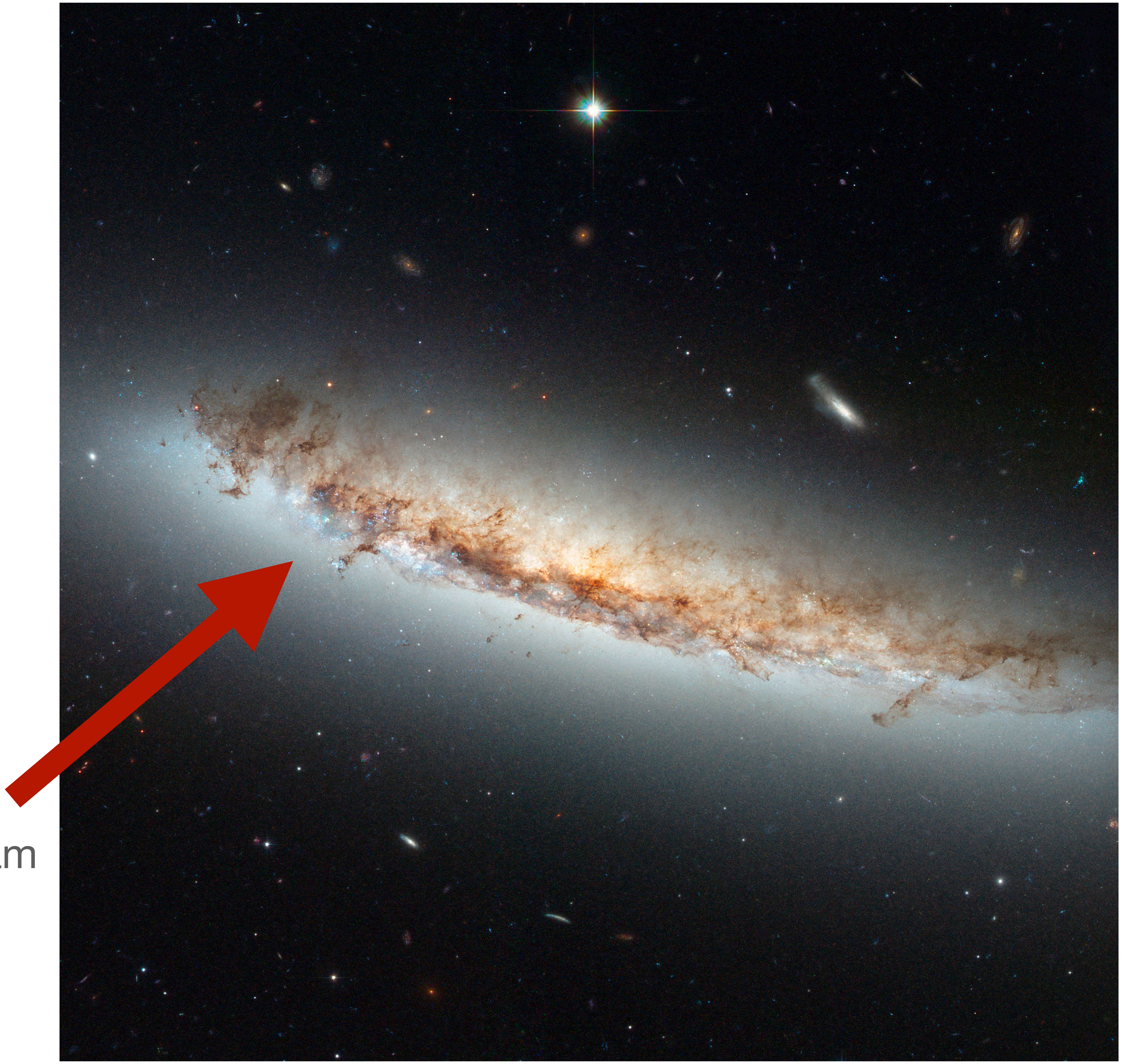
The formation of protostars

The Jeans mass can be written in the form of the Bonnor Ebert mass with $c_J \simeq 5.46$ replacing C_{BE}.

The smaller constant for the Bonnor–Ebert mass is to be expected since an **external compression force** due to P_0 is being exerted on the cloud.

Some examples of external compression can be:

- winds from star formation regions
- Winds from Supernovae.
- Ram Pressure from the intergalactic medium.

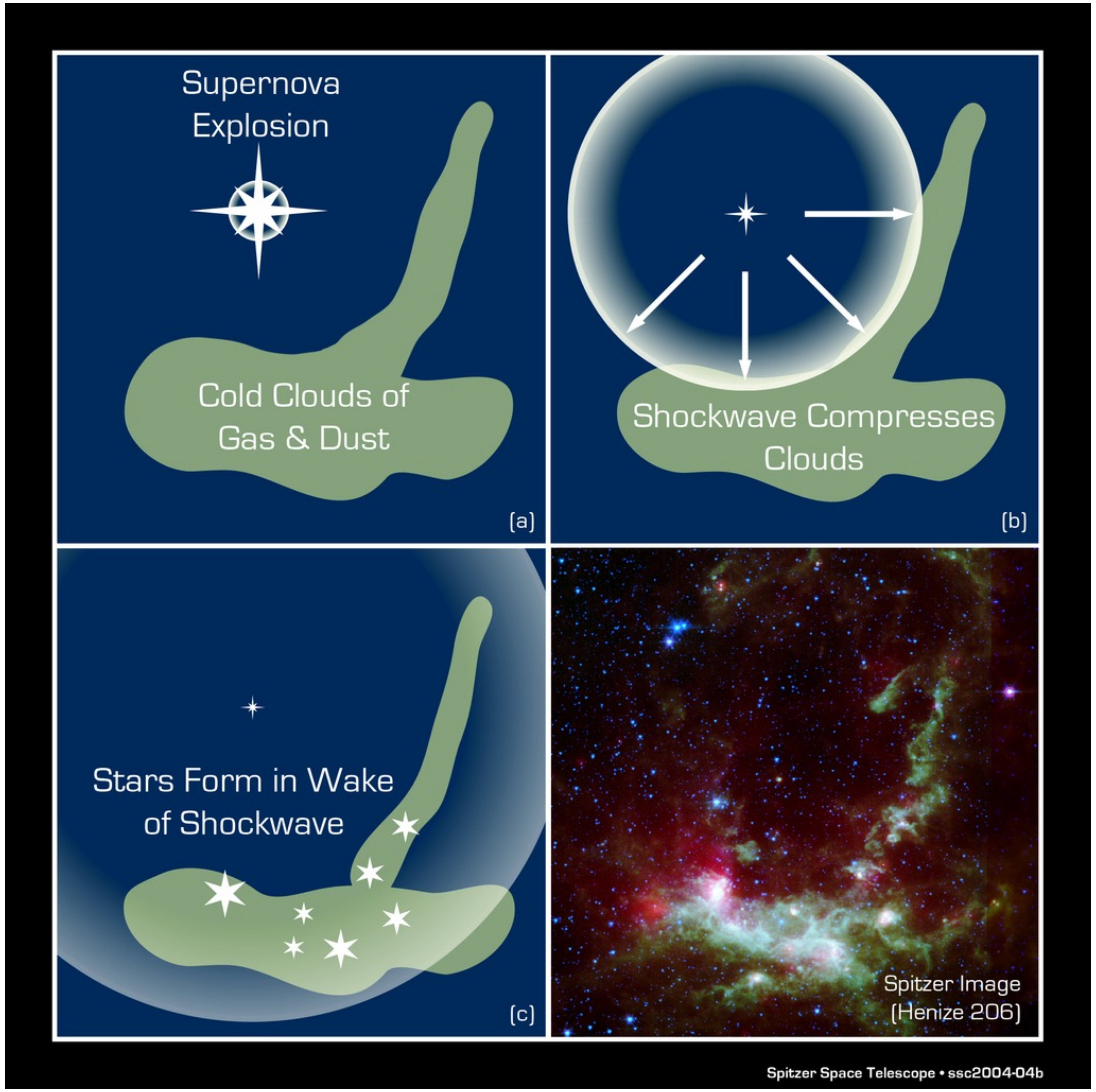


Young blue stars at the leading edge of a ram pressure stripped galaxy NGC 4402

The formation of protostars

An example of a shock wave from a Supernova triggering star formation. This process is called **triggered star formation.**

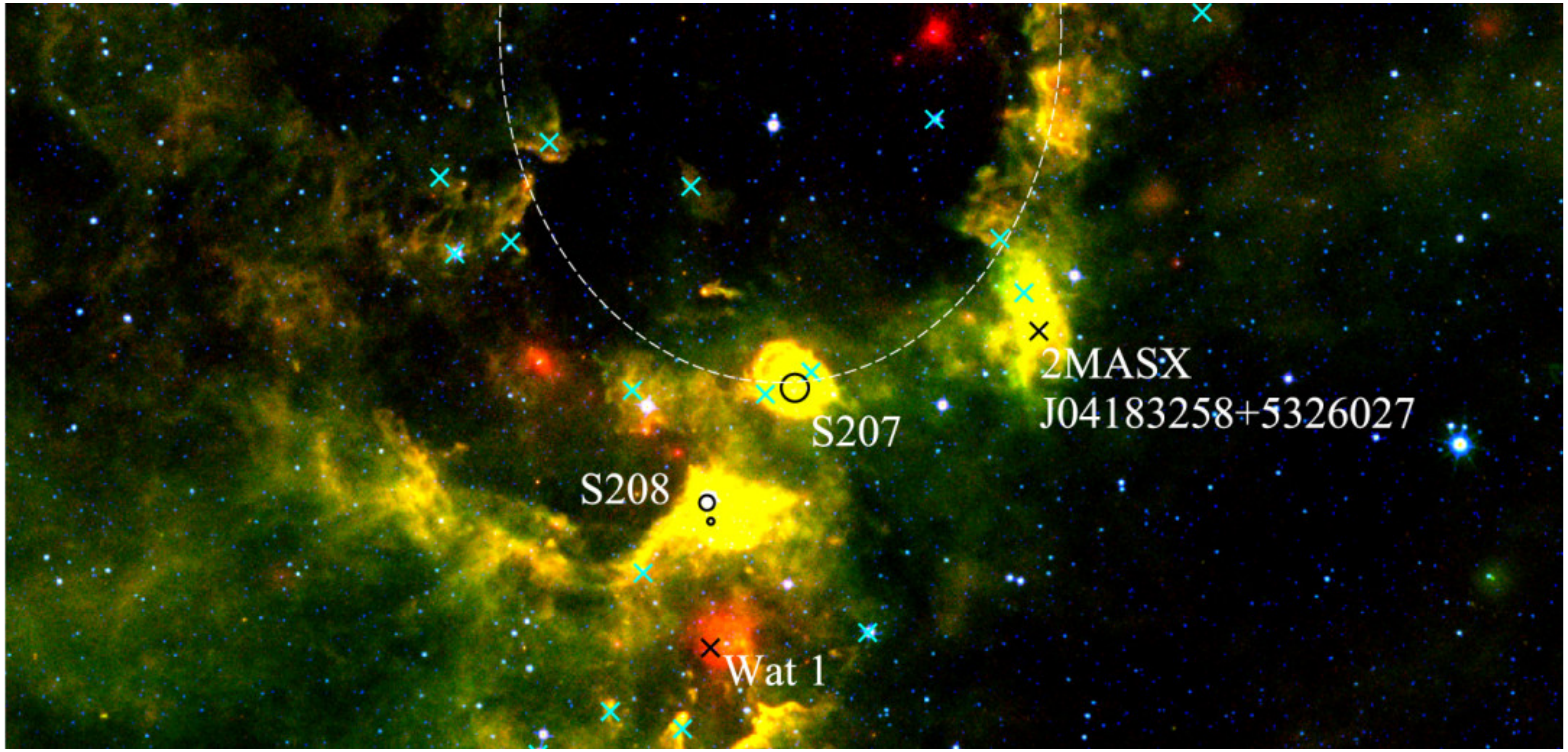
- In the first panel, a massive, dying star explodes or "goes supernova."
- In the second panel, the shock wave from this explosion passes through clouds of gas and dust (green).
- In the third panel, a new wave of stars is born within the cloud, induced by the shock from the supernova blast. The whole progression, from the death of one star to the birth of others, takes millions of years to complete.



https://www.spitzer.caltech.edu/image/ssc2004-04b-illustration-of-star-formation-in-henize-206

The formation of protostars

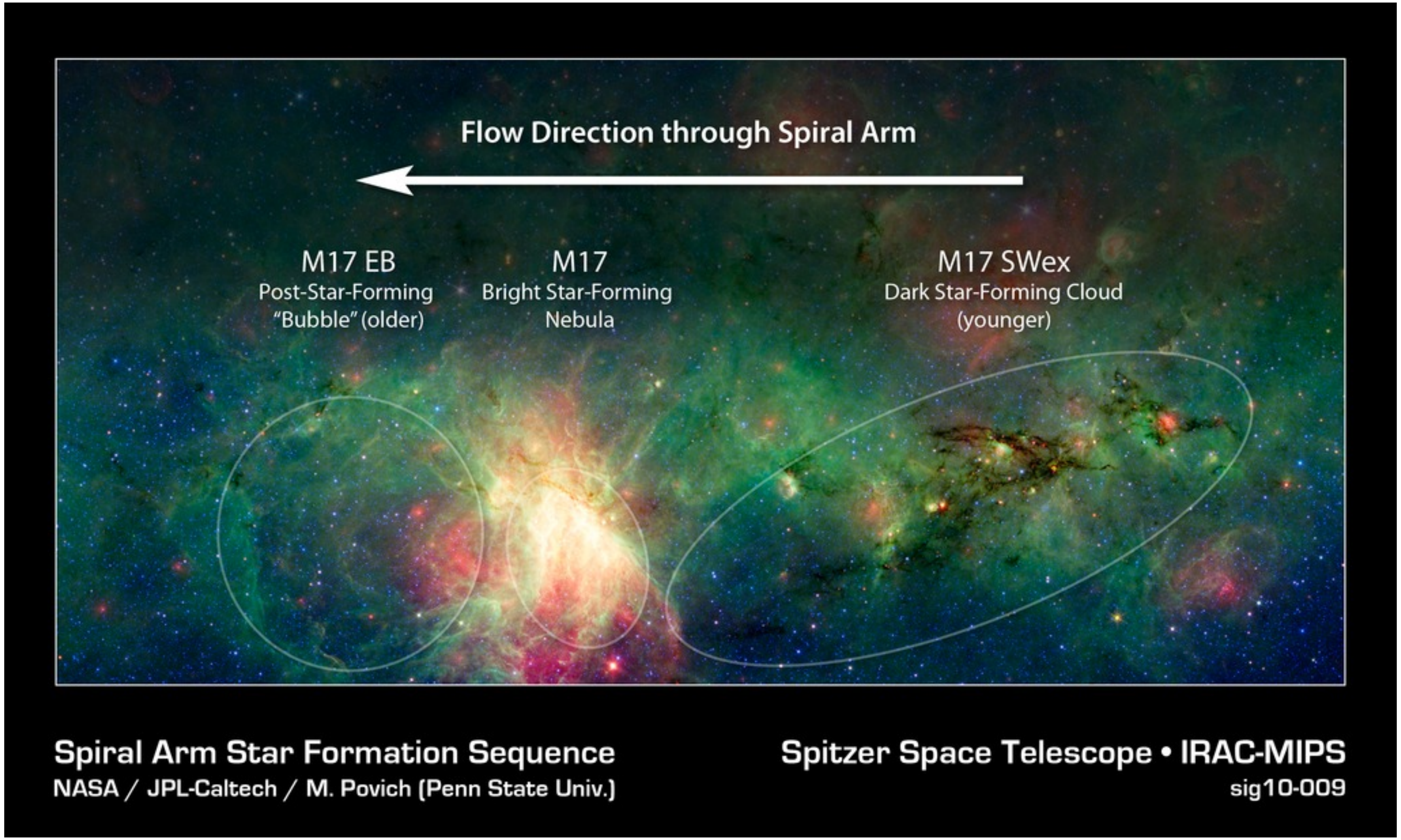
- WISE infrared image of Sh 2-207 and Sh 2-208.
- The data analysis suggests that sequential star formation is taking place in these low-metallicity regions, triggered by an expanding bubble (the large dashed oval indicated in the image) with a ~30 pc radius.



https://aasnova.org/2016/05/13/featured-image-a-bubble-triggering-star-formation/

The formation of protostars

- Star formation due to the pressure wave of the spiral arms in the Milky Way



The formation of protostars

Example:

For a typical **diffuse hydrogen cloud**, $T = 50$ K and $n = 5 \times 10^{8}$ m^{-3}. If we assume that the cloud is entirely composed of HI, $\rho_0 = m_H n_H = 8.4 \times 10^{-19}$ kg m^{-3}. Taking $\mu = 1$, the **minimum mass** necessary to cause the cloud to collapse spontaneously is approximately $M_J \sim 1500\ M_\odot$. However, this value **significantly exceeds** the estimated 1 to 100 $M_\odot$ to be contained in H I clouds. Hence **diffuse hydrogen clouds are stable against gravitational collapse.**

On the other hand, for a **dense core of a giant molecular cloud,** typical temperatures and number densities are $T = 10$ K and $n_{H2} = 10^{10}$ m^{-3}. Since dense clouds are predominantly molecular hydrogen, $\rho_0 = 2m_H n_{H2} = 3 \times 10^{-17}$ kg m^{-3} and $\mu \simeq 2$. In this case the **Jeans mass is $M_J \sim 8M_\odot$**, characteristic of the masses of dense cores being on the order of $10M_\odot$. The **dense cores of GMCs are unstable to gravitational collapse,** consistent with being sites of star formation.

If the **Bonnor–Ebert mass** is used as the critical collapse condition, then the required **mass reduces to approximately 2 $M_\odot$**.

Homologous Collapse

In the case that the criterion for gravitational collapse has been satisfied.

If we make the simplifying (and possibly unrealistic) **assumption that any existing pressure gradients are too small to influence the motion** appreciably, then the **cloud is essentially in free-fall during the first part of its evolution**. Furthermore, throughout the free-fall phase, the **temperature of the gas remains nearly constant** (i.e., the collapse is said to be *isothermal*).

- This is true as long as the cloud remains optically thin and the gravitational potential energy released during the collapse can be efficiently radiated away.
- In this case the spherically symmetric hydrodynamic equation can be used to describe the contraction if we assume that $|dP/dr| \ll GM_r\rho/r^2$.

After canceling the density on both sides of the expression, we have

$$\frac{d^2r}{dt^2} = -G\frac{M_r}{r^2}.$$

Homologous Collapse

$$\frac{d^2r}{dt^2} = -G\frac{M_r}{r^2}.$$

Of course, the right-hand side is just the local acceleration of gravity at a distance r from the center of a spherical cloud. The mass of the sphere interior to the radius r is denoted by M_r.

To describe the behavior of the surface of a sphere of radius r within the collapsing cloud as a function of time, the equation must be integrated over time.

Since we are interested only in the surface that encloses M_r, the mass interior to r will remain a constant during that collapse. As a result, we may **replace M_r by the product of the initial density ρ_0 and the initial spherical volume**, $4\pi r_0^3/3$.

Then, if we multiply both sides of the equation by the velocity of the surface of the sphere:

$$\frac{dr}{dt}\frac{d^2r}{dt^2} = -\left(\frac{4\pi}{3}G\rho_0 r_0^3\right)\frac{1}{r^2}\frac{dr}{dt},$$

which can be integrated once with respect to time to give

Homologous Collapse

$$\frac{dr}{dt}\frac{d^2r}{dt^2} = -\left(\frac{4\pi}{3}G\rho_0\, r_0^3\right)\frac{1}{r^2}\frac{dr}{dt},$$

which can be integrated once with respect to time to give

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \left(\frac{4\pi}{3}G\rho_0\, r_0^3\right)\frac{1}{r} + C_1.$$

The integration constant, C_1, can be evaluated by requiring that the velocity of the sphere's surface be zero at the beginning of the collapse, or $dr/dt = 0$ when $r = r_0$. This gives

$$C_1 = -\frac{4\pi}{3}G\rho_0\, r_0^2.$$

Homologous Collapse

Substituting and solving for the velocity at the surface, we have

$$\frac{dr}{dt} = -\left[\frac{8\pi}{3} G\rho_0 r_0^2 \left(\frac{r_0}{r} - 1\right)\right]^{1/2}.$$

Note that the negative root was chosen because the cloud is collapsing.
To integrate this equation, so that we can obtain an expression for the position as a function of time, we make the substitutions

$$\theta \equiv \frac{r}{r_0} \qquad \chi \equiv \left(\frac{8\pi}{3} G\rho_0\right)^{1/2},$$

which leads to the differential equation:

$$\frac{d\theta}{dt} = -\chi \left(\frac{1}{\theta} - 1\right)^{1/2}.$$

Homologous Collapse

Making another substitution: $$\theta \equiv \cos^2 \xi,$$

We get:

$$\cos^2 \xi \frac{d\xi}{dt} = \frac{\chi}{2}.$$

The equation may now be integrated directly with respect to t to yield:

$$\frac{\xi}{2} + \frac{1}{4}\sin 2\xi = \frac{\chi}{2}t + C_2.$$

Lastly, the integration constant, C_2, must be evaluated. Doing so requires that $r = r_0$ when $t = 0$, which implies that $\theta = 1$, or $\xi = 0$ at the beginning of the collapse. Therefore, $C_2 = 0$.

Homologous Collapse

We have finally arrived at the equation of motion for the gravitational collapse of the cloud, given in parameterized form by

$$\xi + \frac{1}{2}\sin 2\xi = \chi t.$$

Now we can extract the behavior of the collapsing cloud from this equation.

It is possible to calculate the **free-fall timescale** for a cloud that has satisfied the Jeans criterion. Let $t = t_{ff}$ when the radius of the collapsing sphere reaches zero ($\theta = 0$, $\xi = \pi/2$). (This is unphysical, but gives a reasonable approximation) Then

$$t_{\rm ff} = \frac{\pi}{2\chi}.$$

Substituting the value for χ, we have

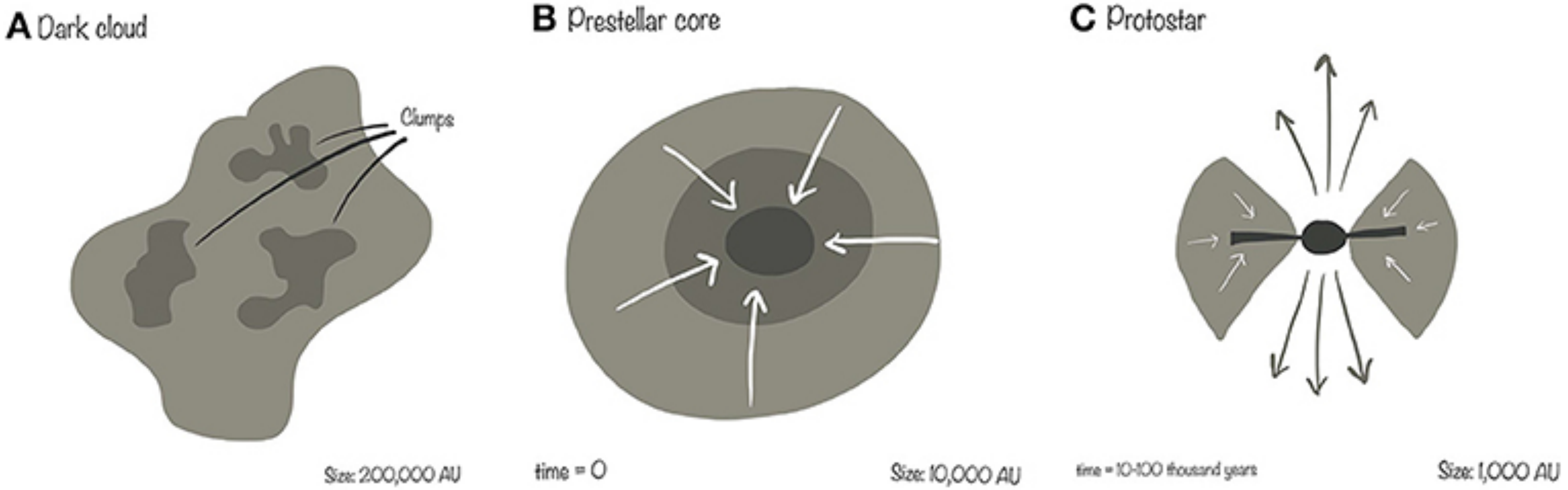
$$\boxed{t_{\rm ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}}$$

Homologous Collapse

$$t_{\rm ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}$$

You should notice that the **free-fall time is** actually **independent of the initial radius** of the sphere.

- Consequently, as long as the original **density of the spherical molecular cloud was uniform**, all parts of the cloud will take the same amount of time to collapse, and **the density will increase at the same rate everywhere**. This behavior is known as a **homologous collapse**.
- However, **if the cloud is somewhat centrally condensed** when the collapse begins, the **free-fall time will be shorter for material near the center** than for material farther out. Thus, as the collapse progresses, the **density will increase more rapidly near the center** than in other regions. In this case the collapse is referred to as an **inside-out collapse**.



https://kids.frontiersin.org/articles/10.3389/frym.2019.00092

Homologous Collapse

Example: Using data given in the previous Example for a dense core of a giant molecular cloud, we may estimate the amount of time required for the collapse.

Assuming a density of $\rho_0 = 3 \times 10^{-17}$ kg m^{-3} that is constant throughout the core,

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}$$

$t_{ff} = 3.8 \times 10^5$ yr.

To investigate the actual behavior of the collapse in our simplified model, we must first solve for ξ for a given t,

$$\xi + \frac{1}{2}\sin 2\xi = \chi t.$$

then find θ = r/r0.

$$\theta \equiv \cos^2 \xi,$$

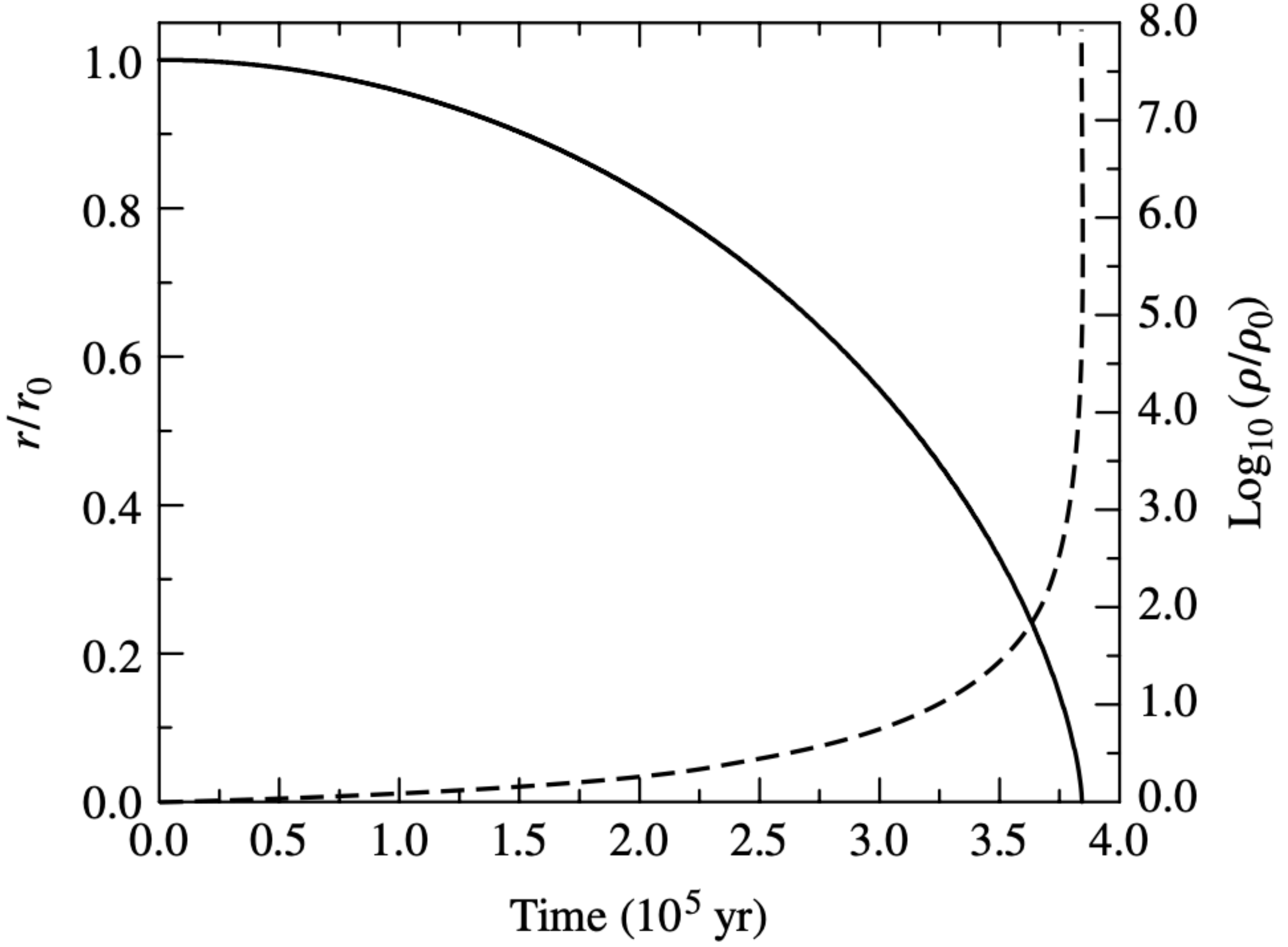
However, the equation for ξ cannot be solved explicitly, so numerical techniques must be employed.

Homologous Collapse

The numerical solution of the homologous collapse of the molecular cloud is shown in the figure.

Notice that the **collapse is quite slow initially and accelerates quickly as t_{ff} is approached**.

At the same time, the **density increases very rapidly during the final stages of collapse.**



r/r_0 is shown as the solid line and $log10(\rho/\rho_0)$ is shown as the dashed line.

The initial density of the cloud was $\rho_0 = 3 \times 10^{-17}$ kg m^{-3} and the free-fall time is 3.8×10^5 yr.

The Fragmentation of Collapsing Clouds

Since the masses of fairly large molecular clouds could exceed the Jeans limit, our **simple analysis seems to imply that stars can form with very large masses,** possibly up to the initial mass of the cloud.

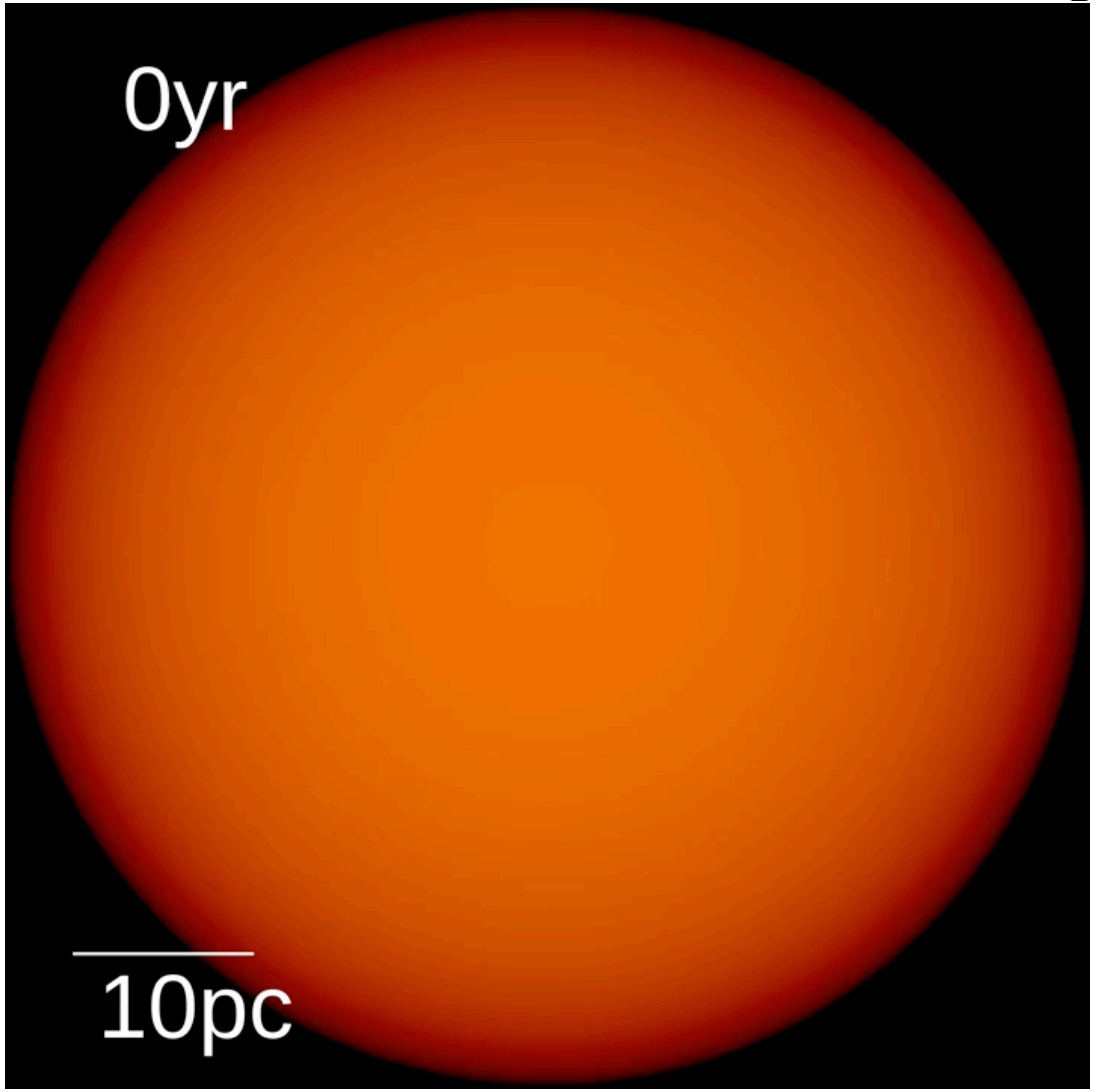
However, observations show that **this does not happen.** (Stars have masses between 0.1 to 100 $M_{\odot}$)

Furthermore, **stars preferentially form in groups,** ranging from binary star systems to clusters that contain hundreds of thousands of members.

The process of **fragmentation** that segments a collapsing cloud is an aspect of star formation that is under significant investigation. To see that fragmentation must occur by some mechanism(s), refer again to the equation for the Jeans mass. An important consequence of the collapse of a molecular cloud is that the density of the cloud increases by many orders of magnitude during free-fall. Consequently, since T remains nearly constant throughout much of the collapse, it appears that the **Jeans mass must decrease**.

After collapse has begun, any initial inhomogeneities in density will cause individual sections of the cloud to satisfy the Jeans mass limit independently and begin to collapse locally, producing smaller features within the original cloud. This cascading collapse could lead to the formation of large numbers of smaller objects.

The Fragmentation of Collapsing Clouds



https://www.youtube.com/watch?v=vU8vwaMTS7Y&ab_channel=MikeGrudi%C4%87

The Fragmentation of Collapsing Clouds

https://www.youtube.com/watch?v=PUyE3j0aoMw&ab_channel=ComputervisualistikKoblenz

The Fragmentation of Collapsing Clouds

It is important to point out that one challenge with the overly **simplified scenario** described here is that the process implies that far **too many stars would be produced.** It is likely that **only about 1% of the cloud actually forms stars.**

What is it that stops the fragmentation process?

The Fragmentation of Collapsing Clouds

It is important to point out that one challenge with the overly **simplified scenario** described here is that the process implies that far t**oo many stars would be produced.** It is likely that **only about 1% of the cloud actually forms stars.**

What is it that stops the fragmentation process?

Since we observe a galaxy filled with stars that have masses on the order of the mass of the Sun, the cascading fragmentation of the cloud cannot proceed without interruption. The **answer** to the question lies in our implicit **assumption that the collapse is isothermal,** which in turn implies that the only term that changes is the density. Clearly this cannot be the case.

- If the **energy that is released during a gravitational collapse is radiated** away efficiently, the temperature can remain nearly constant.
- At the other extreme, if the energy **cannot be transported out of the cloud** at all (an *adiabatic* collapse), then the temperature must rise.
- Of course, the real situation must be somewhere between these two limits, but by considering each of these special cases carefully, we can begin to understand some of the important features of the problem.

The Fragmentation of Collapsing Clouds

If the collapse changes from being essentially isothermal to adiabatic, the associated **temperature rise would begin to affect the value of the Jeans mass**.

For an adiabatic process the pressure of the gas is related to its density by γ , the ratio of specific heats. Using the **ideal gas law**, an adiabatic relation between density and temperature can be obtained,

$$T = K''\rho^{\gamma-1},$$

where K'' is a constant.

Substituting this expression, we find that for an adiabatic collapse, the **dependence of the Jeans mass on density becomes**

$$M_J \propto \rho^{(3\gamma-4)/2}.$$

For atomic hydrogen $\gamma = 5/3$, giving $M_J \propto \rho^{1/2}$; the **Jeans mass *increases* with increasing density** for a perfectly adiabatic collapse of a cloud. This behavior means that **the collapse results in a minimum value for the mass of the fragments produced.** The minimum mass depends on the point when the collapse goes from being predominantly isothermal to adiabatic.

The Fragmentation of Collapsing Clouds

Of course, this transition is not instantaneous or even complete.

However, it is possible to make an **order-of-magnitude estimate** of the lower mass limit of the fragments. According to the virial theorem, energy must be liberated during the collapse of the cloud.

The energy released is roughly

$$\Delta E_g \simeq \frac{3}{10} \frac{G M_J^2}{R_J}$$

for a spherical cloud just satisfying the Jeans criterion at some point during the collapse.

Averaged over the free-fall time, the luminosity due to gravity is given by

$$L_{\rm ff} \simeq \frac{\Delta E_g}{t_{\rm ff}} \sim G^{3/2} \left(\frac{M_J}{R_J}\right)^{5/2}$$

where we have made use of t_{ff} and have neglected terms of order unity.

The Fragmentation of Collapsing Clouds

If the cloud were **optically thick** and in thermodynamic equilibrium, the energy would be emitted as **blackbody radiation**. However, during collapse the **process of releasing the energy is less efficient** than for an ideal blackbody. We may express the radiated luminosity as

$$L_{\mathrm{rad}} = 4\pi R^2 e \sigma T^4,$$

where an efficiency factor, $0 < e < 1$, has been introduced to indicate the deviation from thermodynamic equilibrium.

- If the collapse is perfectly **isothermal** and escaping radiation does not interact at all with overlying infalling material, $e \sim 0$.
- If, on the other hand, **energy emitted** by some parts of the cloud **is absorbed and then re-emitted** by other parts of the cloud, thermodynamic equilibrium would more nearly apply and $e \sim 1$.

The Fragmentation of Collapsing Clouds

Equating the two expressions for the cloud’s luminosity,

$$L_{\mathrm{ff}} = L_{\mathrm{rad}},$$

Rearanging:

$$M_J^{5/2} = \frac{4\pi}{G^{3/2}} R_J^{9/2} e\sigma T^4.$$

Eliminate the radius, and then writing the density in terms of the Jeans mass, we arrive at an estimate of **when adiabatic effects become important**, expressed in terms of the **minimum obtainable Jeans mass:**

$$M_{J_{\mathrm{min}}} = 0.03 \left(\frac{T^{1/4}}{e^{1/2} \mu^{9/4}} \right) \mathrm{M}_\odot,$$

where T is expressed in kelvins.

$$\boxed{M_J \simeq \left(\frac{5kT}{G\mu m_H} \right)^{3/2} \left(\frac{3}{4\pi \rho_0} \right)^{1/2}}$$

The Fragmentation of Collapsing Clouds

Example:

- If we take $\mu \sim 1$, $e \sim 0.1$, and $T \sim 1000$K at the time when adiabatic effects may start to become significant, $M_J \sim 0.5\ M_\odot$; **fragmentation ceases when the segments of the original cloud begin to reach the range of solar mass objects.**
- The estimate is relatively insensitive to other reasonable choices for T , e, and μ.
- For example, if $e \sim 1$ then $M_J \sim 0.2\ M_\odot$.

Additional Physical Processes in Protostellar Star Formation

We have, of course, **left out a number of important features** in our calculations.

The estimate of the Jeans criterion was based on a perturbation of a static cloud;

- no consideration was made of the initial velocity of the cloud's outer layers
- we have also neglected the details of radiation transport through the cloud,
- as well as vaporization of the dust grains,
- dissociation of molecules,
- and ionization of the atoms.

Nevertheless, it is worth noting that as unsophisticated as the preceding analysis was, it did illustrate important aspects of the fundamental problem and left us with a result that is reasonable.

Such preliminary approaches to understanding complex physical systems are powerful tools in our study of nature.

More sophisticated estimates of the complex process of **cessation of fragmentation** place the limit an order of magnitude lower than determined above, at **about 0.01 $M_\odot$.**

Additional Physical Processes in Protostellar Star Formation

Perhaps just as important to the problem of the collapse process are the possible effects of:

- rotation (angular momentum),
- the deviation from spherical symmetry,
- turbulent motions in the gas,
- and the presence of magnetic fields.

That mechanisms other than gravity must be involved becomes clear in simply **considering the free-fall time of the dense core.** From the calculation, the collapse of the dense core should occur on a timescale on the order of 10^5 yr. This is **quite short** on stellar evolution timescales. This would imply that almost as soon as a dense core forms, it begins producing stars. This would also imply that **dense cores should be very rare**; however, many dense cores are observable throughout our Galaxy.

For example, an appreciable amount of **angular momentum present in the original cloud** is likely to **result in a disk-like structure** for at least a part of the original material, since collapse will proceed at a more rapid rate along the axis of rotation relative to collapse along the equator.

Additional Physical Processes in Protostellar Star Formation

It is also apparent from careful investigations of molecular clouds that **magnetic fields** must also play a crucial role and, in fact, are likely to control the onset of collapse.

Zeeman measurements of various molecular clouds indicate the **presence of magnetic fields** with strengths typically on the order of magnitude of 1 to 100 nT.

If the magnetic field of a cloud is "frozen in," and the cloud is compressed, the magnetic field strength will increase, leading to an increase in the **magnetic pressure** and **resistance to the compression**.

In fact, if the cloud is stable to collapse because of magnetic pressure, it will remain so as long as the magnetic field does not decay.

During the derivation of the Jeans criterion, the virial theorem was invoked using a balance between gravitational potential energy and the cloud's internal (thermal) kinetic energy. Absent from that calculation was the inclusion of **energy due to the presence of magnetic fields.**

When **magnetic fields are included, the critical mass** can be expressed as

$$M_B = c_B \frac{\pi R^2 B}{G^{1/2}},$$

where $c_B = 380\ \mathrm{N}^{1/2}\ \mathrm{m}^{-1}\ \mathrm{T}^{-1}$ for a magnetic field permeating a spherical, uniform cloud.

Additional Physical Processes in Protostellar Star Formation

If B is expressed in nT and R in units of pc, then the equation can be written in the more illustrative form

$$M_B \simeq 70\ \mathrm{M}_\odot \left(\frac{B}{1\ \mathrm{nT}}\right)\left(\frac{R}{1\ \mathrm{pc}}\right)^2 .$$

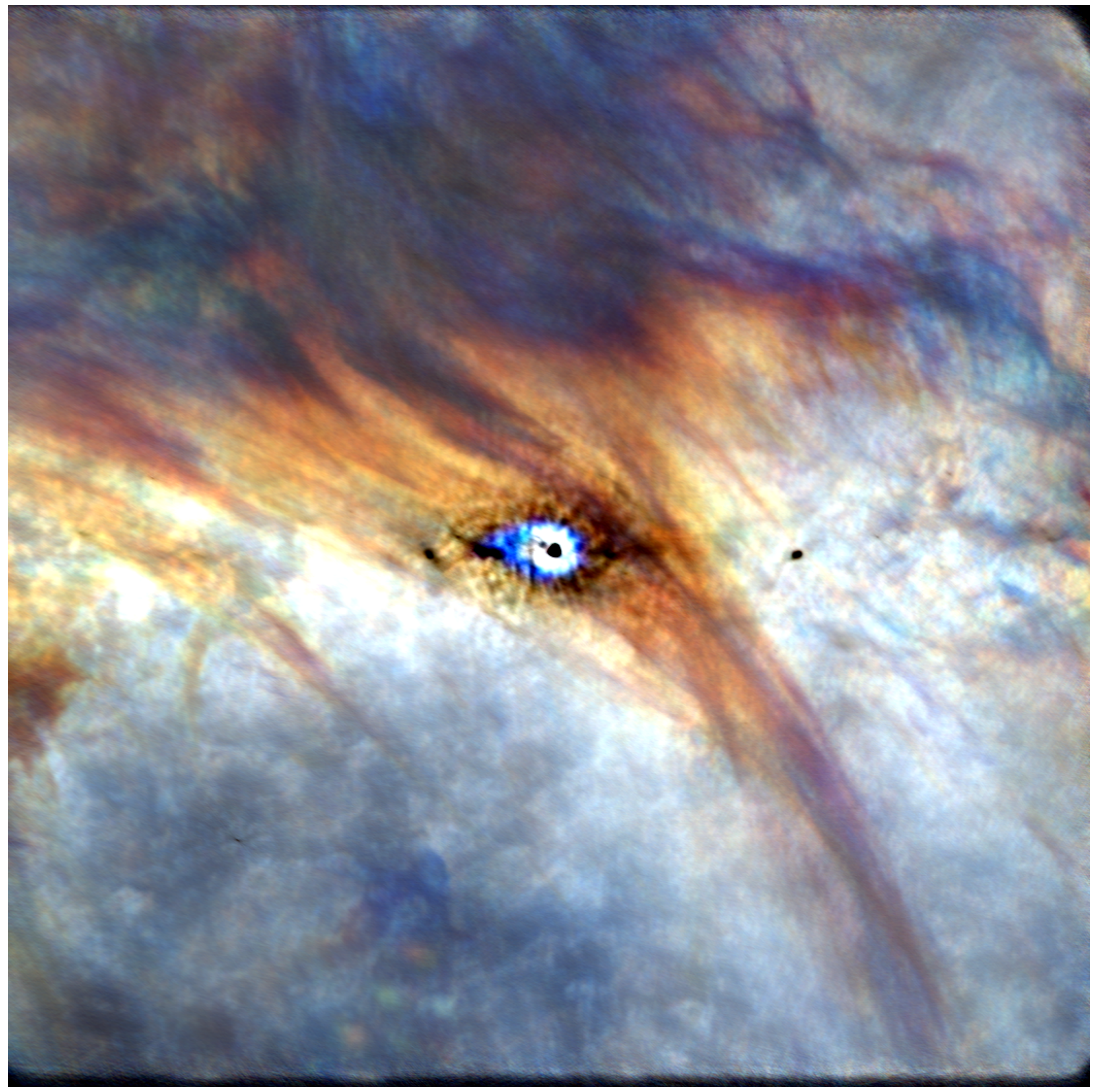
- If the mass of the cloud is less than M_B, the cloud is said to be **magnetically subcritical** and stable against collapse, but
- if the mass of the cloud exceeds M_B, the cloud is **magnetically supercritical** and the force due to gravity will overwhelm the ability of the magnetic field to resist collapse.

Additional Physical Processes in Protostellar Star Formation

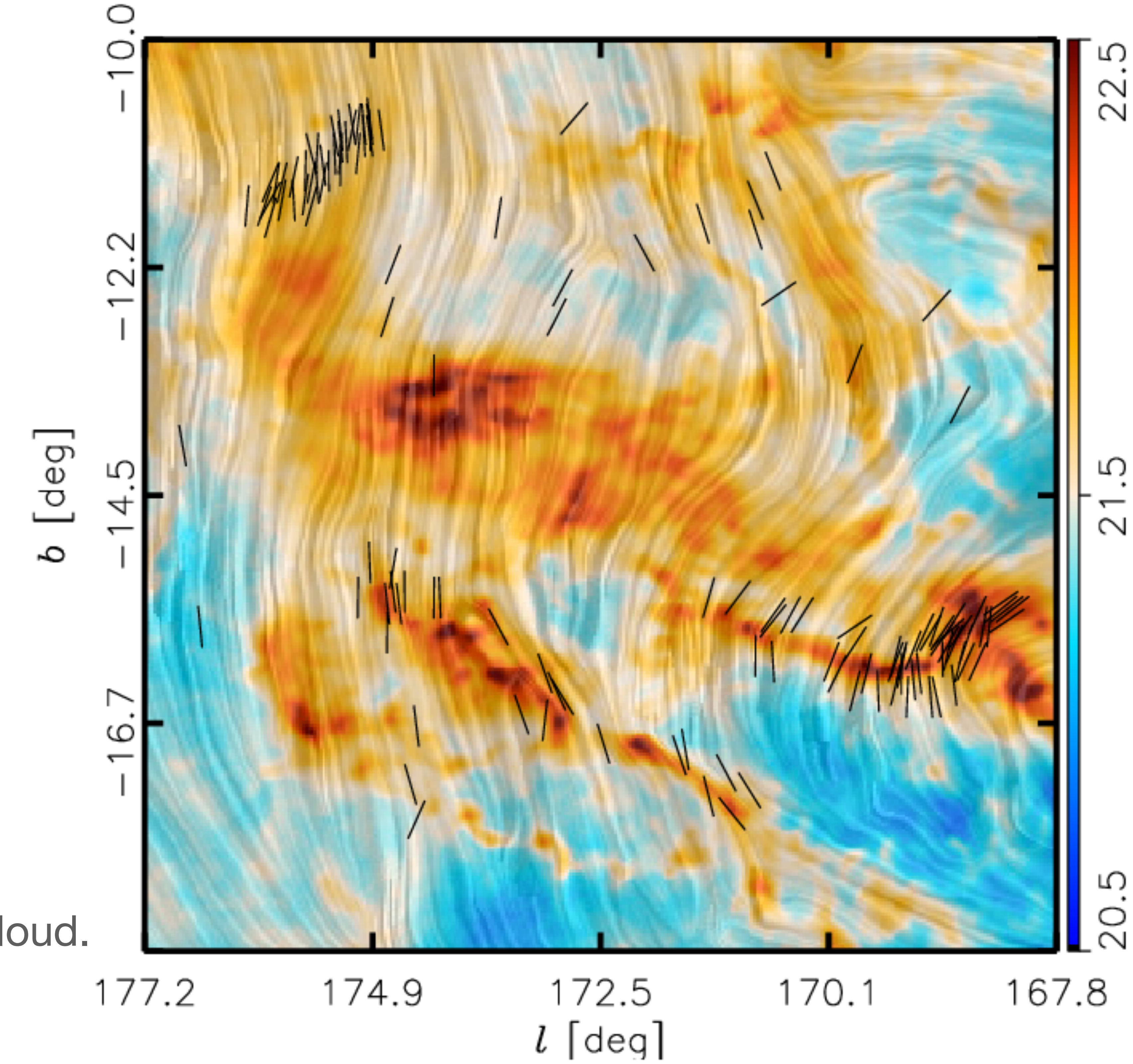
Example:

For the dense core considered in the previous Examples, if the dense core has a magnetic field of **100 nT** threading through it, and if it has a radius of 0.1 pc, the magnetic critical mass would be $M_B \simeq 70\ M_\odot$, implying that a dense core of mass 10 $M_\odot$ would be stable against collapse.

However, if **B = 1 nT**, then $M_B \simeq 0.7\ M_\odot$ and collapse would occur.



The Riegel-Crutcher HI self absorption cloud
The filamentary structure is due to the presence of magnetic fields.



Magnetic fields in the Taurus molecular cloud.
Soler et al. 2016

Ambipolar diffusion

The last example hints at another possibility for triggering the collapse of a dense core. If a core that was originally subcritical were to become supercritical, collapse could ensue.

This could happen in one of two ways:

- a group of subcritical clouds could combine to form a supercritical cloud,
- or the magnetic field could be rearranged so that the field strength is lessened in a portion of the cloud.

It appears that both processes may occur, although the latter process seems to dominate the pre-collapse evolution of most molecular clouds.

Only charged particles such as electrons or ions are tied to magnetic field lines; neutrals are not affected directly. **Given that dense molecular cores are dominated by neutrals, how can magnetic fields have any substantial effect on the collapse?**

Ambipolar diffusion

Given that dense molecular cores are dominated by neutrals, how can magnetic fields have any substantial effect on the collapse?

The answer lies in the collisions between neutrals and the ions (electrons do not significantly affect neutral atoms or molecules through collisions). As neutrals try to drift across magnetic field lines, they collide with the **"frozen-in" ions, and the motions of the neutrals are inhibited.**

However, if there is **a net defined direction for the motion of neutrals due to gravitational forces,** they will still tend to **migrate slowly in that direction.** This slow migration process is known as **ambipolar diffusion**.

To determine the relative impact of ambipolar diffusion, we need to estimate a character- istic timescale for the diffusion process. This is done by comparing the size of the molecular cloud to the time it takes for a neutral to drift across the cloud. It can be shown that the timescale for ambipolar diffusion is approximately

$$t_{\mathrm{AD}} \simeq \frac{2R}{v_{\mathrm{drift}}} \simeq 10\ \mathrm{Gyr}\left(\frac{n_{\mathrm{H}_2}}{10^{10}\ \mathrm{m}^{-3}}\right)\left(\frac{B}{1\ \mathrm{nT}}\right)^{-2}\left(\frac{R}{1\ \mathrm{pc}}\right)^{2}.$$

Once collapse begins, magnetic fields can be further altered by undergoing reconnection events.

Ambipolar diffusion

Example:

Returning to the dense core we used in previous examples, if B = 1 nT and R = 0.1 pc, we find that the timescale for ambipolar diffusion is 100 Myr.

This is several hundred times longer than the free-fall timescale determined in the previous example. Clearly the **ambipolar diffusion process can control the evolution of a dense core for a long time before free-fall collapse begins.**