EXPLAINING KEPLER PLANETS; ALTERNATIVE PLANET FORMATION SCENARIOS

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ABSTRACT

The Kepler team has produced data for 15 confirmed and about 1200 candidate exoplanets (Borucki et al. 2011). Transit surveys like Kepler are constrained by selection effects to finding mainly planets with properties orthogonal to the properties of the planets in our solar system which were formed in the protostellar disk. Our planets are nearly in the ecliptic plane, in prograde orbits with low eccentricity, with orbits uniformly increasing in radius, with small rocky planets within 4 AU and gas giants further out. Exoplanets can have small periastrons, can be prograde or retrograde, can be in or out of the ecliptic, can have multiple planets within a small fraction of an AU of the star, and those close-in planets can be rocky or gas giants.

The explanation for all of these characteristics is that exoplanets with small periastrons were not formed in the protostellar disk but that their planetary cores were ejected from the protostar during the last FU Orionis event that the protostar experienced. Ejected stellar material was trapped and compressed by collapsing magnetic fields to form self-gravitating cores that subsequently accreted gas and dust to grow into exoplanets. These tightly packed planets interact and can produce resonant orbits, or they can knock each other into eccentric, or out-of-ecliptic, or retrograde orbits.

I discuss catastrophic FU Orionis events, catastrophic magnetically-driven planet formation, catastrophic radiatively-driven planet formation, and slow uniformitarian classical planet formation.

FU Orionis events:

I have worked out a process in which infall during an FU Ori event causes protostellar material to flow outward at low latitudes. Excess infall blocks convective downflow but not convective upflow. Stellar material inside the dipole torus that connects the star to the disk flows outward while reducing its rotation velocity to make an oblate envelope that extends to 10 or 15 stellar radii and has the spectrum of a supergiant. When the infall drops back to normal levels, the oblate envelope is slowly evaporated by strong UV and X radiation from the protostar. Some matter flows or blows into the inner wall of the disk.

Magnetically-driven planet formation:

If the dipole field pulls out of the disk during an FU Ori event, the field wraps and tangles around the extended envelope. Reconnections compress the trapped plasma into an unstable magnetic torus orbiting the star (a tokamak). The torus reconnects into self-gravitating magnetic spheroids (spheromaks) that become planetary cores. The reconnection radiation and winds heat and compress the disk causing agglomeration out to the snow line. The cores grow by collecting material infalling toward the star. They are in unstable orbits that can change radically or they can be ejected from the system. A core in a highly eccentric orbit that goes far into the disk can become very massive because it sweeps up material over a wide range of radii.

Radiatively-driven planet formation:

If the dipole field pulls out of the disk when the protostar is not in an FU Ori phase, the field wraps and tangles but there is no large reservoir of plasma to compress. The reconnections fill 75% of the surface of the star. The reconnection radiation and winds heat and compress the disk causing agglomeration out to the snow line. The agglomerated material rapidly forms planetesimals and inner planets.

Classical planet formation:

Outer disks form planets by slow uniformitarian processes.

[This is the writeup of a lunch talk.]

STAR AND PLANET FORMATION FACTOIDS

Lynne Hillenbrand commented at "Stromfest 2008", Steve and Karen Strom's 65th birthday party, that as a child she saw a cartoon of planet formation in a disk and since then she has been trying to make it come true.

Steve Strom reviewed the whole picture of planet formation in a lunch talk April 19, 2010. Sean Andrews reviewed the whole picture of planet formation in his colloquium May 20, 2010. Both emphasized forming planets in the disk and minimized the role of the dipole field except as a conveyor belt to slowly channel infall to the protostar. Figure 1 is my version of Lee Hartmann's (2000) standard cartoon of a T Tauri star that shows the dipole field channeling inflow to hot spots at high latitudes.

A protostar experiences 10 to 15 prepartum FU Orionis events in which infall increases and overwhelms the disk flow pattern. The system brightens by 4 to 7 magnitudes in 1 to 10 years and has the spectrum of a supergiant. It decays over many decades, perhaps centuries.

Define the birth of a late-type star as the pullout of the dipole field from the disk. The protostar and the disk decouple. What happens to the dipole field?

The birthrate for FGK stars in our galaxy is between 1/decade and 1/century. It is a once in a lifetime experience. It has, probably, never been observed. The formation of a star with giant planets orbiting close to the star happens, perhaps, 1/millennium.

UNIFORMITARIANISM AND CATASTROPHISM

Current theories of planet formation and planet migration are uniformitarian. Humans have been making sophisticated observations for less than a lifetime. They generalize observed "calm" periods into the past and into the future.

Nature does not believe in slow evolution. Catastrophes are built into slowly evolving systems or come from outside. Long boring intervals are always punctuated by exciting catastrophes. For example, we do not understand the magnetic field in the sun. At any time there can be a flare 100 times stronger than has ever been observed (in 1859) that will wipe out all our electronics and power. That will be exciting.

CONVECTION

Late-type stars transport energy produced by contraction and fusion from the interior to the surface by convection. The energy brought to the surface is radiated into empty space by the atmosphere.

Figures 2 and 3 show the process schematically, first when there is only slight plume convection, and second when there is strong cellular convection. A blob of gas in the interior is heated and becomes buoyant relative to its surrondings. It rises. Since the density of the star decreases outward, the blob expands as it rises. If we assume that the star is not losing mass, the upward velocity eventually goes to zero and any remnant velocity is transverse. In plume convection the blob ends up as a warm spot on the surface that radiates outward and diffuses into its surroundings. There is no downward flow except for slow settling to balance the mass flow.

As convection grows stronger, many plumes form; they interact to produce cellular convection. Fig. 3 shows two plumes rising, expanding, flaring outward, and colliding near the surface. The colliding gas is denser than its surroundings so that it radiates rapidly and cools to a lower temperature than its surroundings. Since the dense, cool gas has negative buoyancy it falls inward in a narrow plume. The rising plumes are surrounded by falling plumes. The gas completes a full cycle and is reheated. The many rising and falling plumes jostle each other so that they do not follow straight paths in reality. The plumes locally determine their buoyancy relative to their surroundings and twist and turn their way up or down. There are always transverse velocity components. In addition magnetic fields constrain the gas motions while, also, the gas motions move and abrade the magnetic structures.

In the sun the round trip travel time for gas is about two days for a depth of 30000 km. The velocities are on the order of 1 km/s. For a depth of 100000 km (14% of Rsun or 0.004 of Msun) the turnover time is more than a week.

Assuming that there is no mass loss, the mass flux in the warm, upward flowing plumes must equal the mass flux in the cool, downward flowing plumes.

Since the area of the downward flowing material is less than that of the upward flowing material, downward flowing material must move faster to maintain a constant zero mass flux.

The upward flowing material carries angular momentum upward and tries to force the stellar envelope to rotate more slowly. The downward flowing material tries to spin up the envelope. The changes in angular momentum and rotation cancel. This is a really big heat engine that depends on radiative cooling at the surface to stay in balance.

If there is no radiative cooling at the surface, the gas cannot densify and cool. There is no downward flow. But there is an upward flow. It takes days before the deep layers find out that cellular convection has stopped. Material continues to flow upward and expands the envelope. The envelope must rotate more slowly and decouple from the core of the star to conserve angular momentum. The star must expand. The effective gravity is lowest at the equator so the star becomes oblate.

FU ORIONIS EVENTS

Start with the standard protostar assembly machinery in Fig. 1 that assumes isolated evolution. Note that figures are not drawn to scale. In the late T Tauri phase the distance from the protostar to the inner wall of the disk is about 20 stellar radii according to Lee Hartmann's book on star formation.

But stars are formed in clusters. If there is a collision with a dense cloud, or with a star, or if an OB star forms nearby, or if there is a supernova, there can be a pulse of enhanced density, Fig. 4. The complex machinery is overwhelmed by the excess infall. The disk becomes turbulent, is heated, and puffs up (Hartmann and Kenyon 1996).

The dipole field cannot control the infall to the star. Infall bombards the star and spreads over the surface. It is heated by UV and X-radiation and it collides with magnetic structures as it falls. It is heated enough to populate the upper levels of hydrogen and become optically thick in the visible and near IR.

The infall is a warm blanket over the surface that prevents rising convective streams from radiating out of the star and cooling, Fig. 5. Downward convective flows stop but upward flows continue. The star puffs up, Fig. 6 and 7. Envelope and atmosphere material flows outward. Some infall is dragged along. At the equator the effective gravity is low because of high protostar rotation velocity. The star puffs outward into the the dipole torus. The outward flowing envelope rotates more slowly than the star to conserve angular momentum. The inner cylinder of the protostar continues to rotate rapidly and remains a dwarf while the envelope decouples into a slower rotating low-density oblate structure. Depending on stochastic infall events over 1 to 10 years it expands to 15 to 20 stellar radii and shows a G0 supergiant spectrum (Herbig, Petrov, and Duemmler 2003). The luminosity increases 5 to 7 magitudes, up to a factor of 300, which is just the increase in surface area.

The infall returns to normal. The extended envelope is evaporated by the strong UV and X radiation produced at high latitudes by normal infall. Some of the envelope flows or blows toward the inner wall of the disk. After decades or centuries everything returns to uniformitarian normalcy as if nothing had happened.

These FU Orionis events are stochastic and can happen a dozen times to the protostar.

MAGNETICALLY-DRIVEN PLANET FORMATION

During an FU Orionis event the magnetic coupling between the protostar and the disk is stressed. If the coupling becomes unstable, the field lines wrap and pull out of the disk.

This is a random event influenced by the amount of infall. If it does not happen during one of the FU Ori events, the star eventually produces normal planets in the disk.

Figure 8 shows the dipole field lines wrapping. In Fig. 9 the field lines pull out of the disk and wrap closely around and compress the slowly rotating envelope of the star The structure is unstable. When a thin spot forms from oscillations or external stress from a flare or mass ejection, the field lines can reconnect, Fig. 10. The reconnection can drive part of the field and its trapped plasma back toward the star to make a "super reconnection event" (SRE). Simultaneously the reconnection drives the remaining field and trapped plasma outward to form a toroidal ring (a tokamak), Fig. 11. The density in the ring increases until the plasma can support the compresssion by the magnetic field, Fig. 12 and 13.

The ring is unstable and reconnects in sections, Fig. 14-17. In practice, the chance of forming a complete ring is small. Radial and tangential compression occur simultaneously so that Fig. 11 ends up as Fig. 14. Hot, dense plasma blobs are encapsulated in spherical magnetic bottles (spheromaks). Ions cannot escape but radiation can. The magnetic bottles shield the plasma from ablation by the stellar wind and evaporation by radiation.

The ring and SRE are very luminous in X rays and UV and the SRE produces tremendous particle outbursts. The SRE illuminates both sides of the disk as well as the inner wall. Radiation and wind blow away infall above and below the disk, Fig. 18 and 19. The radiation and wind push inward on both surfaces of the disk, vaporize the surfaces, heat the dust, drive it inward, and agglomerate it in a thinner warm disk.

The spheromaks are large enough and dense enough to be gravitationally bound. They are planetary cores when they cool. The cores grow by accreting material falling toward the protostar. The number of cores is random.

Some of the cores are ejected from the system, or evaporate, or fall into the star, or merge. Some of the cores are knocked into eccentric ecliptic orbits, or into retrograde orbits, or into out-of-ecliptic orbits. Some of the cores continue in low eccentricity orbits near the star, perhaps with resonances. The number that survive is random.

These planets grow by intercepting infall headed toward the star: gas, dust, planetesimals, comets. Their sizes are random. They can remain small. In eccentric orbits they can collect large quantities as they pass through the disk, Fig. 20. Some can grow as large as brown dwarfs.

Magnetically-driven planet formation can account for all the confirmed Kepler planets, all 80 or so transiting planets found in other surveys, most of the planets that will eventually be found in Kepler's candidate list of 1200, and all the planets with small periastrons found in radial velocity searches.

RADIATIVELY-DRIVEN PLANET FORMATION

What happens if the dipole field pulls out of the disk when the torus is "empty", instead of during an FU Ori event?

The inner wall and both surfaces of the disk, which flares outward, are continually illuminated by the stochastically varying UV and X radiation field from star, especially from the high latitude hot points where matter falls onto the star after flowing along the field lines. Radiation pressure pushes disk material outward and forms a wall of dense, warm gas and dust that absorbs 10% of the radiation from the star. As the inner wall is pushed outward the magnetic field is stretched outward because it is pinned to the disk, Fig. 21. As the coupling weakens the field lines wrap, Fig. 22 and 23. The dipole field pulls out of the disk, tangles, and starts reconnecting. The field forms a super reconnection event (SRE) that fills the surface of the star from +70 to -70 degrees latitude, Fig. 24.

The SRE illuminates both sides of the disk as well as the inner wall. Radiation and wind blow away infall above and below the disk, vaporize the surfaces of the disk, heat the dust, drive it inward, and agglomerate it in a thinner warm disk, Fig. 25. I call the agglomerated dust popcorn.

Disk material is radioactive, self-heating; magnetic, Fe$\sim$Si; carbonaceous. It is damaged by radioactivity, radiation, and particles so that it is full of free radicals, broken molecules, positive and negative charges; it is carcinogenic; it is generally sticky. It is hot or warm near the star and icy far from the star.

Popcorn is low density, tacky, crushable, insulating, radioactively self-heating, warmed and annealed by the star, Fig. 26. It is not like particles in many body calculations. In low velocity collisions popcorn sticks; in moderate velocity collisions it sticks and crushes. In collisions with small dense fast particles, popcorn slows the particles and traps them.

Popcorn is self-agglomerating and will slowly form popcorn balls and then planetesimals on its own. But radiation and wind from the star heat popcorn and push it outward, and thus form planets sequentially outward. Orbits moving outward cross stationary orbits and orbits moving inward at a shallow angle so collisions are slow. A wall of agglomerated popcorn forms that absorbs 3-5% or the radiation from the star. Near the star volatiles are cooked out.

In the wall popcorn and popcorn balls agglomerate and consolidate into planetesimals. The wall become optically thin. Radiation from the star can then reach material farther out that had been in the wall's shadow. A new wall forms and the process repeats, Fig. 27 and 28. The dispersion of the dots in the cartoons is greatly exaggerated. Planetesimals formed in the wall are in nearby orbits. They rapidly merge and form a planet, Fig. 29 and 30.

As bodies grow large, heat from radioactivity is trapped in the center and differentiation begins. A self-gravitating planetestimal crushes under its own weight. Denser material moves toward the center. Differentiation increases; melting begins. Differentiation is maintained when bodies merge, Fig. 31.

There is not enough mass in the "asteroid" wall to form a planet. It remains planetesimals.

Next comes the snow belt. Ice is added to the popcorn and dust in "Jupiter"'s wall. A massive core forms that is able to pull in gas infalling to the disk and grow into a large planet. Repeat for "Saturn", Fig. 32.

The disk has a large central hole in which planets have already formed. Usually, the hole can only be inferred from the lack of IR radiation in the energy distribution that would be produced by warm dust near the star.

CLASSICAL PLANET FORMATION

If there is no super reconnection event, the inner planets form in slow, uniformitarian fashion by accretion. They form concurrently over a long time.

Uniformitarianism is the only scenario that works for forming the outer planets. Since radiation from the star is so weak at those distances, the planets accrete slowly over hundreds of millions of years.

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Hartmann, L. 2000. Accretion Processes in Star Formation. (Cambridge: Cambridge University Press) 237pp.

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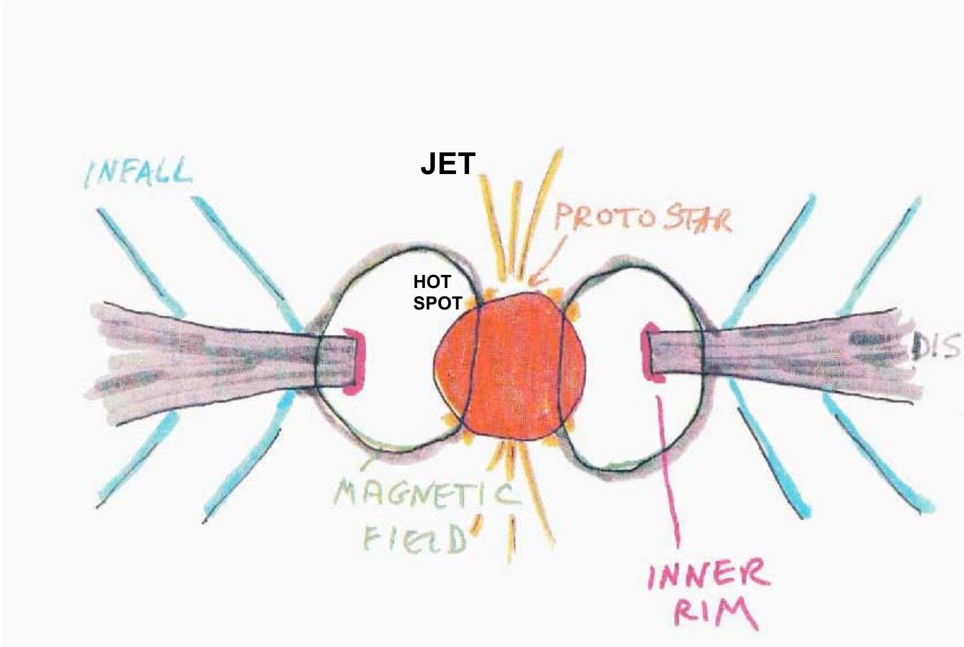
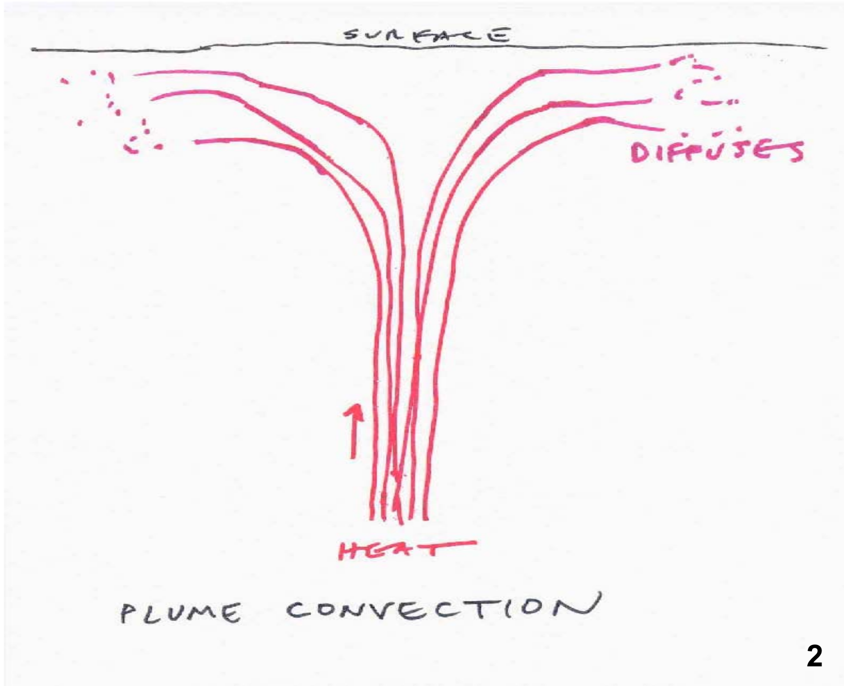
Herbig, G.H., Petrov, P.P., and Duemmler, R. 2003. ApJ. 591, 384-401.

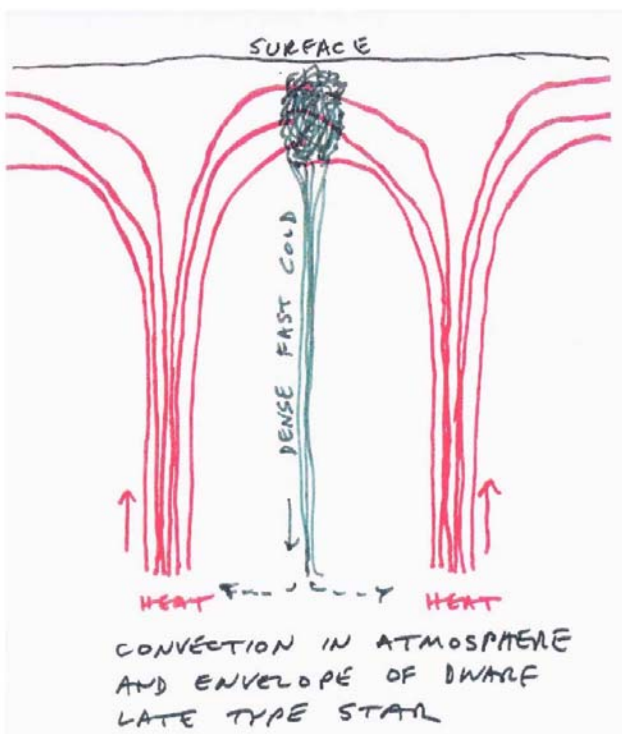


INFALL
JET
PROTO STAR
HOT SPOT
DISK
MAGNETIC FIELD
INNER RIM

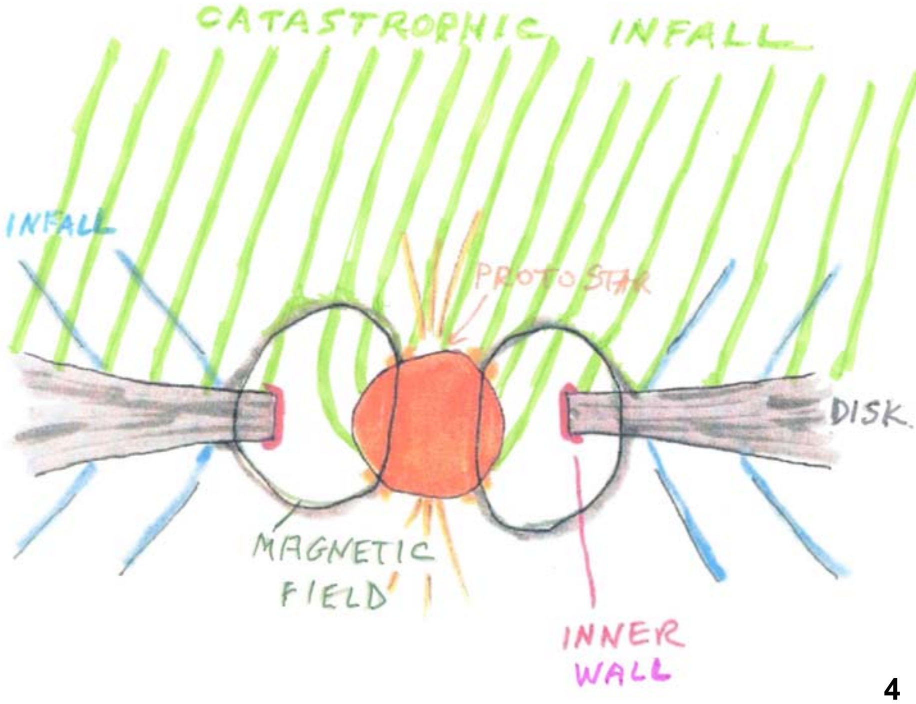
1


SURFACE
DIFFUSES
HEAT
PLUME CONVECTION

2


SURFACE
DENSE FAST COLD
HEAT
HEAT
CONVECTION IN ATMOSPHERE
AND ENVELOPE OF DWARF
LATE TYPE STAR

3



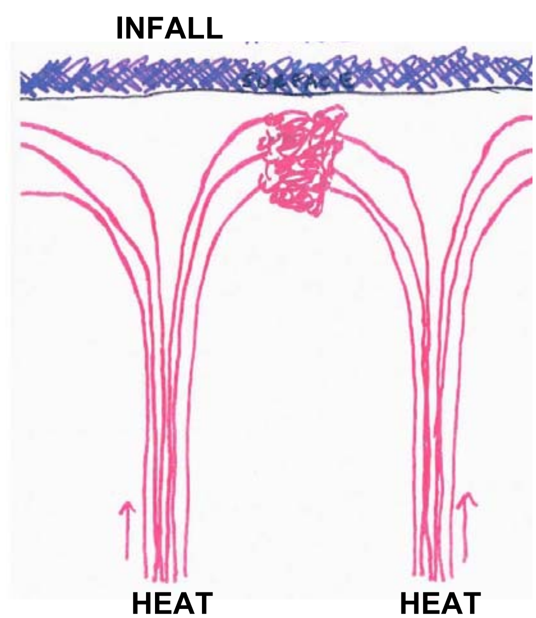
4

EXCESS INFALL
BLOCKS CONVECTION.

RISING HOT MATERIAL
CANNOT RADIATE AT THE
SURFACE TO COOL.

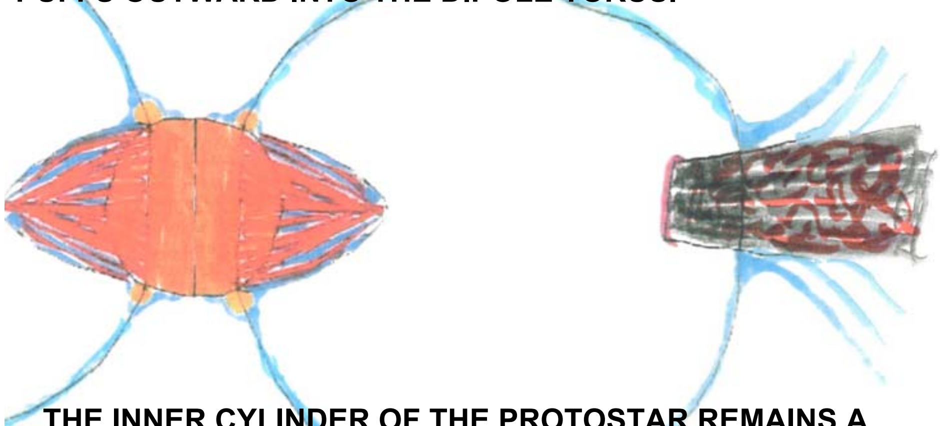
THERE IS NO FALLING
COOL MATERIAL.

THE STAR PUFFS UP.



5

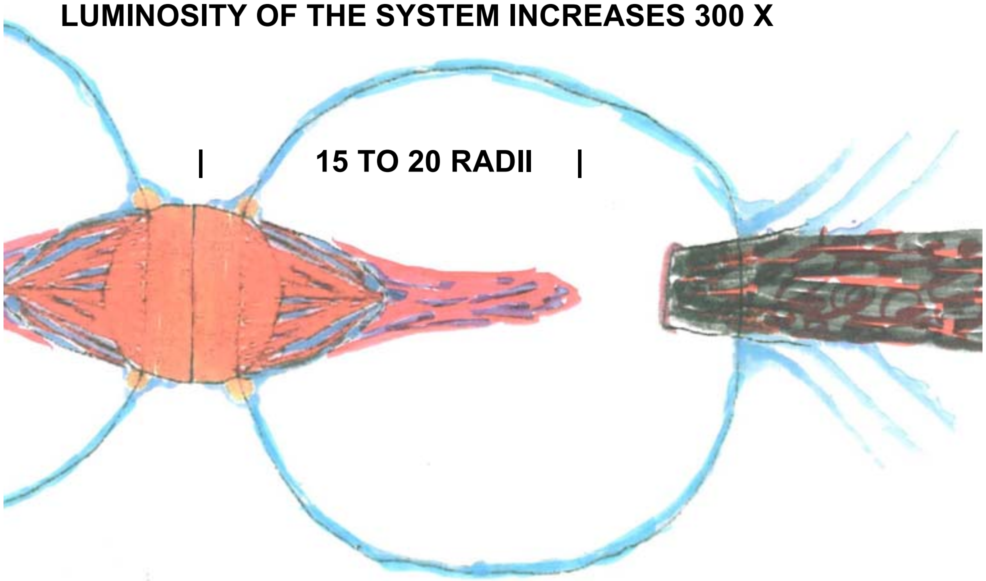
ENVELOPE AND ATMOSPHERE MATERIAL FLOW OUTWARD. SOME INFALL IS DRAGGED ALONG. AT EQUATOR EFFECTIVE GRAVITY IS LOW BECAUSE OF HIGH ROTATION. THE STAR PUFFS OUTWARD INTO THE DIPOLE TORUS.



THE INNER CYLINDER OF THE PROTOSTAR REMAINS A DWARF WHILE THE OUTER PART EXPANDS AND SHOWS A G0 SUPERGIANT SPECTRUM (HERBIG, PETROV, AND DUEMMLER 2003).

6

LUMINOSITY OF THE SYSTEM INCREASES 300 X



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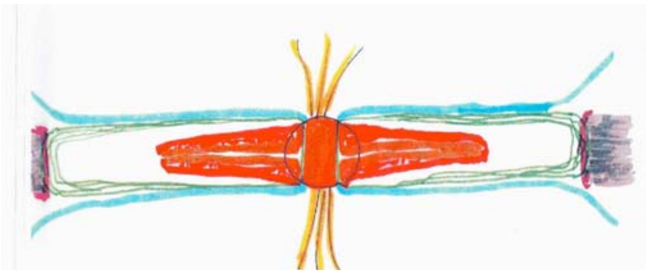

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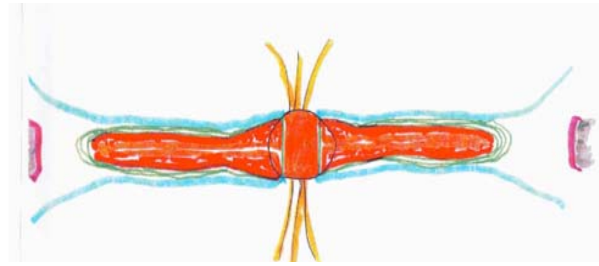
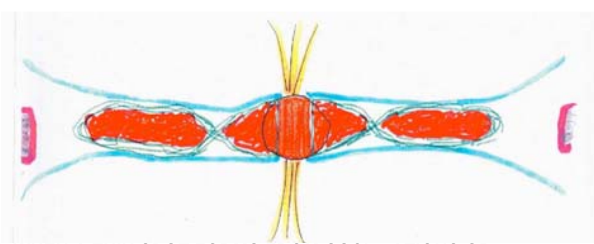


THE FIELD LINES PULL OUT OF THE DISK AND FORM AN UNSTABLE TORUS FILLED WITH DENSE GAS.

9

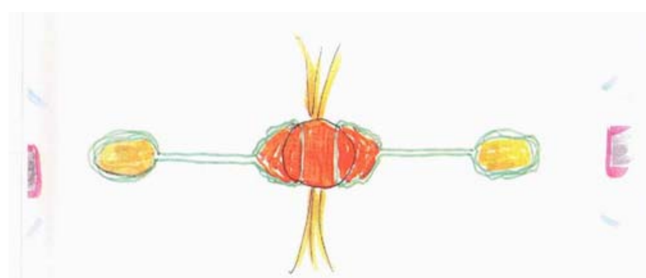


WHEN A THIN SPOT FORMS FROM OSCILLATIONS OR WHATEVER, THE MAGNETIC FIELD LINES CAN RECONNECT.

PART OF THE FIELD FALLS BACK TOWARD THE STAR TO MAKE A SUPER-CME.

PART FORMS A TOROIDAL RING, A TOKAMAK.

10



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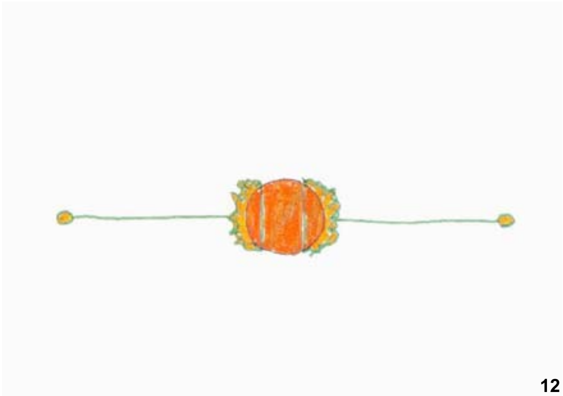

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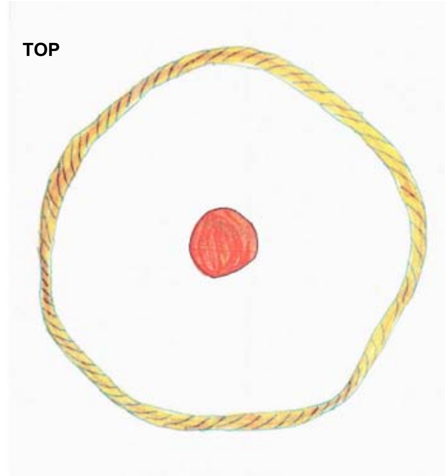

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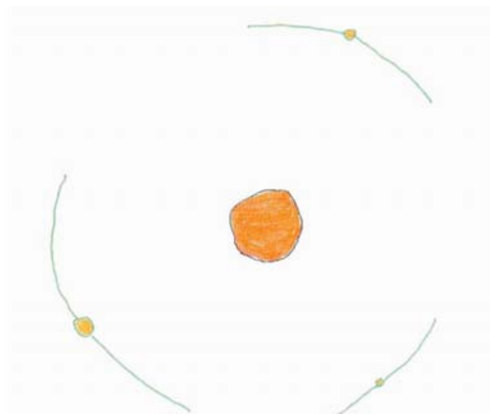

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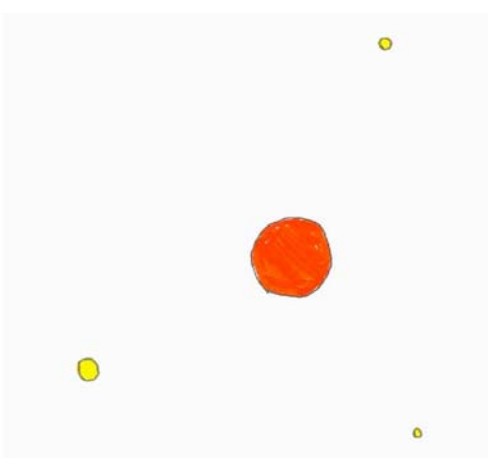

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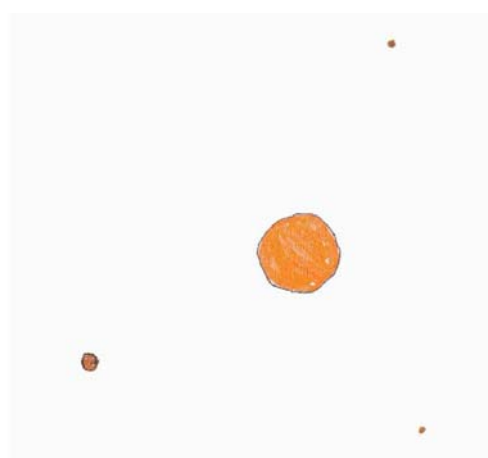

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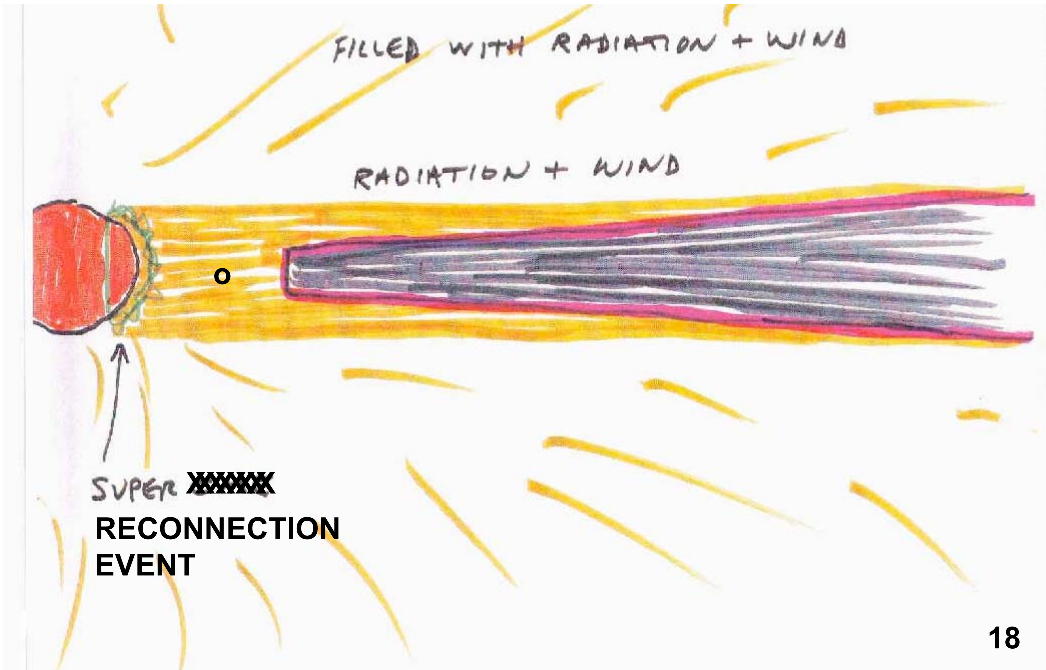
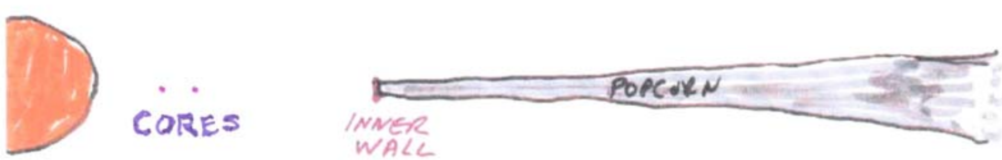
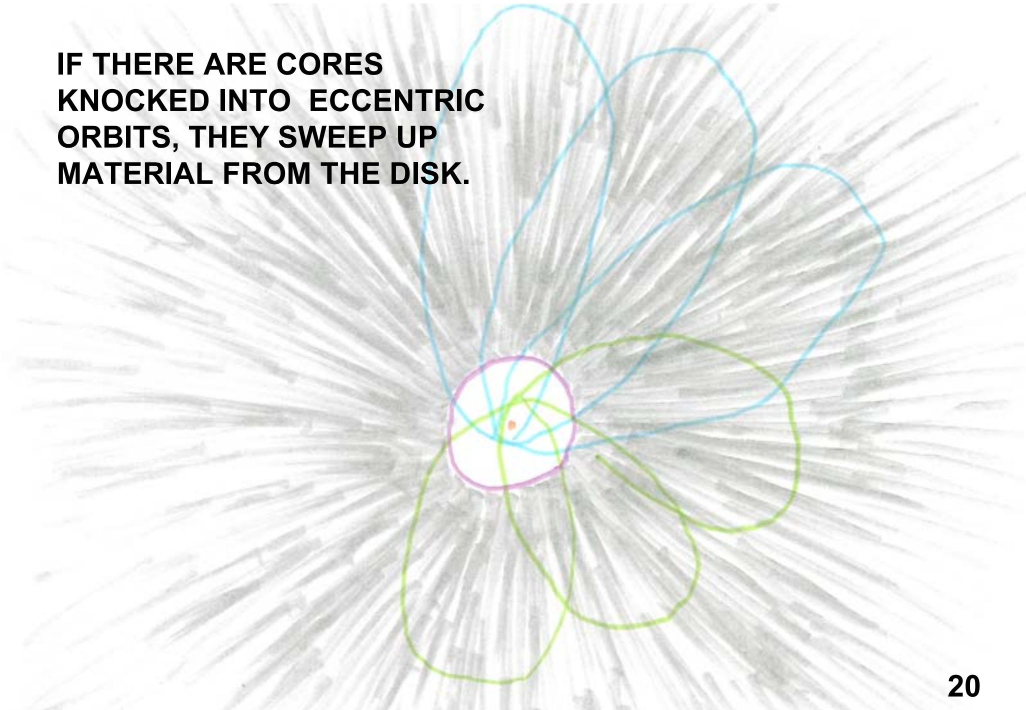

FILLED WITH RADIATION + WIND
RADIATION + WIND
o
SUPER [redacted]
RECONNECTION
EVENT

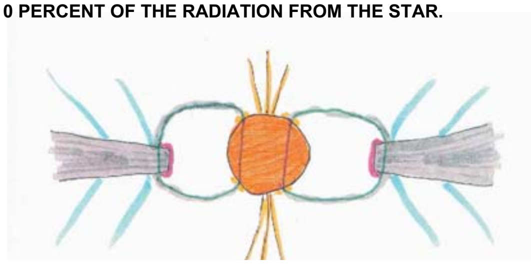
18


CORES
INNER
WALL
POPCORN

19

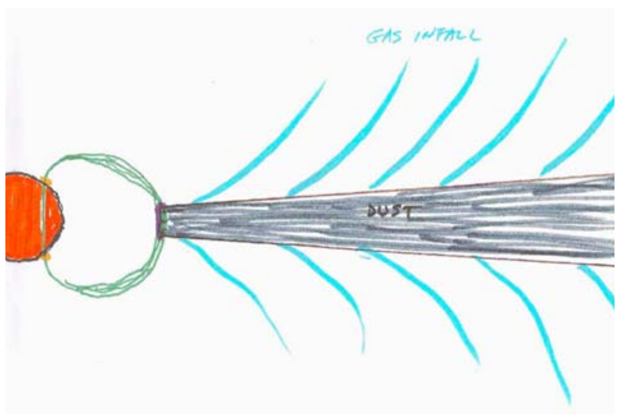

IF THERE ARE CORES
KNOCKED INTO ECCENTRIC
ORBITS, THEY SWEEP UP
MATERIAL FROM THE DISK.

RADIATION PRESSURE PUSHES DISK MATERIAL AND FORMS
A WALL OF DENSE, WARM GAS AND DUST THAT ABSORBS
10 PERCENT OF THE RADIATION FROM THE STAR.



MAGNETIC FIELD IS STRETCHED OUTWARD WITH THE DISK
SINCE IT IS PINNED TO THE DISK. AS THE COUPLING
WEAKENS THE FIELD LINES WRAP.

21



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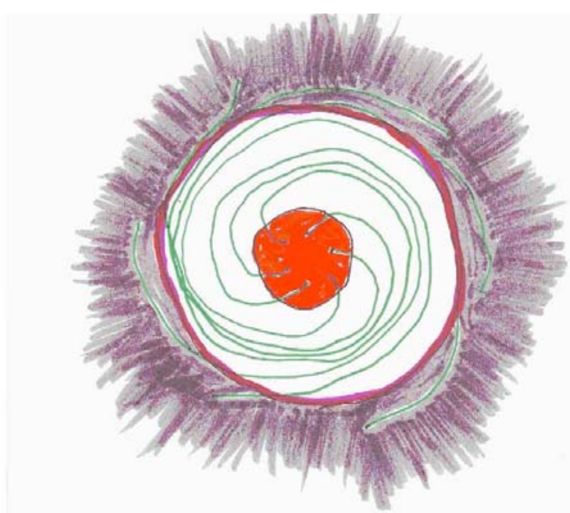

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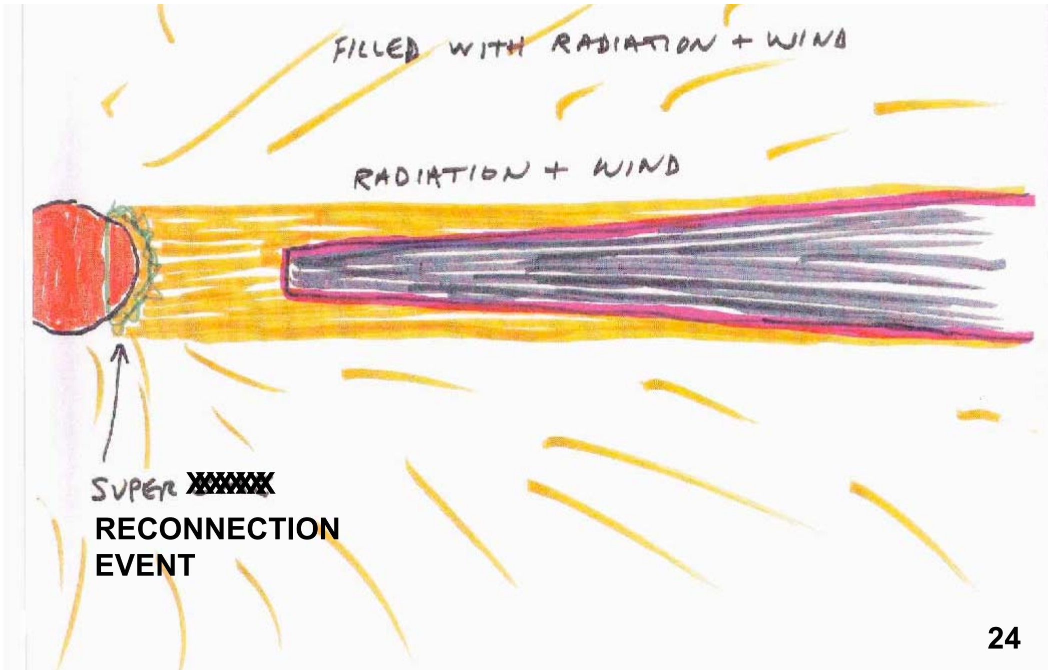
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RECONNECTION
EVENT
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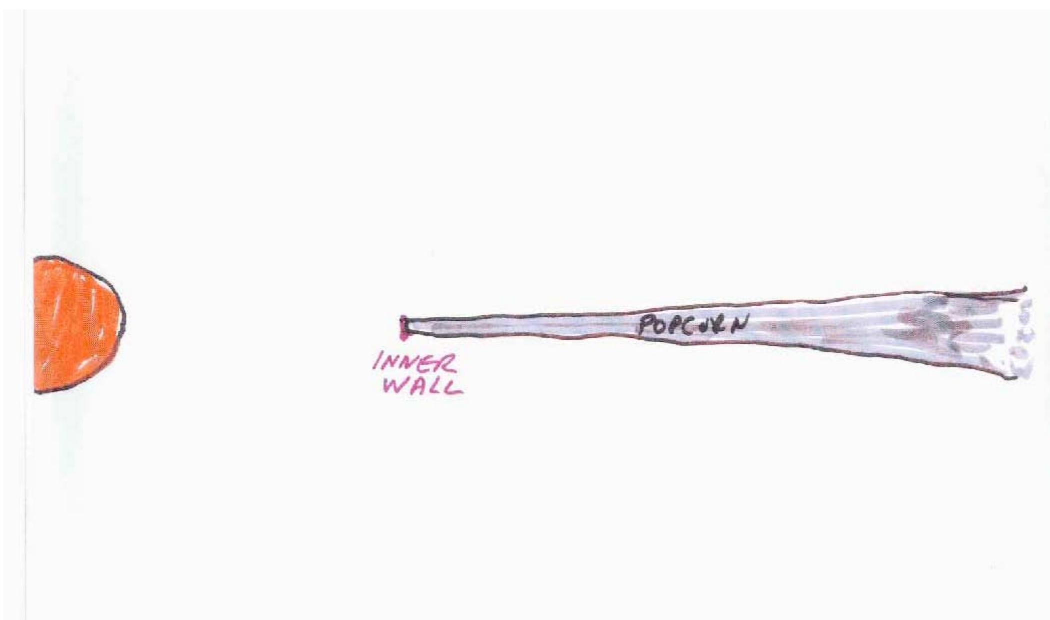
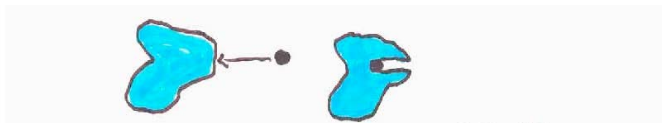

POPCORN
INNER
WALL

25

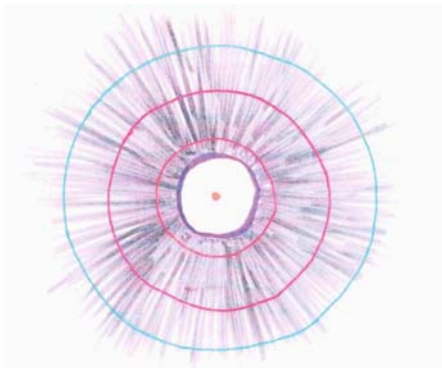
POPCORN

STICKY
CRUSHABLE
INSULATING
RADIOACTIVELY SELF-HEATING
WARMED AND ANNEALED BY STAR
NOT LIKE PARTICLES IN MANY BODY CALCULATIONS

LOW VELOCITY COLLISION STICKS   MODERATE VELOCITY COLLISION CRUSHES



COLLISION WITH SMALL DENSE FAST PARTICLES PENETRATE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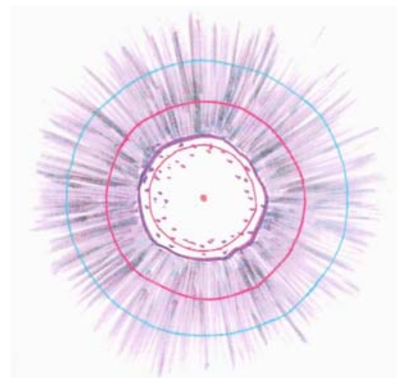
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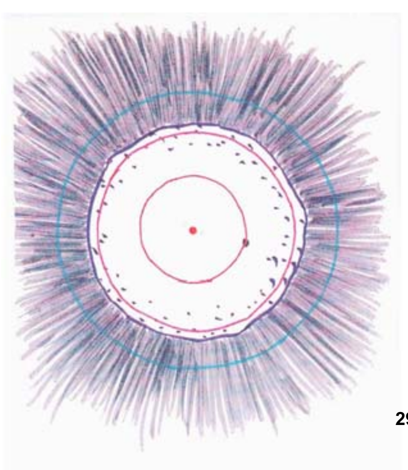
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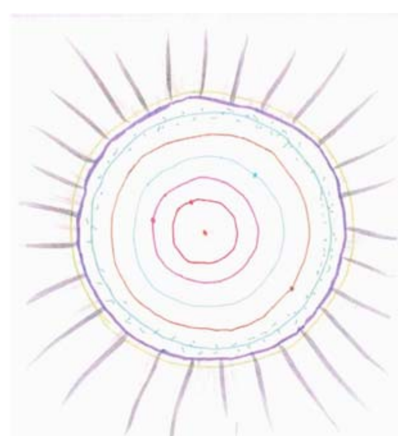
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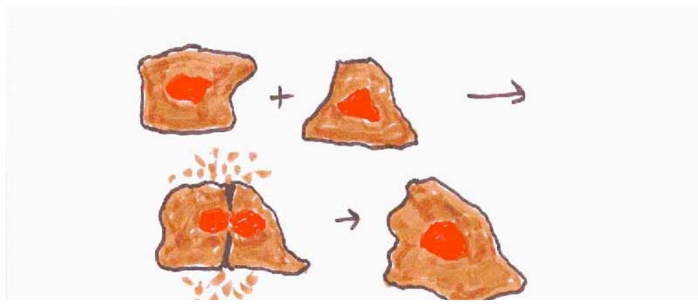
WHEN A BODY GROWS LARGER, HEAT FROM RADIOACTIVITY IS TRAPPED IN THE CENTER AND DIFFERENTIATION BEGINS.

A SELF-GRAVITATING PLANETESIMAL CRUSHES UNDER ITS OWN WEIGHT. DIFFERENTIATION INCREASES. MELTING BEGINS.

DIFFERENTIATION IS MAINTAINED WHEN PLANETESIMALS MERGE.



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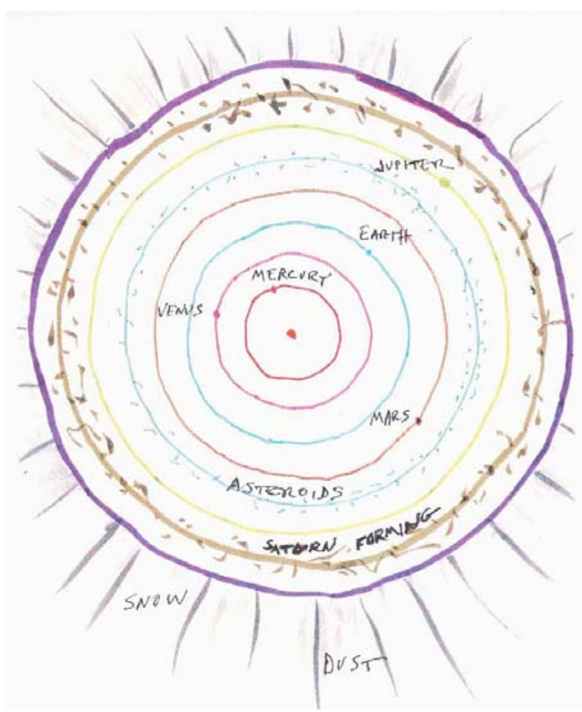

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