Planet Formation by Concurrent Collapse

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This talk presents ideas discussed in:

Wilkinson M and Mehlig B,
Planet Formation by Concurrent Collapse, arXiv:0802.4099 (astro-ph).

Other relevant works:

Ribas I. and Miralda-Escudé J.,
The eccentricity-mass distribution of exoplanets: signatures of different formation mechanisms?,
Astron. & Astrophys., **464**, 779-85, (2007).

Wilkinson M., Mehlig B. and Uski V.,
Stokes trapping and planet formation,
Astrophysical J. Suppl., **176**, 484, (2008).

Overview

I will contrast two views of planet formation.

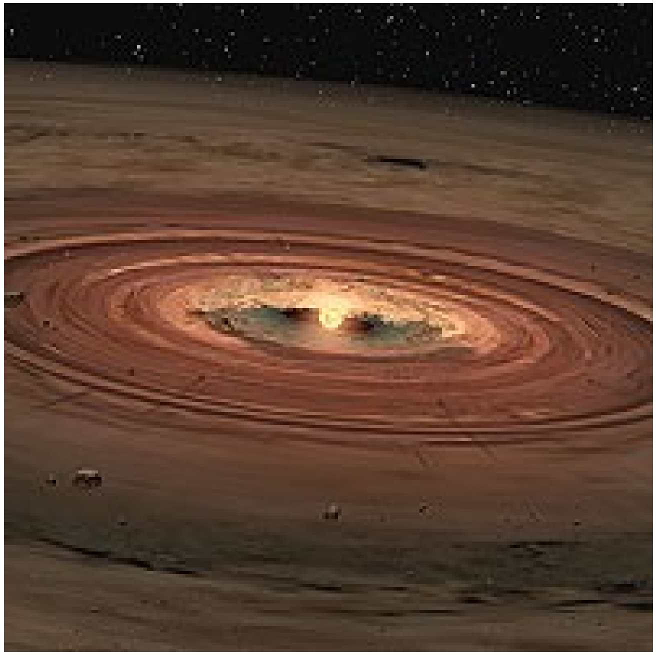
The conventional approach relies upon ***dust aggregation in a circumstellar disc***. It explains why the solar system has planets in nearly circular and coplanar orbits, but there are several observational and theoretical problems, apart from the well-known issues of metre-scale objects sprailling in.

Our alternative mechanism, ***concurrent collapse***, gives a more plausible explanation for the origin of large extra-solar planets in eccentric orbits. I will argue that it provides an at least equally plausible route to explaining the origin of all planetary systems, and that it provides new theories for the origin of ***FU Orionis outbursts*** and of ***chondrules***.

The standard model

It is widely accepted that planets form by aggregation of dust in a circumstellar disc.

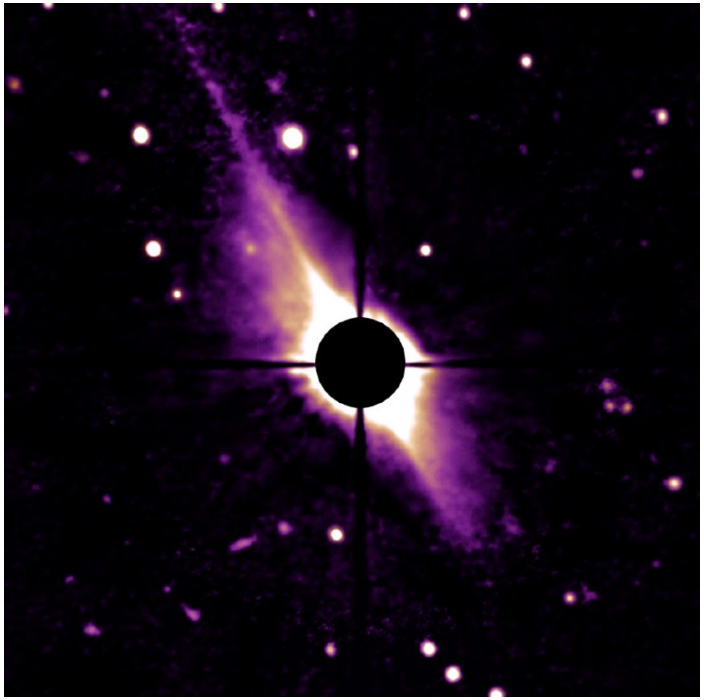
Artist's impression



http://www.daviddarling.info/images/dust_disk_080205.jpg

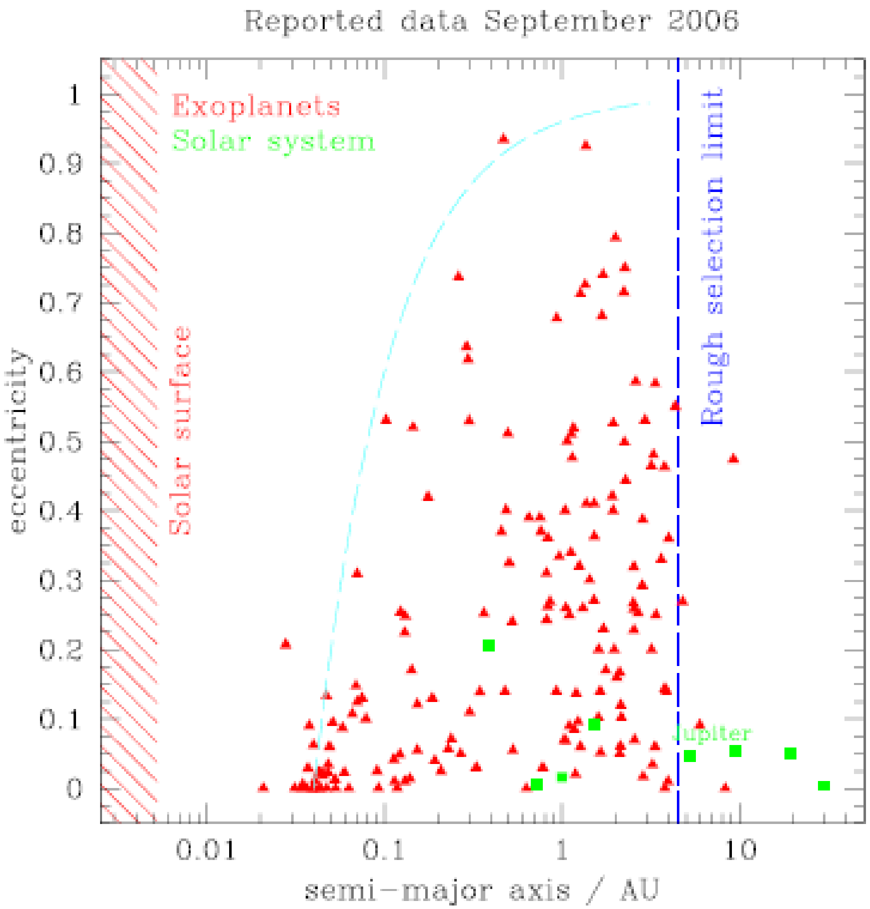
Beta Pictoris at 0.5 micron

http://astro.berkeley.edu/~kalas/disksite/pages/bpic.html



This model explains why the major planets have near-circular orbits in the equatorial plane of the sun. But apart from metre-sized objects spiralling-in, there are several other difficulties with this model.

Exo-solar planets with eccentric orbits



It has been proposed that planets with eccentric orbits arise because of long term instabilities of planetary systems.

In systems with more than one heavy planet, orbital parameters may drift. Eventually there is a scattering event in which one planet is ejected, leaving the another in an eccentric orbit.

It is not clear whether this mechanism can explain the large proportion of planetary systems where a large planet has reached a significantly eccentric orbit.

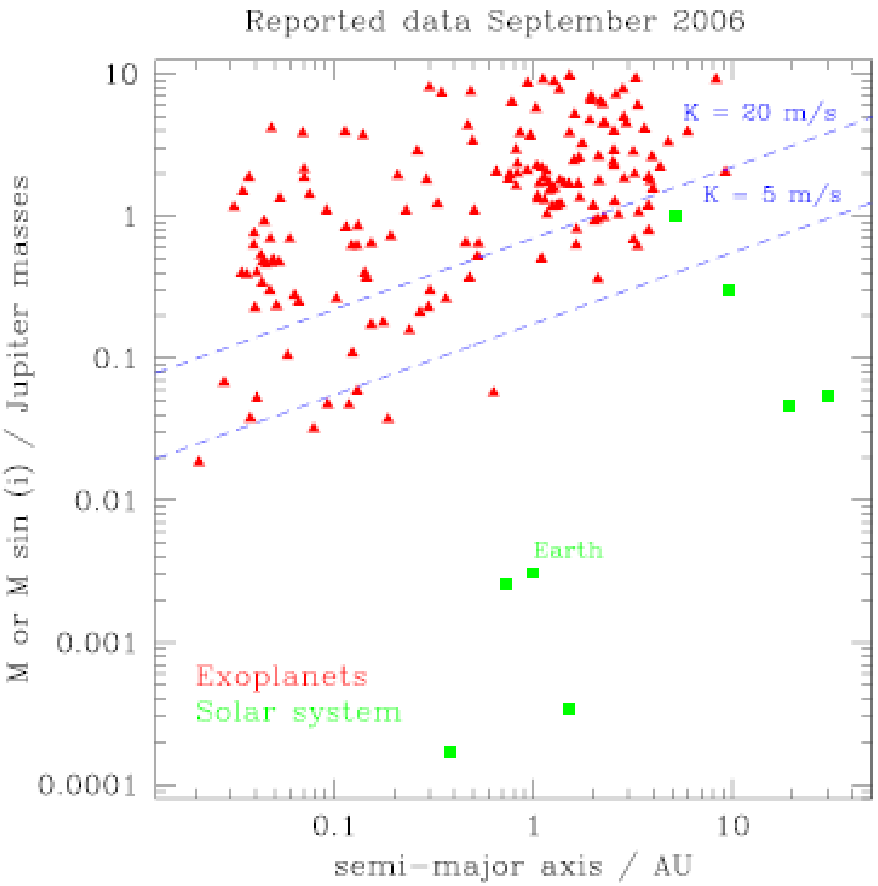
Data:

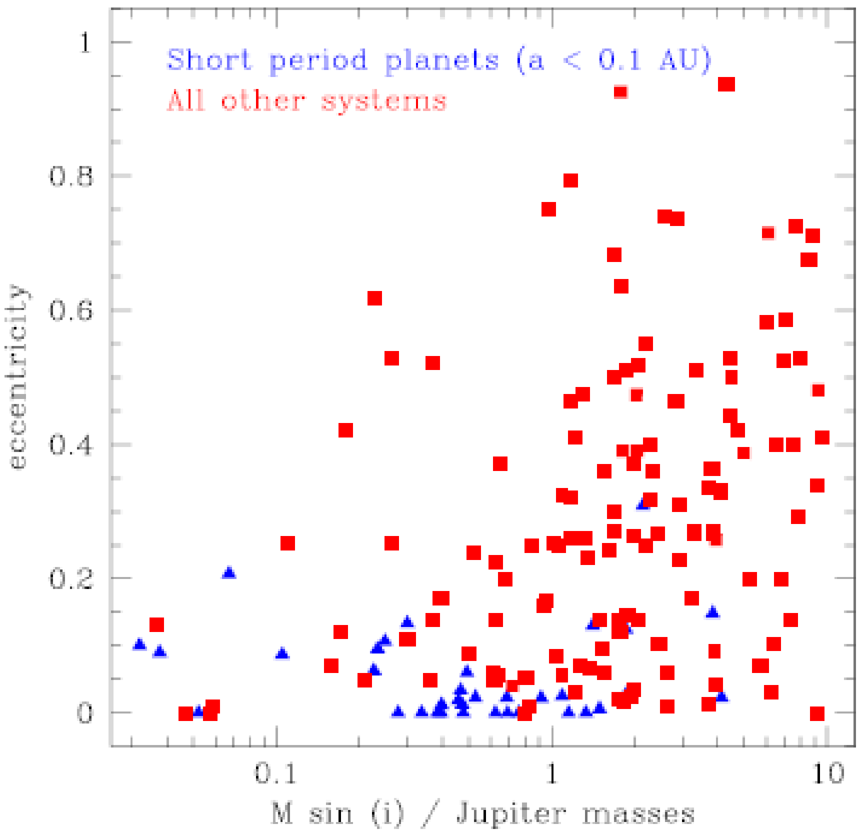
R. P. Butler *et al*, *Astrophysical J.*, **646**, 505, (2006).

Orbital instability theory:

E. B. Ford, F. A. Rasio. and K. Yu, in *Scientific Frontiers in Research on Extrasolar Planets*, ASP Conference Series, **294**, eds. Deming D. and Seager S., ASP, San Francisco, p.181, (2003).

Data on exo-solar planets : masses





Kinetics of aggregate growth

If the particle aggregation model is to be justified, we have to be satisfied that the kinetics of the motion allow aggregates to grow, and at a sufficient rate. Two problems must be considered:

1. What is the rate of collision between dust grains and aggregates of dust grains. The collision rate must be sufficient to allow large bodies to form over the lifetime of the accretion disc.
2. What are the relative velocities of collisions? And at what value of the relative velocity will the clusters of grains tend to fragment rather than adhere.

The rate of collision is initially low because of the low density of particles. As they aggregate, the number of particles for subsequent collisions will decrease markedly. Also, we shall see that the time available for collision is limited because objects can spiral in to the star quite quickly.

The aggregates form in a turbulent environment. Their relative velocities at collision are high, and increase with cluster size. We have argued that this is a very severe limitation to fragment growth.

Wilkinson M., Mehlig B. and Uski V., *Astrophysical J. Suppl.*, **176**, 484, (2008).

Properties of circumstellar accretion disks

Evidence from lifetimes and luminosities indicate that material falls onto the star at a rate of roughly

$$\dot{M} = 10^{-7} M \mathrm{yr}^{-1}$$

The accretion rate determines the rate at which energy is dissipated by turbulent motion. Using a standard model for an accretion disk we can estimate:

Variable	Symbol	$X(R_0)$	δ_R	δ_ℓ
Surface temperature	T	$130\,\mathrm{K}$	$-3/4$	0
Speed of sound	c_s	$670\,\mathrm{m\,s^{-1}}$	$-3/8$	0
Disk height	H	$3.4 \times 10^9\,\mathrm{m}$	$9/8$	0
Surface density	Σ	$280\,\mathrm{kg\,m^{-2}}$	$-3/4$	-2
Gas density	ρ_g	$3.3 \times 10^{-6}\,\mathrm{kg\,m^{-3}}$	$-15/8$	-2
Dissipation rate	$\mathcal{E}$	$0.11\,\mathrm{m^2 s^{-3}}$	$-9/4$	2
Gas mean-free path	λ	$0.42\,\mathrm{m}$	$15/8$	2
Kinematic viscosity	ν	$280\,\mathrm{m^2 s^{-1}}$	$3/2$	2
Kolmogorov length	η	$120\,\mathrm{m}$	$27/16$	1
Kolmogorov time	τ	$52\,\mathrm{s}$	$15/8$	0
Kolmogorov velocity	u_K	$2.3\,\mathrm{m\,s^{-1}}$	$-3/16$	1
Integral velocity	u_L	$710\,\mathrm{m\,s^{-1}}$	$-3/8$	1
Integral timescale	t_L	$4.6 \times 10^6\,\mathrm{s}$	$3/2$	0

$$X = X(R_0) \left(\frac{R}{R_0} \right)^{\delta_R} \ell^{\delta_\ell}$$

These estimates apply at a distance of $1\,\mathrm{AU}$ from a solar mass star.

$$\alpha \sim \ell^2 , \quad \ell = \frac{L}{H(R)}$$

Motion of dust particles

Model the dust grains as spheres of radius a moving in a gas with a turbulent velocity field $\boldsymbol{u}(\boldsymbol{r},t)$. The equation of motion is

$$\ddot{\boldsymbol{r}} = \gamma(\boldsymbol{u}(\boldsymbol{r},t) - \dot{\boldsymbol{r}})$$

Damping rate for a spherical particle of radius a in a conventional fluid was given by Stokes

$$\gamma = \frac{6\pi a \rho_{\mathrm{f}} \nu}{m}$$

In gases with very low density (mean free path large compared to the particle), the same equation of motion hold. The damping rate was obtained by Epstein (1923):

$$\gamma = \frac{c_{\mathrm{s}} \rho_{\mathrm{g}}}{\rho_{\mathrm{p}} a}$$

The relative velocity of colliding particles only depends upon the flow only through the dissipation rate per unit mass, $\mathcal{E}$. Dimensional arguments then imply that

$$\langle \Delta v^2 \rangle = K \frac{\mathcal{E}}{\gamma}$$

where K (dimensionless) has a weak dependence upon Reynolds number.

Collision velocity as a function of size

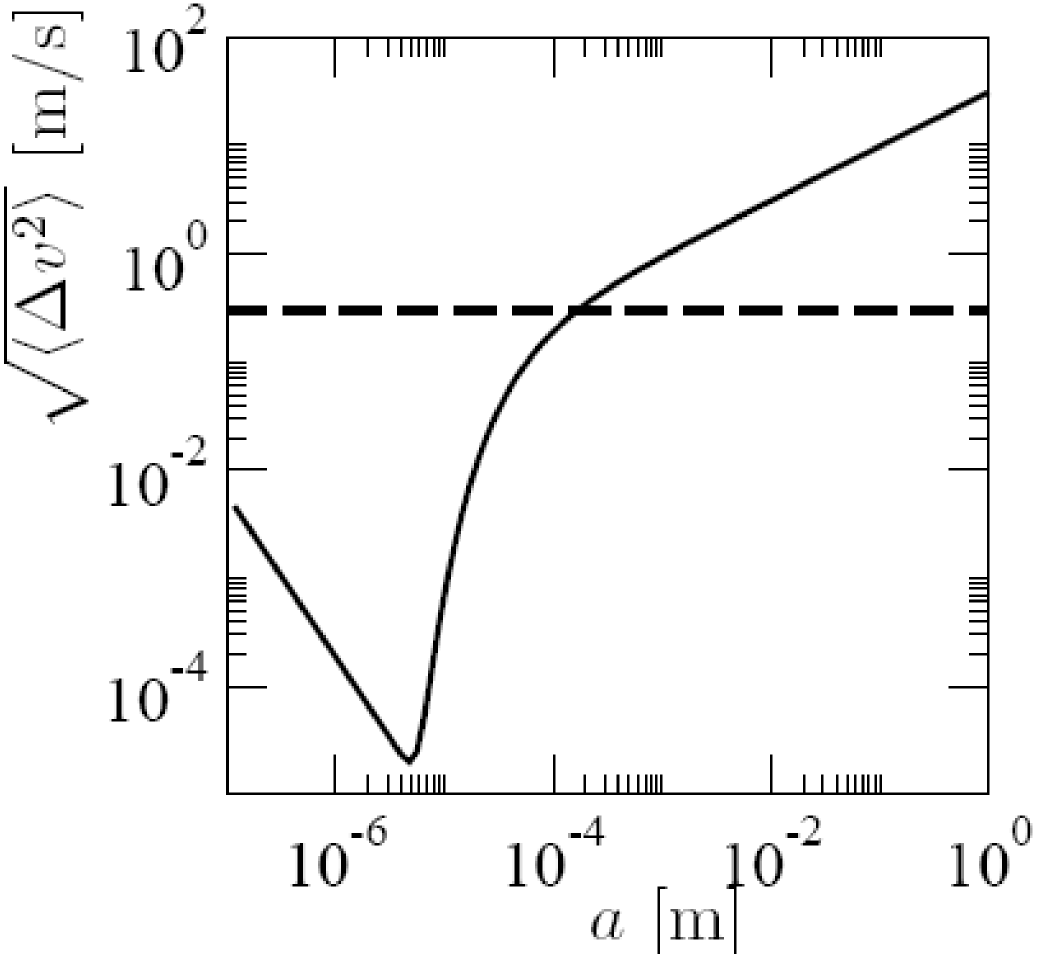


Fig. 4.— Representative plot of relative collision velocity $\sqrt{\langle \Delta v^2 \rangle}$ as a function of the aggregate size, a, illustrating the abrupt increase of the collision velocity at Stokes number unity. The plot, using data from table 2 in equations (3)-(5), applies to compact ($D = 3$), equal-sized aggregates, for the case $\ell = 0.1$. The critical $v_{\rm cr}$ is shown as a horizontal line.

FU Orionis outbursts

FU Orionis is a star which started to increase in luminosity in 1937. Over a few years the luminosity increased by six orders of magnitude, before starting to decrease.

The star appears to be surrounded by a dusty cloud, consistent with it being a young star.

http://www.daviddarling.info/images/FU_Orionis.jpg

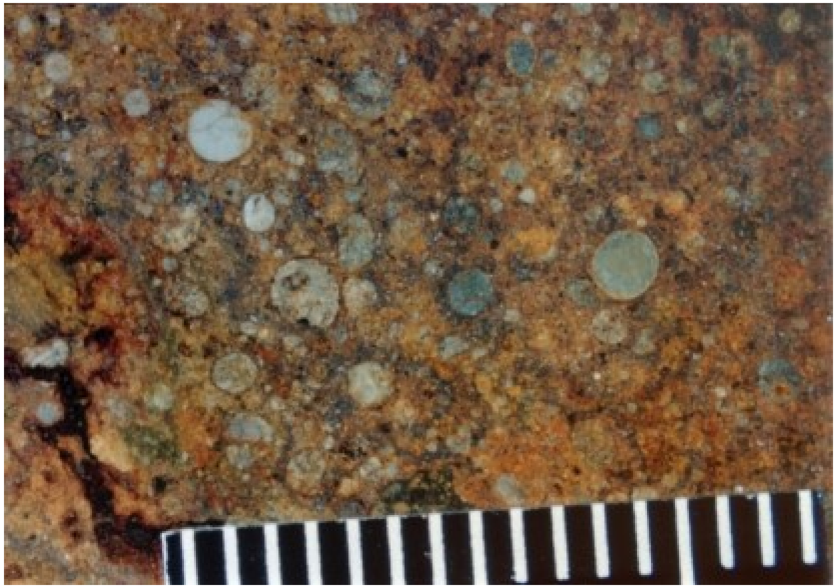
Since them many other outburst events have been observed in other young stars. The events are very diverse. Common features are: quick rise time (1-10 years), relatively slow decay (10-100 years), increase in magnitude is very large (2-6 orders). There is no apparent change preceding the outburst. Surveys suggest that most young stars experience a few outbursts.

Most published explanations assume an instability of the accretion disc. These instabilities require the gas to become opaque due to ionisation of hydrogen. This requires very high temperatures, and does not explain the diversity of the events.

L. Hartman and S. J. Kenyon, *Ann. Rev. Astron. & Astrophysics*, **34**, 207, (1995).

Chondrules

Meteorite fragment are often chondrites, pieces of rocky material. These usually contain granules termed chondrules, which consist of glassy material which appears to have been melted while suspended in gas.



Scale: millimetre divisions

R. H. Hewins, Chondrules, *Ann. Rev. Earth & Planetary Sci.*, **25**, 61-83, (1997).

The chondrules are very variable in size and chemical composition: they can be silicate, carboniferous or ferrous minerals. It is thought that they were melted over a short period, perhaps minutes, because longer periods of heating would cause them to evaporate.

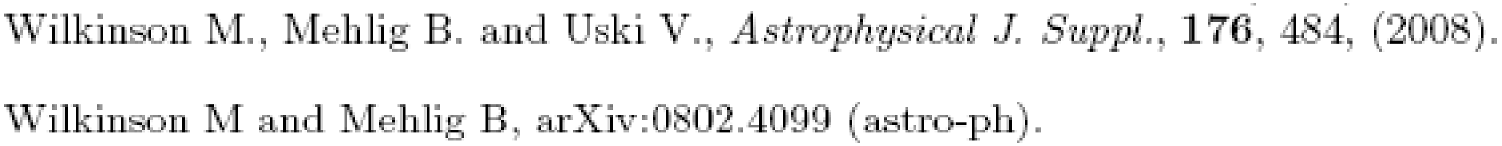
Published explanations include heating by shocks, lightning in the circumstellar disc, which do not appear to provide adequate heating.

Concurrent collapse hypothesis

Stars form when a molecular cloud undergoes gravitational collapse. As it collapses it fragments, breaking up into pieces with masses which are assumed to be comparable to those of stars.

Smaller fragments of the cloud in the vicinity of a nascent star may also condense by gravitational attraction, resulting in gravitationally self-bound objects which are themselves bound by the gravitational field of the star. We call this *concurrent collapse*, and the sub-stellar objects are termed *juvenile planets.*

The juvenile planets must initially have a composition which is similar to that of the interstellar medium. They would have to undergo a radical transformation to become rocky or icy planets. We propose that such transformations can occur due to interaction with the residual gas in the protostellar nebula, or by collisions.

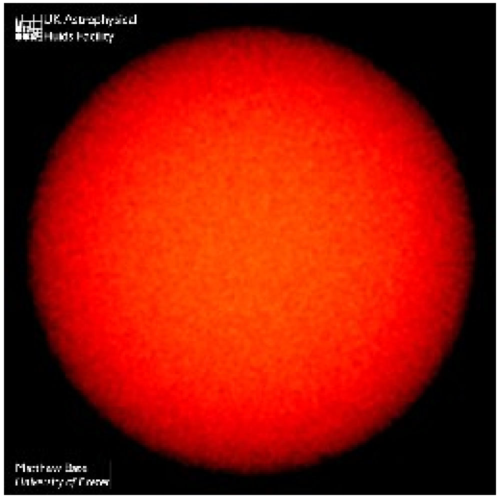


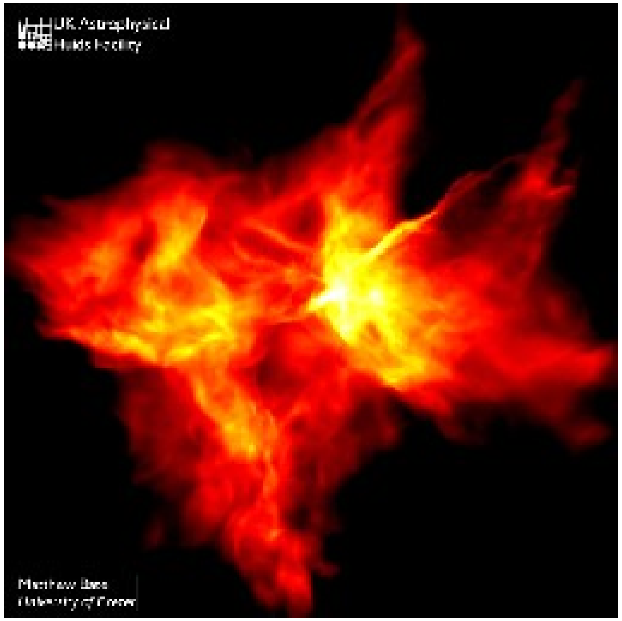
Wilkinson M., Mehlig B. and Uski V., *Astrophysical J. Suppl.*, **176**, 484, (2008).

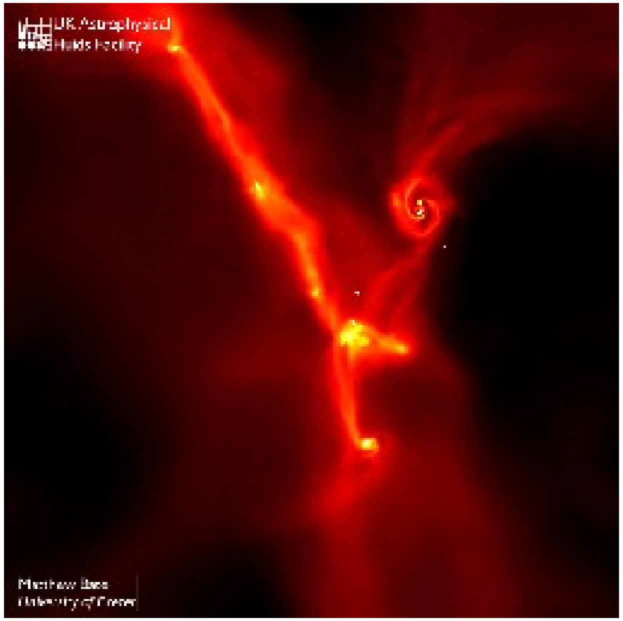
Wilkinson M and Mehlig B, arXiv:0802.4099 (astro-ph).

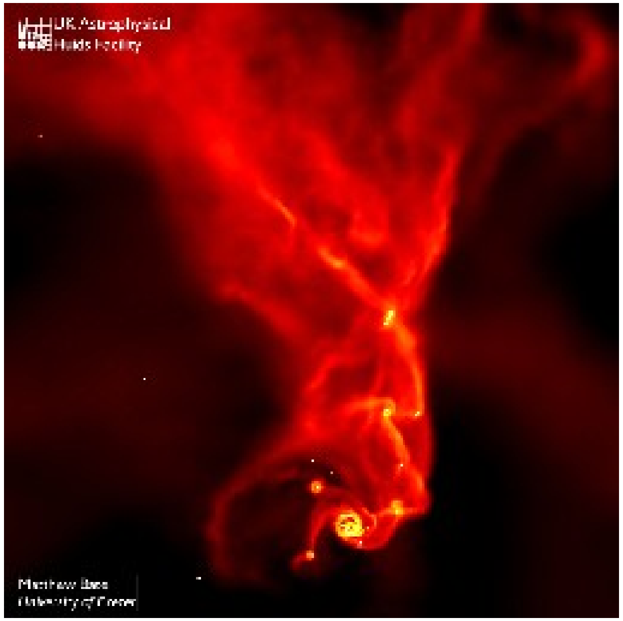
Ribas and Miralda-Escude make a similar proposal, but only apply it to very large exoplanets with highly eccentric orbits.

Gravitational collapse









Simulations of gravitational collapse by Matthew Bate,

http://www.astro.ex.ac.uk/people/mbate/Research/pr.html)

Evolution of juvenile planets

If juvenile planets are formed concurrently with a protostar,

1. They have a composition which is similar to the interstellar medium.
2. They are likely to have eccentric orbits outside the equatorial plane of the protostar.
3. Like the protostar, they will be loosely bound, still losing energy by radiation, and surrounded by their own accretion disc.

The juvenile planets will move through the nebula of their protostar, which is in the process of forming a circumstellar accretion disc. There are two types of process which can be significant.

1. The juvenile planet will move at high speed through the circumstellar disc. Both material and momentum can be transferred, and the friction can generate high temperatures.

2. Because the juvenile planets are created in elliptical orbits, there is a possibility that they will collide, or suffer very close encounters.

Interaction of juvenile planet with gas disc

Juvenile planet may pass through the gas disc at a high velocity, of order $10^4\,\mathrm{m\,s^{-1}}$ Material can be removed from its outer layers, reducing the fraction of lighter elements (because heavier elements may sink to its core).

Also, momentum is transferred, and the motion of the juvenile planet might become entrained to the disc (reaching a nearly circular, nearly in-plane orbit). Can this happen?

The planet becomes entrained to the disc if the mass of gas displaced is comparable to the mass of the juvenile planet. Estimate the number of orbits for this to be achieved:

Planet mass, density, size $M_\mathrm{p} = 10^{27}\,\mathrm{kg}$ $\rho_\mathrm{p} \approx 10^3\,\mathrm{kg\,m^{-3}}$ $a \approx 10^8\,\mathrm{m}$

Gas disc density, orbit radius $\rho_\mathrm{g} \approx 10^{-6}\,\mathrm{kg\,m^{-3}}$ $R \approx 10^{12}\,\mathrm{m}$

Mass of gas displaced per orbit $10^{23}\,\mathrm{kg}$ planet entrained in 10^4 orbits

The numbers in this estimate are uncertain by orders of magnitude. This implies that in some cases juvenile planets would be entrained to circular orbits, in other cases the orbits remain elliptical.

Collisions between juvenile planets

Let us estimate the probability for collision of two juvenile planets, in eccentric orbits of approximate radius $1\,\mathrm{AU}$:

Approximate area swept out by orbit of one planet: $10^{22}\,\mathrm{m}^2$

Approximate cross sectional area of a planet: $10^{16}\,\mathrm{m}^2$

Probability of collision per orbit: 10^{-6}

We conclude that collisions between juvenile planets in elliptical orbits are possible. Depending upon parameters, they may be unlikely or almost inevitable.

What are the consequences of a collision? Large amounts of debris would be produced. If two Jupiter size planets collide, large amounts of debris will be scattered into orbits which will reach the star. The first fragments will reach the star in a fraction of the orbital period (perhaps 1-10 years), and material will continue to reach the star at a significant rate for several multiples of the orbital period (perhaps 10-100 years). The total amount of material is 10^{-3} solar masses, which gives a rate of accretion three orders of magnitude higher than the typical rate. Collisions can explain the magnitude and timescale of outbursts.

Mechanisms for producing rocky planets

The juvenile planets initially have a composition typical of the interstellar medium (mainly hydrogen and helium).

Heavy elements will fall to the centre of the planet. Because the interior is hot, some quite exotic mechansims could be invoked (for example, molten droplets of rocky material could form ‘rain’).

W. L. Slattery, W. M. DeCampli and A. G. W. Cameron, *Moon and Planets*, **23**, 381, (1980).

There are two possible mechanisms for making rocky planets:

1. The lighter elements could be removed as the juvenile planet moves at high speed relative to the gas in the circumstellar disc.
2. After a collision of two juvenile planets, rocky debris will remain. Some will spiral into the star. The heavier fragments will remain in orbit, and can form planets by the same mechanisms as are involved in the later stages of the standard planet formation model.

Size of chondrules

Chondrules are small glassy globules found in meteorites. Can we estimate their size?

We consider a collision between two juvenile planets which contain a core of silicate minerals. The high energy of the collision creates a mass of molten glassy material in turbulent motion, which fragments into globules. Their size is determined by the condition that their kinetic and surface energies are comparable:

$$E_{\mathrm{kin}} \sim \rho r^3 v^2 \qquad E_{\mathrm{surf}} \sim \gamma r^2 \qquad \gamma \sim 3 \times 10^{-2}\,\mathrm{Nm}^{-1}$$

Use Kolmogorov theory of turbulence to relate v , r

$$v \sim r/\tau \qquad \tau = \sqrt{\nu/\mathcal{E}}$$

These give an estimate for the droplet size: $r \sim \left(\frac{\gamma\nu}{\rho\mathcal{E}}\right)^{1/3}$

Using $\mathcal{E} \sim v_{\mathrm{col}}^2/t_{\mathrm{col}}$, $\nu \sim 10^{-2}\,\mathrm{m}^2\mathrm{s}^{-1}$, estimate: $r \sim 10^{-3}\,\mathrm{m}$

The brown-dwarf desert

An argument against the common origin of stars and planets is the existence of the *brown-dwarf desert* : the distribution of masses of known objects has a minimum for masses intermediate between stars and planets.

Theoretical approaches based upon opacity considerations produce very low estimates for stellar masses. This indicates that juvenile planets could form by gravitational collapse, but it is a long standing puzzle that there is no first-principles estimate for the mass of a star.

The simulations of gravitational collapse by Bate *et al* suggest a reason for the discrepancy. They find that after small gravitationally self-bound objects form, they accrete residual gas from the molecular cloud, until they achieve masses of conventional stars.

This also suggests a reason for the brown-dwarf desert. If all objects start with similar sizes and accrete material at different rates, an instability can develop. Those objects which accrete at a higher rate grow more rapidly, and their greater gravitational potential causes their accretion rate to increase further.

The brown-dwarf desert appears to be explicable by a ‘winner takes it all’ competitive growth process.

Conclusions

The *concurrent collapse* hypothesis avoids the problems of having to build planets by aggregation of dust in a turbulent environment. It suggests simple models or explanations for some observations:

1. The juvenile planets are formed in eccentric orbits. The existence of circular orbits can be explained by entrainment to the gas disc.
2. Collisions between juvenile planets can explain FU Orionis outbursts.
3. Debris scattered across a circumstellar disc by collisions can provide raw material for standard planetesimal growth scenarios, avoiding all of the difficult problems.
4. Also, collisions might provide the heat source for melting the chondrule particles.
5. The model is consistent with planetary systems being highly variable in structure.

The juvenile planets are created with a composition reflecting that of the interstellar medium. Rocky or icy planets can be formed if heavier elements sink to the core of the juvenile planet, and if motion through the gas in the circumstellar disc strips away the outer layers.