BROWN DWARF FORMATION BY DISC FRAGMENTATION

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PLAN:

Stars vs planets
Constraints on brown dwarf formation

The Toomre condition
The Gammie condition
Dust opacity and the disc fragmentation condition
Existence of massive extended discs
Fragment parameters

Numerical simulations

Conclusions

``STARS''

In the context of this talk, brown dwarfs are "stars"

Brown dwarfs form just like hydrogen-burning stars;

i.e. by gravitational instability;

on a dynamical time-scale, $t_{\rm DYN} \sim 600\,{\rm years}\left(\frac{M_\star}{\rm M_{JUPITER}}\right)$;

normally in clusters;

initially with uniform (interstellar) composition.

There is continuity of stellar statistical properties across the hydrogen-burning limit at $M_H \sim 0.075\ M_\odot$.

The opacity limit at ~ 3-7 $M_{JUPITER}$ is the minimum mass for "star formation".

``PLANETS''

In contrast, planets form by accumulation of a rocky core,

on a much longer timescale, > 10^6 years;

with subsequent acquisition of a gas envelope (if circumstances allow);

and with initially fractionated elemental composition.

Stars (brown-dwarf stars) and planets probably co-exist somewhere in the mass range 0.003 - 0.010 $M_{\odot}$.

It may be hard to distinguish very low-mass stars from very high-mass planets, without information on their internal composition, but they should be viewed as distinct objects.

CONSTRAINTS ON BROWN DWARF FORMATION

Stellar IMF (low-mass end, minimum mass)

Relationship to core MF (2-5 stars per core, 20-50% efficiency)

Incidence of accretion discs, magnetospheric accretion signatures, outflows (scaled-down versions of hydrogen-burning stars)

Maps and SEDs of Class 0 and I protostars (but short-lived).

Spatial and velocity distribution in clusters:
- primordial mass segregation (may not be necessary);
- diaspora relative to birth core/system (*eigen-evolution*);
- diaspora relative to birth cluster (less centrally condensed).

MORE CONSTRAINTS ON BROWN DWARF FORMATION

Binary statistics

As M_1 decreases	For $M_1 \lesssim 0.1\mathrm{M}_\odot$
f_{BIN} decreases	$0.15 \lesssim f_{\mathrm{BIN}} \lesssim 0.45$
$\overline{a}$ decreases	$\overline{a} \lesssim 5\,\mathrm{AU}$
$\sigma_{\log(a)}$ decreases	$\sigma_{\log(a)} \gtrsim 0.4$
$\overline{q}$ increases	$0.7 \lesssim \overline{q} \lesssim 0.9$

The brown-dwarf desert, and location of BD/BD binaries

If $M_1 \sim \mathrm{M}_\odot$ and $M_2 \lesssim 0.1\,\mathrm{M}_\odot$, then $\overline{a} \sim 200\,\mathrm{AU}$ ($a \gtrsim 50\,\mathrm{AU}$), **and** these BDs in orbit around Sun-like stars have a higher chance of having a close ($\lesssim 10\,\mathrm{AU}$) BD companion than BDs in the field.

THE TOOMRE CONDITION

$$\ddot{r} = -\frac{Gm}{r^2} + \frac{1}{\rho}\frac{dP}{dr} + r\omega^2$$
$$= -\pi G\Sigma(R) + \frac{a^2(R)}{r} + \frac{r\Omega^2(R)}{4},$$

$$m = \pi r^2 \Sigma(R)$$

$$\frac{dP}{dr} \sim \frac{P}{r} = \frac{\rho a^2(R)}{r}$$

$$t_{\rm COND} = \left(\frac{r}{-\ddot{r}}\right)^{1/2} = \left(\frac{\pi G\Sigma(R)}{r} - \frac{a^2(R)}{r^2} - \frac{\Omega^2(R)}{4}\right)^{-1/2},$$

$$t_{\rm FAST} = 2\left(\left\{\frac{\pi G\Sigma(R)}{a(R)}\right\}^2 - \Omega^2(R)\right)^{-1/2}$$

Must be real, so $\Sigma(R) \gtrsim \dfrac{a(R)\Omega(R)}{\pi G}.$

$$a \propto R^{-1/4}$$
$$\Omega \propto R^{-3/2}.$$

THE GAMMIE CONDITION

A proto-fragment must be able to radiate away its compressional energy on a dynamical timescale, otherwise it undergoes an adiabatic bounce and is sheared apart.

$$t_{\rm COOL} \;\lesssim\; t_{\rm DYN}\,,$$

$$t_{\rm COOL} \;\simeq\; \frac{\Sigma(R)a^2(R)}{2\sigma_{\rm SB}T^4(R)/\Sigma(R)\bar{\kappa}_{\rm R}(R)}$$

$$t_{\rm DYN} \;\simeq\; \frac{2\pi}{\Omega(R)}$$

$$\Sigma(R) \;\lesssim\; \left(\frac{2^3\pi^4\bar{m}^{\,4}\,a^7(R)}{15Gc^2h^3\bar{\kappa}_{\rm R}(R)}\right)^{1/3}\,.$$

DUST OPACITY

$$\kappa_\lambda \propto \lambda^{-2} \longrightarrow \bar{\kappa}_{\rm R} \propto T^2 \longrightarrow \bar{\kappa}_{\rm R} \simeq \kappa_{\rm O}\, a^4$$

$$\kappa_{\rm O} \simeq 3 \times 10^{-19}\,{\rm s}^4\,{\rm cm}^{-2}\,{\rm g}^{-1}$$

$$\Sigma(R) \lesssim \left(\frac{2^3\pi^4\bar{m}^4}{15Gc^2h^3\kappa_{\rm O}}\right)^{1/3} a(R)$$ GAMMIE CONDITION

$$\Sigma(R) \gtrsim \frac{a(R)\Omega(R)}{\pi G}$$ TOOMRE CONDITION

$$\Omega(R) \lesssim \left(\frac{2^3\pi^7G^3\bar{m}^4}{15c^2h^3\kappa_{\rm O}}\right)^{1/3}$$ GAMMIE + TOOMRE

$$R \gtrsim \left(\frac{15^2c^4h^6\kappa_{\rm O}^2{\rm M}_\odot^3}{2^6\pi^{14}G\bar{m}^8}\right)^{1/9}\left(\frac{M_1}{{\rm M}_\odot}\right)^{1/3} \sim 100\,{\rm AU}\left(\frac{M_1}{{\rm M}_\odot}\right)^{1/3}$$

THE EXISTENCE OF EXTENDED MASSIVE DISCS

To form a disc with radius R > 150 AU only requires the collapse of a prestellar core with

$$\beta \equiv \frac{U_{\rm ROT}}{|U_{\rm GRAV}|} \gtrsim 0.005 \left(\frac{M_{\rm CORE}}{\rm M_\odot} \right) ;$$

Alternatively, a protostar of mass M_1 must capture material with specific angular momentum

$$h \gtrsim h_{\rm MIN} \sim 3 \times 10^{20}\,{\rm cm^2\,s^{-1}} \left(\frac{M_1}{\rm M_\odot} \right)^{1/2} ,$$

$$\equiv (0.1\,{\rm km\,s^{-1}})\,(0.01\,{\rm pc}) \left(\frac{M_1}{\rm M_\odot} \right)^{1/2} ,$$

It must happen pretty often

FRAGMENT PARAMETERS

$$a(R) \simeq 10^5 \,\mathrm{cm\,s^{-1}} \left(\frac{L_1}{\mathrm{L_\odot}}\right)^{1/8} \left(\frac{R}{\mathrm{AU}}\right)^{-1/4}$$

$$\Omega(R) \simeq 2\times 10^{-7}\,\mathrm{s^{-1}} \left(\frac{M_1}{\mathrm{M_\odot}}\right)^{1/2} \left(\frac{R}{\mathrm{AU}}\right)^{-3/2}$$

radius

$$r_{\mathrm{FRAG}} \simeq \frac{2a(R)}{\Omega(R)} \gtrsim 20\,\mathrm{AU} \left(\frac{M_1}{\mathrm{M_\odot}}\right)^{5/12} \left(\frac{L_1}{\mathrm{L_\odot}}\right)^{1/8}$$

mass

$$m_{\mathrm{FRAG}} \simeq \frac{4a^3(R)}{G\Omega(R)} \gtrsim 0.004\,\mathrm{M_\odot} \left(\frac{M_1}{\mathrm{M_\odot}}\right)^{1/6} \left(\frac{L_1}{\mathrm{L_\odot}}\right)^{3/8}$$

NUMERICAL SIMULATIONS

We solve the energy equation, and associated transport of cooling radiation

Equation of state

- Vibrational & rotational degrees of freedom of H_2
- H_2 dissociation
- H ionisation
- Helium first and second ionisation

Dust & gas opacities

- Ice mantle melting
- Dust sublimation
- Molecular opacity
- H^- absorption
- B-F/F-F transitions

Sink particles are only introduced at 10^{-2} g cm^{-3}.

The Jeans, Toomre and Nelson resolution conditions are satisfied at all times

Massive disk around low-mass hydrogen-burning star,

$$M_\star = 0.7 M_\odot$$
$$M_{\rm DISC} = 0.7 M_\odot$$

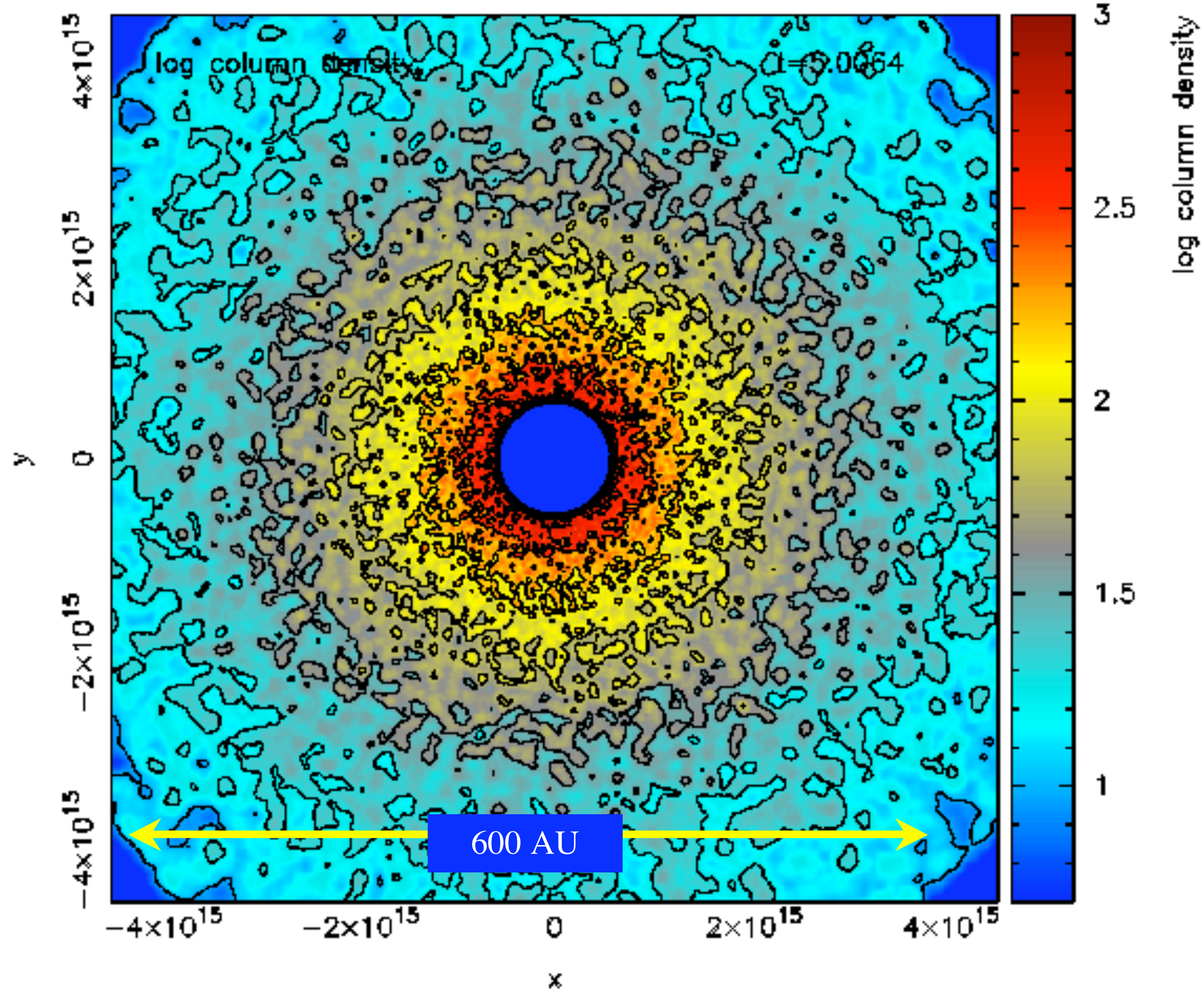
$$\Sigma(R) \sim R^{-7/4}$$

$$T(R) \sim R^{-1/2}$$

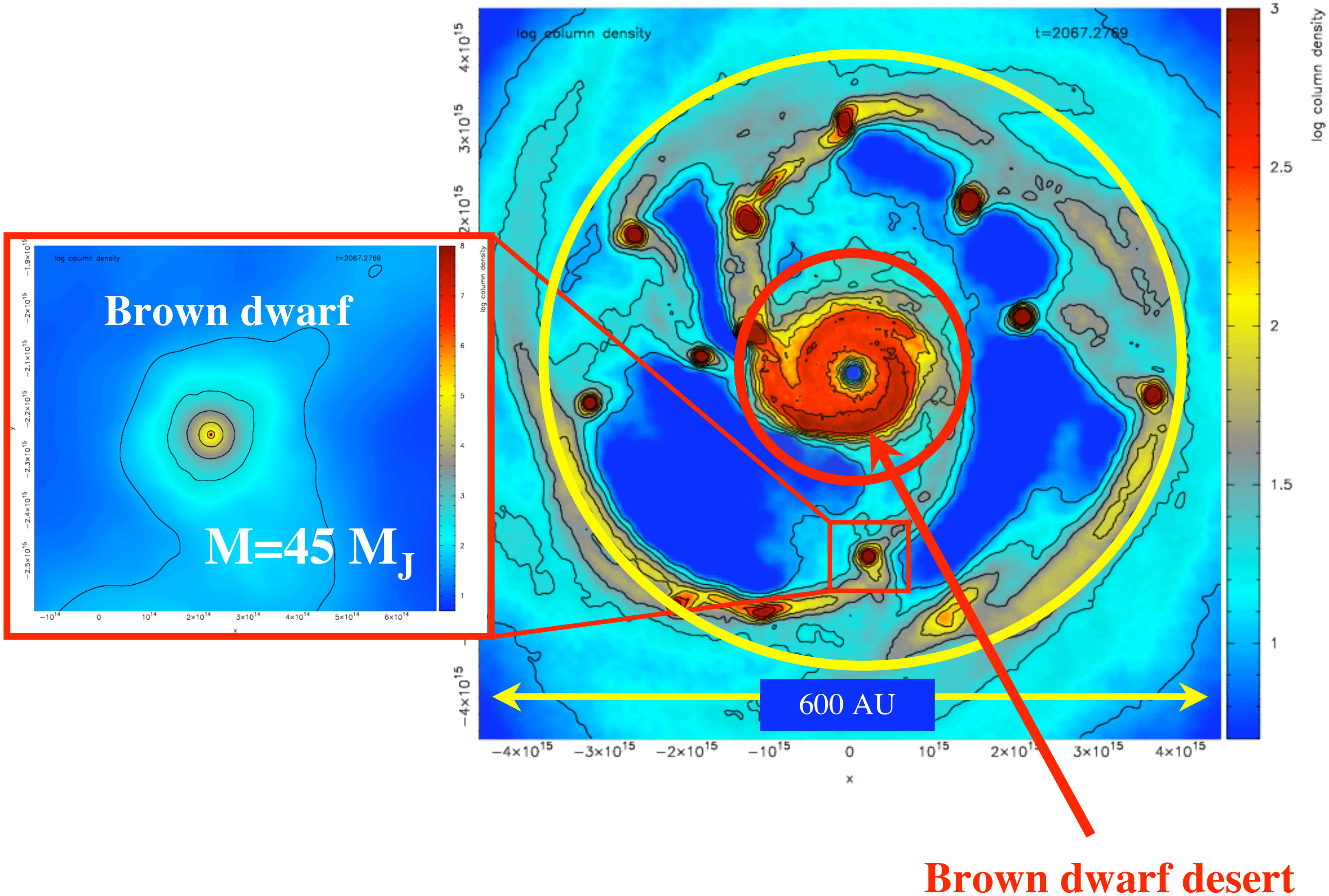
$$Q(R) \ \sim \ 1$$

500,000 particles (disc resolved)

No sink particles, condensations followed to density $\sim \ 10^{-2}\,{\rm g\,cm^{-3}}$.



Final frame of simulation:



CONCLUSIONS

As one proceeds to lower masses, an increasing fraction of stars are formed as secondaries by disc fragmentation, rather than as the primary in their own core.

Disc fragmentation produces brown dwarfs, planemos and low-mass hydrogen-burning stars.

Only the outer parts of a disc can fragment, hence the brown dwarf desert.

Numerical simulations support these conclusions.

Some of the simulated brown dwarfs form close BD/BD binaries.

Their binary properties are similar to observed systems

The simulated brown dwarfs have significant discs.

Simulated brown dwarfs and BD/BD binaries are liberated into the field.

There is no evidence for the H_2 dissociation instability.

Convection and impulsive perturbations won't help to produce fragmentation in the inner disc.

Many properties are determined by the eigen evolution of the small-N system formed from a single core, and are therefore independent of the global environment