Gas giant migration

Hot Jupiters and Solar System formation

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16.09.2015

Core accretion mechanism

Gas giants are believed to form trough the core accretion mechanism, in which a $10\,\mathrm{M}_\oplus$ solid core starts to attract a gaseous envelope.

Once the envelope becomes massive enough, rapid accretion of surrounding gas commences.

Gas giant formation

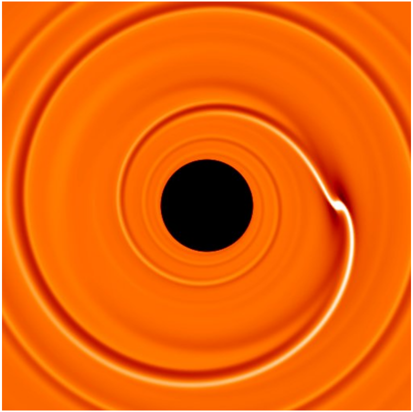
The gaseous component of a protoplanetary disc dissipates within 10 million years. Gas giants must form within this time.

A solid core cannot form that fast without enough solid material to begin with.

Close to the star temperatures are too high for most of the substances to be in solid phase.

Hot Jupiters must have formed further away from their stars and then migrated to where they are now.

Type I migration

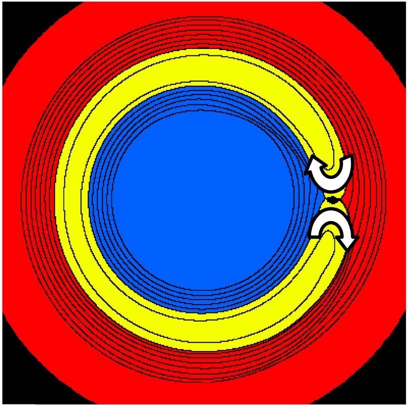


A planet perturbs the gas it orbits in, creating a spiral pressure wave. Interactions between the planet and the gas cause it move inward.

The migration timescale is inversely proportional to the mass of the planet.

Left: Figure by F. Masset.

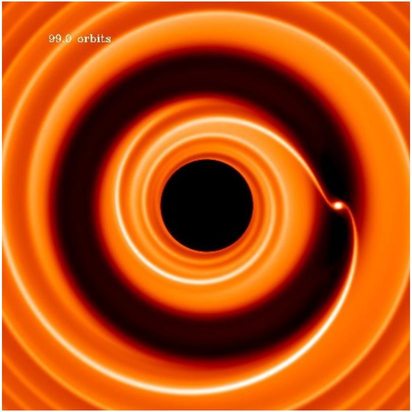
Corotation torque



The torque caused by corotating gas has been found to be significant and can under certain conditions even cause the planet to move outwards.

Left: Figure by F. Masset.

Type II migration



If a planet becomes massive enough, it will clear a gap into the protoplanetary disk.

The planet and it's gap will start migrating inwards due to gas accretion into star. For a moderately massive planet the migration timescale does not depend on the planet's mass.

Left: Figure by F. Masset.

Type III migration

A planet that is almost massive enough to form a gap can experience very rapid migration. It may reach the inner edge of the disk in as few as few dozens of orbits.

This usually requires massive disks.

Planet-planet scattering

Close encounters of similarly sized planets can change their orbits significantly.

If a planets orbital eccentricity increases, it's periastron distance decreases. Tidal effects can reduce the semi-major axis of a planet if it's periastron distance is small enough.

The Kozai mechanism

If a massive central body is orbited by two well-separated bodies, then the inner body can exchange it's orbital eccentricity for orbital inclination and vice versa.

$$\sqrt{1-e^2}\cos i = const.$$

Tidal circularization can reduce the semi-major axis of a planet with a highly eccentric orbit.

Planetary migrations

Gas giants are formed in a gas disk, so there must be planet-disk interactions that lead to type I and II migrations.

If the young planetary system has several gas giants, then there will also be planet-planet interactions.

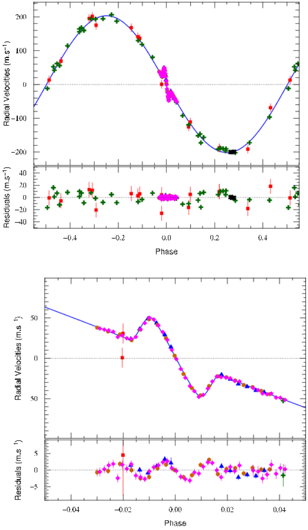
How important are these different types of interactions for gas giant migration?

Orbital inclination

Planet-disk interactions keep the orbital inclinations of planets small, but planet-planet scattering and the Kozai mechanism can produce high orbital inclinations.

Is there a way to measure the orbital inclinations of exoplanets?

Radial velocities



The gravitational pull of an orbiting planet periodically changes the radial velocity of it's host star.

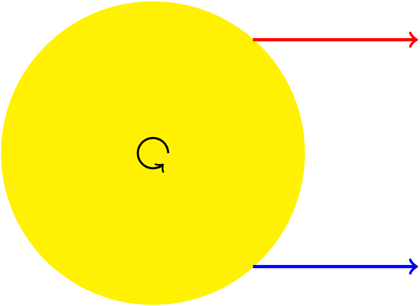
During a planetary transit an additional apparent radial velocity change, known as the Rossiter-McLaughlin effect, can be observed.

Left:
The radial velocity of HD 189733 measured by Triaud et al. (2009).

The Rossiter-McLaughlin effect

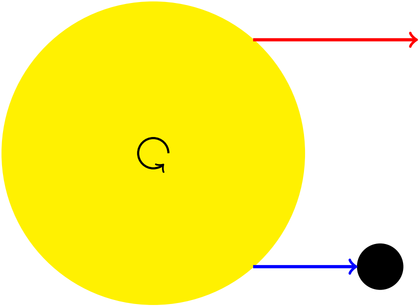
Unless the line of sight is parallel with the stellar rotation axis, different parts of the stellar disk have different radial velocities due to the rotation of the star.

Some of the light is slightly bluer and some slightly redder because of the Doppler effect.



The Rossiter-McLaughlin effect

If a transiting planet blocks some of the blueshifted light the total stellar spectrum will appear redder and vice versa.

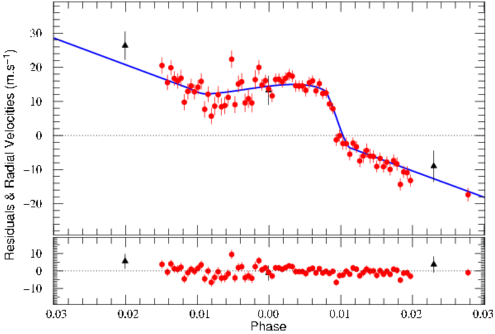


The Rossiter-McLaughlin effect

If multiple high-resolution spectra are taken during different phases of a transit, it is possible to obtain a lot of information about the orbit of the exoplanet.

The Rossiter-McLaughlin effect even allows to estimate sky-projected spin-orbit angles i.e. how is a planet's orbit oriented with respect to the rotation axis of it's host star.

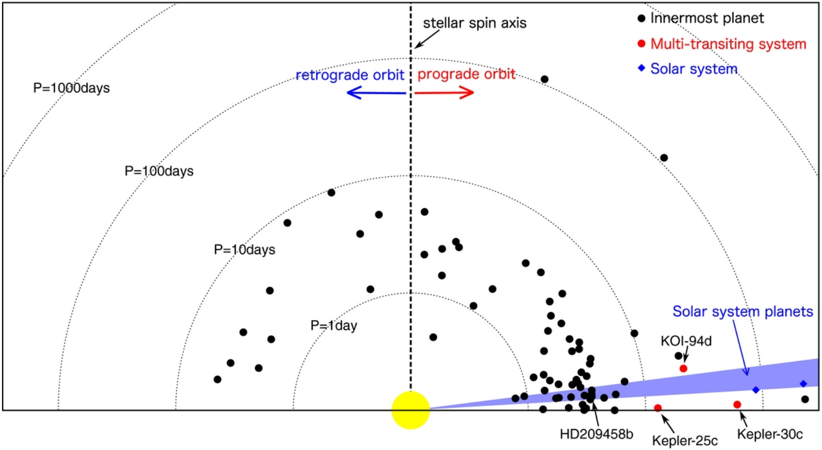
Retrograde orbits



High-resolution spectra allowed to determine that the exoplanet WASP-8b has a retrograde orbit around it's host star.

Left: The radial velocity of WASP-8 measured by Queloz et al. (2010).

Spin-orbit angle distribution



The known sky-projected spin-orbit angles and orbital periods of exoplanets as of August 2013. Figure taken from Xue et al. (2014).

Spin-orbit angle

The large number of exoplanets with very large spin-orbit angles suggests that many hot Jupiters have migrated to where they are due to planet-planet interactions.

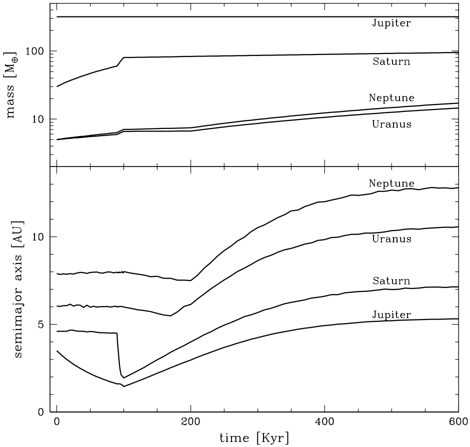
Some researchers believe that it's the stellar rotation axis that is not aligned with the rotation axis of the protoplanetary disks (Lai et al., 2011).

Solar system

Gas giant migration occurred in the young Solar System as well.

Simulations by Walsh et al. (2011) were able to reproduce the properties of the Solar System by including significant gas giant migration.

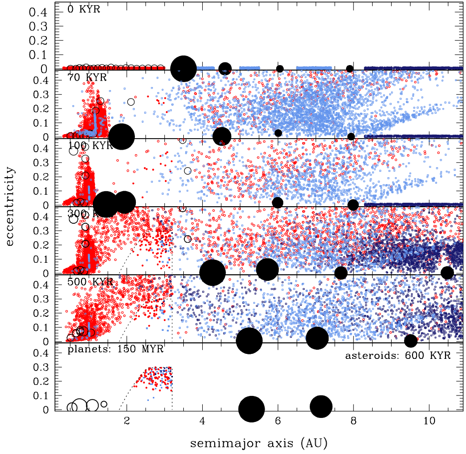
The Grand Tack



Their scenario included Jupiter migrating to 1.5 AU from the Sun and then migrating outward due to the influence of Saturn.

Left: Gas planet parameters by Walsh et al. (2011).

Inner planet formation



Simulations by Walsh et al. (2011) managed to not only reproduce the inner planets but also the asteroid belt.

The Grand Tack model also seems to produce the initial conditions of the Nice Model (Levison et al., 2011).

Left: Figure by Walsh et al. (2011).

Conclusion

Planetary migration is not only responsible for the existence of hot Jupiters, but also for the existence of our Solar System.

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