For newborn planets, solar systems are naturally baby-proof

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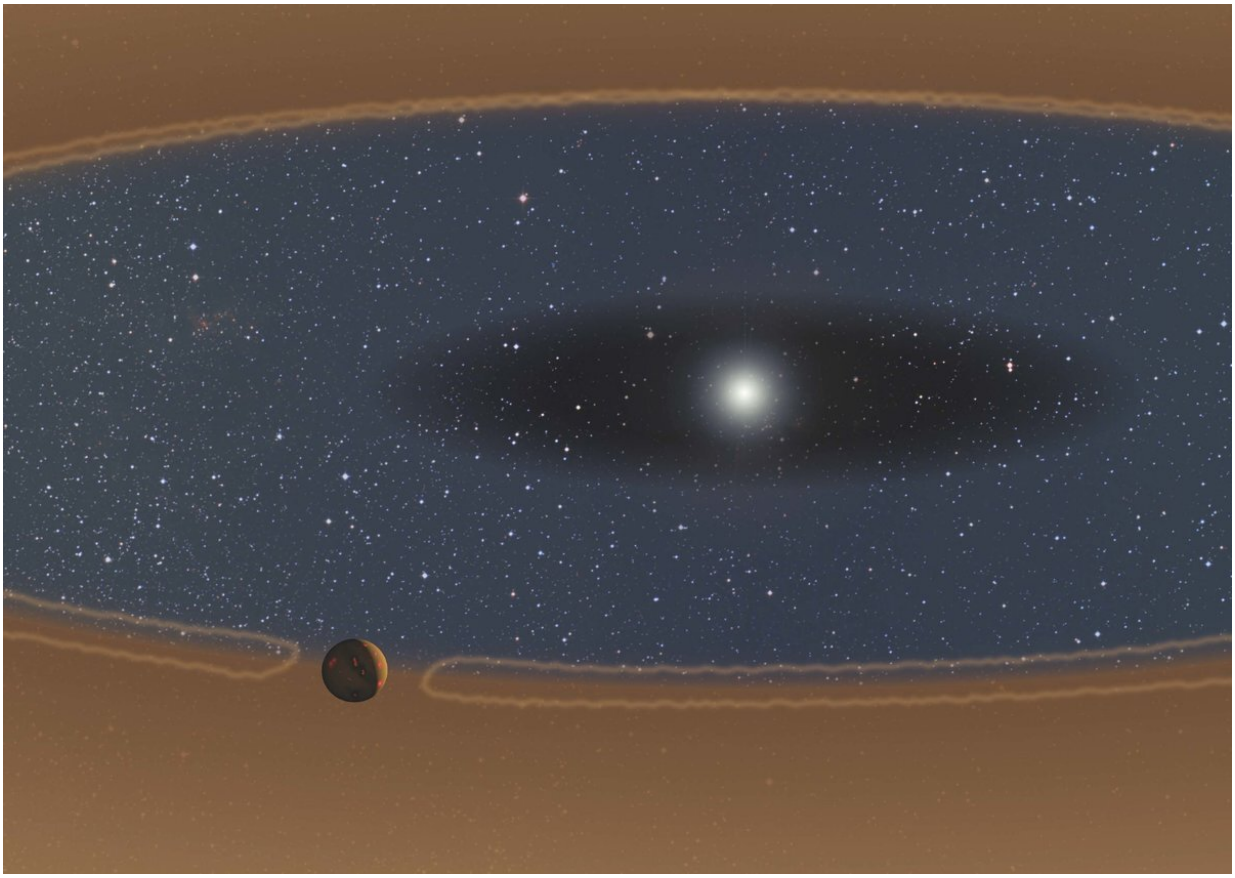

Young planet in a baby-proof system: the new results shows how a boundary within the disk around a young, Sun-like star acts as a barrier that keeps planets from falling into the star. Credit: MPIA Graphics Department

Numerical simulations by a group of astronomers, led by Mario Flock

from the Max Planck Institute for Astronomy, have shown that young planetary systems are naturally "baby-proof": Physical mechanisms combine to keep young planets in the inner regions from taking a fatal plunge into the star. Similar processes also allow planets to be born close to stars—from pebbles trapped in a region close to the star. The research, which has been published in the journal *Astronomy & Astrophysics*, explains findings by the Kepler space telescopes that show a large number of super-Earths orbiting their stars very closely, at the edge of the baby-proof region.

When a child is born, parents will make sure they have baby-proofed their home, setting up safety barriers which keep the child away from particularly dangerous areas. New research on the formation of planets show that something very similar happens in young planetary systems.

Planets form around a young star, which is surrounded by a disk of gas and dust. Inside this protoplanetary disk, dust grains stick together, growing larger and larger. After a few million years, they have reached a few kilometers in diameter. At that point, gravity is strong enough to pull such objects together to form planets, round objects, solid or with a solid core, with diameters of a few thousand kilometers or more.

A curious crowding at the inner boundary

Just like toddlers, solid objects in such a young planetary system tend to move in all directions—not only orbiting around the star, but drifting inwards or outwards. This can become potentially fatal for planets that are already relatively close to the central star.

Near the star, we will only encounter rocky planets, with solid surfaces, similar to our Earth. Planetary cores can only capture and keep significant amounts of gas to become gas giants much further out, away from the hot star. But the simplest kind of calculation for the motion of

a planet near the star, in the gas of a protoplanetary disk, shows that such a planet should continually drift inwards, plunging into the star on a time scale of less than a million year, much shorter than the lifetime of the disk.

If this were the whole picture, it would be puzzling that NASA's Kepler satellite, examining stars similar to the sun (spectral types F, G and K), found something completely different: numerous stars have very closely orbiting so-called super-Earths, rocky planets that are more massive than our own Earth. Particularly common are planets with periods around 12 days, going down to periods as low as 10 days. For our sun, that would correspond to orbital radii around 0.1 astronomical units, only about one quarter of the orbital radius of Mercury, the planet closest to our sun in our own solar system.

This was the puzzle that Mario Flock, a group leader at the Max Planck Institute for Astronomy, set out to solve, together with colleagues from the Jet Propulsion Laboratory, the University of Chicago and Queen Mary University, London. The researchers involved are experts in simulating the complex environment in which planets are born, modelling the flows and interactions of gas, dust, magnetic fields, and of planets and their various precursor stages. Faced with the apparent paradox of the close-orbit Kepler super-Earths, they set out to simulate planet formation close to sun-like stars in detail.

Solar-system-scale baby-proofing

Their results were unequivocal, and suggest two possible reasons behind the common occurrence of closely-orbiting planets. The first is that, at least for rocky planets with masses of up to 10 times the mass of the Earth ("super-Earths" or "Mini-Neptunes"), those early star systems are baby-proof.

The safety barrier keeping young planets out of the danger zone works as follows. The closer we get to the star, the more intense the star's radiation. Inside boundary called the silicate sublimation front, the disk temperature rises above 1200 K, and dust particles (silicates) will turn to gas. The extremely hot gas inside that region becomes very turbulent. This turbulence transports the gas towards the star at high speed, thinning out the inner region of the disk in the process.

As a young super-Earth travels through the gas, it is typically accompanied by gas co-rotating with the planet on an orbital path similar to an horseshoe. As the planet drifts inward and reaches the silicate sublimation front, the gas particles moving from the hot thinner gas to the denser gas outside the boundary give the planet a small kick. In this situation, the gas will exert an influence (in physics terms: a torque) on the travelling planet, and crucially, due to the jump in density, that influence will draw the planet away from the boundary, radially outward. In this way, the boundary serves as a safety barrier, keeping the young planets from plunging into the star. And the location of the boundary for a sun-like star, as predicted by the simulation, corresponds to the lower limit for orbital periods found by Kepler. As Mario Flock says: "Why are there so many super-Earths in close orbit, as Kepler has shown us? Because young planetary systems have a built-in baby-proof barrier."

Planet-building at the boundary

There is an alternative possibility: In tracing the movement of pebble-like, smaller objects a few millimeters or centimeters in size, the researchers found that such pebbles tend to collect closely behind the silicate sublimation front. In order for pressure to balance directly at the border, the thin gas in the transition region needs to rotate faster than usual (since there must be a balance between pressure and centrifugal force). This gas rotation is faster than the "Keplerian" orbital speed of an isolated particle orbiting the star on its own. A pebble that enters this

transition region is forced into this faster-than-Keplerian motion, and immediately ejected again as the corresponding centrifugal forces push it outwards, like a small child sliding off the platform of a merry-go-round. This, too contributes to the frequency of closely orbiting super-Earths. Not only do previously formed super-Earths collect at a baby-proof barrier. The fact that pebbles collect at that barrier as well provides ideal conditions for super-Earth newly forming at that location.

The results did not come as a complete surprise for the researchers. In fact, they had found a similar pebble trap in models of much heavier stars ("Herbig stars"), although at a much greater distance from the star. The new results extend this to sun-like stars, and they add the baby-proofing mechanism for newborn planets. Furthermore, the new article is the first that provides a comparison with statistical data from the Kepler space telescope, carefully taking into account that Kepler will only be able to see certain kinds of systems (notably where we see the orbital plane nearly edge-on).

What about our own solar system?

Interestingly, by these criteria, our own solar system could also have harbored an earth-like planet closer to the sun than the current innermost planet, Mercury. Is the fact that there is no such planet a statistical fluke, or did such a planet exist and was ejected from the solar system at some time? That is one interesting question for additional research. As Mario Flock says: "Not only that our solar system was baby-proof—it is possible that the baby thus protected has since 'flown the nest'."

More information: Planet Formation and Migration Near the Silicate Sublimation Front in Protoplanetary Disks, *Astronomy & Astrophysics*, 2019.