Terrestrial Planet Formation in Binary Star Systems

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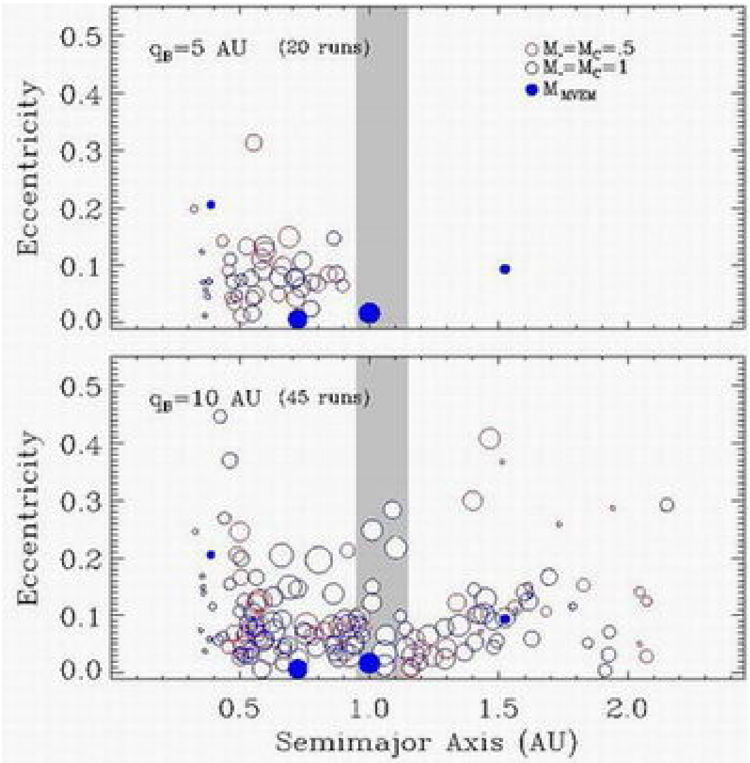
The list of confirmed extrasolar planets keeps growing, and has now passed two hundred members — almost all of which are gas giants like Jupiter and Saturn. But the hunt is on for Earth-like worlds! With the successful launch of France's CoRoT satellite (December 27, 2006) and the promise of NASA's Kepler mission (due to be launched October 2008), the next five years should see the detection of numerous *terrestrial* planets around distant stars. But which stars should these telescopes be pointed at? Recent research has shown that these planets are probably quite common, and can even form in binary star systems.

Scientific interest in the physics of planet formation is at an all-time high. Astronomers and physicists have reached a consensus on the underlying theory, or at least its outlines. A star is born from an immense cloud of gas and dust, which slowly contracts and heats up through the action of gravity. Some of the cloud falls towards the center, where it collects into a hot, dense ball of gas that will eventually become the star. The rest of the cloud orbits the center, contracting and flattening into a *protoplanetary disk*.

Tiny grains of rock and ice stick to each other as they orbit within the disk, eventually growing into 'planetesimals' — small lumps of rock and ice similar to asteroids and comets. At this point gravity speeds up the process of planet formation considerably. Rocky planets form close to the newborn star, where the radiant heat prevents ice from forming. Icy planets form in the cold outer regions, but are much larger to begin with and quickly transform into gas giants.



Each circle in these plots represents a single simulated planet. The horizontal axis gives the radius of its orbit in astronomical units (AU; the Earth's distance from the Sun), and the vertical axis gives the eccentricity of the orbit (zero is a perfect circle). The filled green circles represent our own rocky planets: Mercury, Venus, Earth, and Mars. The grey band indicates the solar system&acutes habitable zone. The lower plot shows planets from simulations where the point of closest approach between the stars is 10 AU (approximately equal to Saturn's distance from the Sun). The inner disk has not been compromised; many planets form in and around the habitable zone. In the upper plot the companion star cuts this distance in half, and planet formation in the habitable zone is no longer likely.

It is now thought that almost all stars are born with a protoplanetary disk — the question is under what circumstances these disks form useful planets rather than a mass of rubble. The method of choice is numerical simulations, which can follow the evolution of a disk by modeling its gas dynamics (in the early stages of planet formation) or the gravitational interactions between planetesimals (in the later stages). Such research has shown that planets should almost always form, at least around an isolated star like our Sun.

Of course, star formation is a more complicated business.

Stars rarely, if ever, form in isolation. More often, a giant molecular cloud will create dozens or hundreds of stars in relatively close proximity. Binary star systems, composed of two stars orbiting their mutual center of gravity, are actually just as common as singles. For stars the size of our Sun, about 50% form in binary systems.

In the search for other worlds like our own, should we limit ourselves to stars like our own? Must we cut the field in half before we start looking? Might binary stars harbor Earth-like planets as well?

The answer, of course, is that it depends on the system. In principle, stable orbits should be possible for planets that are always much closer to one star than the other. But the devil is in the details — if scientists are going to spend valuable telescope time on binary stars, they need to know what they're looking for. How close can two stars be to each other and still form planets? And even if planets form, can their orbits remain stable over billions of years?

A small collaboration of scientists at NASA’s Ames Research Center (Elisa Quintana, Jack Lissauer), University of Michigan (Fred Adams), and the Carnegie Institution of Washington (John Chambers) has taken steps to answer these questions. Modern telescopes can measure the orbital parameters of binary stars quite accurately, so it makes sense to first ask what kinds of star systems will preserve the innermost region of the protoplanetary disk.

The simulations of Quintana and her colleagues are fairly straightforward. After choosing the masses and orbital parameters of the two stars, 140 planetesimals (mass = 1% M_{earth}) and planetary embryos (mass = 10% M_{earth}) are arranged around one of the stars so that their overall mass distribution resembles that of a protoplanetary disk. "The disk is modeled after the Solar nebula," Quintana explains, "we're comparing the planet formation process in these binaries to models of the Solar System." In other words, they are trying to find out what our Solar system might have looked like if the Sun were a binary star.

The simulation calculates the force of gravity between every pair of objects and adjusts their positions accordingly at one-week intervals. When two objects collide, if their speeds are not too high, they stick together into a body of greater mass. Eventually, the system forms a handful of stable, massive planets similar to the inner solar system.

"Each simulation takes approximately 3 - 4 weeks." Quintana tells *PhysOrg.com*. "This corresponds to 100 - 200 million years of simulated time." Dr. Quintana goes on the explain that this is actually rather short, because many planetesimals are thrown out of the disk or into the central star as the simulation progresses. "The same disk of 154 bodies around the Sun, without any giant planets or a stellar companion [to eject particles], takes twice as long."

To explore a wide variety of possible binary star systems and obtain statistically significant results, Quintana and her colleagues performed over a hundred of these simulations — that's several years of computer time!

All of their simulations form at least one planet, an encouraging result. It turns out that the most important factor is the companion star's periastron, or point of closest approach to the star with the disk. A companion that gets as close as the orbit of Saturn (about 10 times farther than the Earth from the Sun) removes very little material from the inner disk, and even speeds up the process of planet formation by nudging the planetesimals into different orbits from time to time. A companion star that gets as close as Jupiter (about 5 times farther than the Earth from the Sun), however, will limit planet formation to the hottest central regions.

“Over half of the binaries [in astronomical surveys] are wide enough to allow planet formation in the habitable zone of solar-type stars.” Quintana concludes. That fraction expands the catalogue of interesting stars significantly, but many possibilities remain unexplored.

For example, it is entirely possible for compact binary systems to share a protoplanetary disk; the planetesimals would just orbit both stars at once. And there is no reason for just one of the stars to have planets!

Another open question in whether icy planetesimals, which normally form beyond 5 AU, can still reach the inner disk to deliver water to the rocky worlds. "It is more difficult," Quintana admits, "but there are many scenarios for having habitable planets in binary star systems." Most of the disk is not treated in these simulations, and there could be plenty of room around or between the two stars for comets and even gas giants to form. The water will probably still be available, but it is too soon to estimate how much of it might reach these worlds.

Physical simulations of planet formation have the potential to answer these questions and more. By the time Kepler and CoRoT start detecting Earth-like worlds, this line of research should have given us a good idea what to expect.

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Dr. Ben Mathiesen teaches physics at the American University of Paris. His agency
Physical Science Editing *helps scientists around the world achieve native English writing standards in their publications.*